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GAS TURBINE ENGINE PERFORMANCE DETERIORATION MODELLING AND ANALYSIS

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SUMMARY

In-service performance deterioration of gas turbine engines can be identified, at the engine module level, in terms of reductions in the component mass flow and the efficiency. Continued operation of a deteriorated gas turbine is (i) uneconomical and (ii) unsafe. Timely identification of the faults and ensuing maintenance could prevent both. Gas Path Analysis is a technique to establish the current performance level of the gas turbines and identify the faulty modules. Computer models can predict the off_design performance of gas turbines by aero-thermo-dynamically matching the engine components. This thesis describes the development of DETEM (DEeteriorated Turbine Engine Model), a generalised computer program, developed to model degraded gas turbine engines and analyse faults.

The program has an integrated graphics module and creates windows on the VDU terminal,for displaying the program output and accepting the user input. This enables the user to compare the results of two different types of runs at the same time. The program incorporates sensor models that modify the output, with noise and in bias, based on the sensor characteristics, thus simulating a real engine. It is possible to simulate the engine performance at design point, off-design and under transient conditions. The runs could be for a "clean" and a deteriorated engine.

Three techniques, iterative, fault coefficient matrix, and a statistical best-estimation technique, have been used to analyse the engine performance and identify the fault. Analysis of two and three shaft turbo-shaft engines and two spool turbo-fan and turbo-jet engines have been worked out in the thesis. Effects of reducing the number of measurements and measuring different engine parameters, on the accuracy of the fault identification, have been studied.

The program is considered to have a potential for the generation of fault trees for rule-based expert system applied to gas turbine diagnostics. Because of the controlled output to the screen, a direct comparison of two different runs side by side, on the same screen, makes the program a good teaching aid for gas turbine diagnostics.

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LIST OF SYMBOLS

a	Matrix coefficients
A	Turbine Inlet Nozzle Effective Area at Station * m2
An	Engine Exhaust Nozzle Effective Area m2,m2
AJN	Exhaust nozzle area
A5	High pressure turbine inlet nozzle effective area
A6	Low pressure turbine inlet nozzle effective area
Apt	Power Turbine Inlet Nozzle Effective Area m2,m2
CN	Corrected Shaft Speed Relative to Design
cp	Specific Heat at Constant Pressure Kg/J K
cv	Specific Heat at Constant Volume Kg/J K
D	Diagnostic matrix
D(subscript)	Refers to design point value
Delta()	Percent change in a variable relative to a design point or a baseline value
DP/P25	(P25-PS25)/P25
DP/P4	(P4-PS4)/P4
E	Scalar quantity representing the sum of the squares of the errors between the actual measurements and the error free measurements
E	Expected value operator
eV	Estimation error vector = x - x
eM	Error vector between actual measurements and noise free measurements = z - Hx
E[·]	Expected Value Operator
ETA-CH(ηCH)	Delta change in high pressure compressor efficiency due to engine degradation
ETA-CL(ηCL)	Delta change in low pressure compressor efficiency due to engine degradation
ETA-F(ηF)	Delta change in fan efficiency due to engine degradation
ETA-TH(ηTH)	Delta change in high pressure turbine efficiency due to engine degradation
ETA-TL(ηTL)	Delta change in low pressure turbine efficiency due to engine degradation
ETACYC(ηCYC)	Overall Cyclic Efficiency
ETASF	Efficiency Scaling Factor
f/a	Fuel/air ratio
g	Acceleration Due to Gravity m/sec2
GAMT2PC(ΓT2)	Change in fan pumping capacity due to engine degradation
GAM2PC(Γ2)	Change in low pressure compressor pumping capacity due to engine degradation

GAM3PC($\Gamma 3$)	Change in high pressure compressor pumping capacity due to engine degradation
H	Output matrix
h	Specific enthalpy J/kg
delh(Δh)	enthalpy change J/kg
hp	Turbine enthalpy drop J/kg
HPpt	Power Turbine Horsepower
In	(n*n) unit matrix
J	Mechanical Equivallent Of Heat m.Kg/J
J	Scalar performance index
Jm	Scalar quadratic cost function representing the weighted sum of the squares of the errors between the actual measurements and the noise free measurements
k	Ratio of Specific Heats (cp/cv)
Mn	Flight Mach Number
M	General (m*m) symmetric positive definite weighing matrix
Mn	Mach number
m	Indicates number of measurement deltas
n	Indicates number of sought for independent deltas
N1	Low pressure turbine rotational speed N1C2 Represents N1/ 2
N2	High pressure turbine rotational speed N2C2 Represents
N1or Ng	Compressor Rotational Speed RPM
Nf	Free Power Turbine Rotational Speed RPM
P	Covariance matrix of estimation error e
P	Designates total pressure when used together with an engine station number. Eg.P2,P3,P6, etc.
Pam	Ambient Pressure N/m^2
PCN	Shaft Rotational Speed Relative to Design
PS	Designates static pressure when used together with an engine station number. Eg. PS25,PS4 etc.
Pr	Probability Function
Pt2	Compressor Inlet Total Pressu N/m^2
Pt3	Compressure Discharge Total Pressure
Pt4	Turbine Inlet Total Pressure
Pt5	Gas Generator Discharge Total Pressure
Pt6	Engine Exhaust Duct Inlet Total Pressure
Pt1/Pam	Flight Ram Pressure Ratio
Q	Mass Flow Function
Qg	Gas Generator Turbine Torque Kg.m
Qpt	Power Turbine Torque Kg.m
Qf	Fuel Heating Value J/Kg
QLR	Quasi-Linear Regression
R	Gas Constant
R	Covariance matrix of random measurement errors

RC	Rating code. Analogous to power lever position
S	variance
SHP	Gas Generator Turbine Shaft Horsepower per
SF	Scaling Factor fo the Specified Parameter
T	Used with engine station numbers to designate total temperatures at the appropriate engine location. Eg. T2, T3, T6, etc.
Tam	Ambient Temperature K
Tt2	Compressor Inlet Total Temperature K
Tt3	Compressor Discharge Total Temperature K
TF	Turbine Flow Function
Wa	Mass Flow Rate of Air HP/Kg/sec
WB3	Change in low pressure compressor discharge bleed
WB4	Change in high pressure compressor discharge bleed
WBH	Change in high pressure turbine cooling bleed
WBL	Change in low pressure turbine cooling bleed
X	Vector representing the Independent Parameter Deltas
X	Estimated Value of X
XN	Engine Net Thrust Kg
XG	Engine Gross Thrust Kg
XR	Engine Ram Drag Kg
Y	Vector of noise free measurement deltas
z	Surge Margin = (PRsurge-PR)/(PRsurge-1)
Z	Vector of actual measurement deltas
(*)	Used to represent engine parameters referred to station 2
2	Relative fan
P	Inlet pressure = P2/101325
2^{o}	Relative fan inlet temperature ratio = T2/288.15
3	Relative high pressure compressor inlet temperature = T3/288.15
	Vector of random measurement errors
*2	Variances of referred measurement deltas.

LIST OF SYMBOLS

Effective Ram	
π_R	Pressure Ratio at Compressor Inlet
π_F	Turbofan Fan Pressure Ratio
π_c	Compressure Pressure Ratio
σ	standard deviation
π_G	Gas Generator Turbine Pressure Ratio

Δ	Difference expressed in %
π_N	Exhaust Nozzle Pressure Ratio
π_t –	Power turbine Pressure Ratio
–	Relative Burner Total Pressure Loss
δ	ratio of Total Pressure to sea-level Pressure in ISA
Θ	ratio of Total Temperatureto sea-level Temperature in ISA
Θ	Engine Performance Noise
η	efficiency
∂	Sign of the Partial Derivative in the Calculus
Γ	Weight Flow rate parameter

SUBSCRIPTS (note that subscipts may be combined, eg., WBlth):

a	air
AB	After burner
act	actual
am	ambient
b	main combustor
Bl	Bleed
c	corrected value
e	exit
f	Fuel
g	gas
id	ideal
H	High-Pressure Spool
L	Low-Pressure Spool
ov	Overboard Bleed
pt	Power-Turbine
th	High-Pressure-Turbine
tl	Low-Pressure-Turbine
1,2,3,4,5,6,7,8,25	refer to station numbers as per ARP and the schematic in Appendix A
T	Transpose of Matrix
-1	Inverse of Matrix

ACRONYMS

BPR	Bypass Ratio
CON	Convergent
DIV	Convergent Divergent
DEL Delta	, Difference Expressed as
EPR	Engine Pressure Ratio
EGT	Exhaust Gas Temperature
ECM	Engine Condition Monitoring
EFF	Efficiency
EGTM	EGT Margin
EMS	Engine monitoring System

FCM	fault Coefficient Matrix
F.A.R	fuel air ratio
FF	Fuel Flow
F.O.D	Foreign Object Damage
GE	General Electric of USA
GPA	Gas Path Analysis
GAM	Mass Flow Function
HPC	High-Pressure Compressor
HPT	High-Pressure Turbine
HD	Hot Day
IPC	Intermediate-Pressure Compressor
IPT	Intermediate-Pressure Turbine
ISA	International Standard Atmosphere (T = 288.15 K, P = 101325 mbar)
JPT	Jet Pipe Temperature
LCV	Low Calorific Value (of fuel)
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
MON	Monitored Parameter
NOZ	Nozzle
OLS	Operating Line Shift
PT	Power Turbine
P&W	Pratt & Whitney
RMS	Root Mean Square
RR	Rolls Royce Ltd
SEN	Sensor
SHP	Shaft Horse Power
TET	Turbine Entry Temperature
TIT	Turbine Inlet Temperature

INTRODUCTION

The phenomenon of deterioration in gas turbine engines can render their operation uneconomical and unsafe. A Knowledge of the true state of the gas turbine is essential to assess its performance capability to meet the operational and the maintenance requirements. An early detection of the cause of a deterioration permits appropriate maintenance activity to be undertaken which can restore the engine performance and/or ensure safe operation. Gas turbine aero - thermodynamic relations have been successfully modelled for some time. Computer programs simulating such models have proved to be a useful tool for developing models of specific engines. An aero thermodynamic interactive generalised program **DETEM** (**DE**teriorated **T**urbine **E**ngine **M**odel) has been developed to simulate the performance of the new and the deteriorated gas turbine engines. The program is similar in concept to the others, utilises steady state component characteristics, and obtains the solution through component matching. This thesis describes the philosophy of the gas path analysis in the gas turbines, the technique of deterioration modelling and analysis to diagnose faults. The description of the computer program and its extension from TURBOMATCH are included.

Computer programs normally incorporate steady state maps for the component modules, and these are modified in the present program to simulate the deteriorated gas turbine engines. The simulation is a generalised program which can model any type of gas turbine. The necessary changes in the characteristics are incorporated for the compressor and the turbine modules only, since they are considered to deteriorate most. Simulation of a deteriorated engine is achieved by re-matching these components with modified characteristic maps.

The structure of the program is modular incorporating integrated graphics. The output of the engine can be directed to a controlled area on the VDU terminal, where separate windows are defined by partitioning the screen. For major outputs, the screen is normally split in two vertical halves, thus allowing the user to make a direct comparison of the two states of the engine that are displayed in each of the halves. Similarly the input to the program is through prompted windows, pasted on the screen at the appropriate time, thus making the program highly user friendly.

In chapter 1 the requirements, benefits and various techniques of Engine Condition Monitoring are discussed. The nature and the causes of degradations in the gas turbines during their operation have been studied in chapter 2. Even though, based on the literature available, the study was primarily on the aero gas turbine engines, similar effects are observed in industrial applications . The industrial gas turbine engines have additional effects which have been discussed. The philosophy and the techniques of the Gas Path Analysis are developed in chapter 3. A review of current mechanical condition monitoring techniques in the gas turbines, has also been made in the study. This aspect of Engine Condition Monitoring is an equally important part of an integrated gas turbine engine condition monitoring system as the gas path analysis. The mechanical condition monitoring techniques including the life usage monitoring applications have been discussed in chapter 4.

The measurements and characteristics of measurement are included in chapter 5, while chapter 6 deals with filtration of the noise in the measurements and the engine performance. The concept of the artificial intelligence, and its applicability to gas turbines has been reviewed in chapter 7. The program structure and modelling technique are described in chapters 8 and 9, while chapter 10 reviews the analytical techniques.

The program is capable of modelling any type of gas turbine engine and outputs the user specified data to a nominated file with or without the measurement error modelling effects. The engine model in DETEM contains a set of steady state performance maps of all the components. The engine degradations are modelled through changes imposed on these steady state maps. Various engine parameters are first calculated using the "clean" component characteristics, then the calculations are repeated after degrading the component characteristics. Based on the factors relating to the engine degradation, only the Compressor and the turbine characteristics are changed as per the level of degradation.

Engine gas path monitoring technique in its simplest form has been achieved through trending, with reference to a base line. Three other techniques of analysis of the measured engine data, have been incorporated in the program. The program has the capability to develop the fault coefficients matrix and the sensor fault coefficients for the engine. All the three techniques of analysis studied utilise the fault coefficient matrix to detect the error in measurement and the level of degradation of the source engine. The first technique is an iterative technique of analysis that does not depend on any prior knowledge of the engine degradation history. Based on the measurements and the base line developed, errors are generated and the component characteristics are altered to eliminate these errors.

Analysis with a single fault and with faults in combinations have been carried out. The ability of the program to detect the module level faults including its power to detect the presence of a new module in a degraded engine, has been shown. This technique though requiring lot of computational effort, is ideal for study of the degradation effects even during design. Since no a-priori knowledge base is required to be build up this technique proves useful to the users of the gas turbines. The sensor validation window is developed by the program along with base line generation and is used to detect and isolate measurement errors.

The fault coefficient matrix technique is a straightforward application of the matrix generated by the program. The detection program is quite accurate for single errors in the vicinity of the values of 0.5 - 1.5% of degradations. The statistical technique requires prior knowledge of the nature of degradations and depends on the probability density function of the engine degradations and the instrumentation. For a representative engine with hypothetical distribution of degradations this technique was applied. The determination of the sensor faults and the level of degradation was computed separately from the main program.

Various faults were implanted in the generating program and were detected by the techniques of gas path analysis. The effects of a change in the number of instruments and of replacing a measured parameter with another was studied. The effects on four different types of engines viz. two spool turbo-jet engine, two spool high by-pass turbo-fan engine, single spool and two spool gas generator turbo-shaft engines were studied. The program being a general one, is considered to be very useful in simulating single or multiple faults in any of the components generating realistic engine data through the sensor models. Paper studies of many different engine configurations and different levels and combinations of deteriorations can be studied with DETEM.

The friendliness of the program and the display of results side by side on the screen gives the program a potential as a teaching aid. It can be effectively used to build the fault trees for application of the expert system to gas path analysis. The program also incorporates a module to build-up, interactively, the input file for the program run. This module also makes use of the VAX screen management system, thus allowing the user to input the data for the initial run through a series of question/answer techniques, and allows data input in the "prompted" windows.

CHAPTER 1

GAS TURBINE ENGINE CONDITION MONITORING

General

A knowledge of the engine condition is important for the assessment of the operating **efficiency**, diagnosis of the engine **deterioration**, and an early prediction of the failures. Deterioration in the gas turbines can be defined as a slow degradation of performance due to a variety of effects. These effects can be either microscopic, eg. change in blade surface roughness, decrease in blade surface area, vane bowing, seal wear, non uniform fuel distribution, choked nozzles, aerofoil contour changes, increased tip clearance, FOD etc, or, they could be macroscopic, such as, change in efficiency, change in area or mass flow etc. An effective way to identify these factors and to determine the damage caused, is, to measure the performance of the engine and diagnose.

Need to Monitor Gas Path

The inherent need for gas turbine engine monitoring and diagnosis is as old as the engine itself. Pilot or other member of flight crew monitor the engine performance in various critical and non critical phases of flight. Similarly the operators of the industrial gas turbines is required to monitor if the power developed by the gas turbine, at a constant rpm for example, is sufficient to maintain the desired output of the equipment. In a given configuration, for a particular setting of controls, when the aircraft fails to achieve a flight speed (or a speed during take off in a specified run length), the engine is termed as "ill". Similarly when a helicopter cannot come to hover at a given all-up-weight and environmental conditions or the engine fails to deliver specified torque at a given rpm the engine requires to be checked.

The basic necessity of monitoring the gas turbine for its control was enhanced by the high costs of the fuel which required the gas turbine engines to operate as close to the peak efficiency as possible. A 0.5% increase of specific fuel consumption as a result of engine degradations, could amount to a million £ for the fuel costs of 200 million £. Similarly for the power consumed in the pipeline operations a typical 9MW gas turbine fuel costs about $160 per hour and maintenance costs $7-10 per hour [1977 data ,Canadian $]. Thus it has been suggested that a 3 % drop in efficiency was enough to justify an engine overhaul of the industrial gas turbines in pipeline operations, regardless of its mechanical health [SARAVANAMUTTOO,1983].

Engine condition monitoring started with the flight crews comparing the level of engine-to-engine performance across the wing. Because of inherent engine-to- engine performance deviations, resulting from the production tolerances during manufacture of the engine and the differences in total time accumulated on each engine, this procedure was only of a limited value and not considered adequate to diagnose the engine fault explicitly. This technique was found to be of limited capability in the industrial field as well. While in this case it was possible to detect the engine deterioration, the cause of the problem could not be easily identified.

<u>Development of Gas Path Analysis</u>

This rough procedure was later followed by comparing the performance of each engine to cruise charts in the aircraft manual; this accordingly, presented cruise tables, suited to allow a direct comparison of the performance of each engine, to the performance of a nominal engine. A follow-up of the above method was the introduction of an engine performance calculator, normally in the form of a circular slide rule, in order to perform the comparison without interpolation, regardless of the altitude, Mach number, ambient temperature and engine thrust level.

Based on these post-flight reports, engine discrepancies were determined. Pilots sometimes are unable to define the exact nature of the fault and assess short-comings quantitatively. Further, in multi-engine aircraft they may not be able to identify as to which engine had malfunctioned [BIRKLER,1984]. In such cases, either trouble-shooting of all the engines is carried out, or an identifying sortie is flown. Because of the involvement of the crew in their other functions, there can be an occasion when a particular message from the engine has either gone unnoticed or has been ignored. An alternative approach, to the crew monitoring the engines, could be to record a few parameters, either as and when required, or, on a continuous basis, and analyse the recorded data after the sortie. Recording of the plant and the engine data at regular intervals has been followed in the industrial field. It is often felt that manual data recording is not adequate for performance monitoring. But this may be because of lack of planning of log sheets, poor instrumentation readouts and the lack of motivation by the operator. If the operator feels that the recorded data that was diligently recorded, was ignored at the head office, the quality of the data recorded later on, is likely to be an eye wash.

The next step in advancing the art of the ECM was the introduction of manual recording and trend analysis procedures. This too had many shortcomings, only cruise data could be recorded, a crew member had to be an expert on trending the un-smoothed data and this method does not always ensure timely discovery of problems which can lead to an emergency situation. This method is however cheap and monitors the engine in real-time. In the industrial field the operator could trend a few parameters at a time and at constant load conditions which enabled the experienced users to diagnose, by comparison between the behaviour of different parameters, and knowing their inter-relationship, the cause of the performance short-fall. The change in compressor mass flows for example gave an extremely simple but effective means of indicating the compressor fouling.

True gas path analysis for predictive/diagnostic purpose had its origin in Project Easy [SMETANA,1974]. Probably the earliest published work in this area came from the US Army AIDAPS (Automatic Inspection Diagnostic and Prognostic System) program, for use with military helicopters. The complexity and cost of modern gas turbine engines requires installation of engine propulsion management system to decrease crew work load. Since most of the parameters to be monitored are available on the propulsion management system or the flight data bus, the best alternative is to is to tap and record this data. The present day monitoring recorders use the data buses such as AIRINC-429, AIRINC-582 and Mil 1553B where almost all the parameters needed for gas path analysis are available eg. on V2500 to effect condition monitoring through Rolls Royce COMPASS, only three additional parameters, other than those available on AIRINC 429, had to be tapped [BARWELL,1987].

Maintenance Requirement

The saturation of today's gas turbines with a large number of complex mechanisms and instrumentation requires a large number of qualified personnel, demands more maintenance time and results in increased operating costs. The unscheduled maintenance performed on basis of flight crew reports or ground maintenance activity (preflight post flight or periodic inspection) works out very costly. Lufthansa estimates that an engine change costs between $20,000 and $250,000 [LEFER,1979] while Quantas estimate a cost of $400,000 [VAN DE WATER,1985]. This led to the concept of Engine Condition Monitoring which following 20 years of development and experience is now an integral part of the economics of large engine operation. For each engine a point of operation is reached, below which expensive repairs and replacements occur too soon; and above which unacceptable deterioration would occur. It is economically essential to defer "heavy maintenance" to this point. This point varies between individual engines and can be determined only by an effective condition monitoring technique. The process of analysing and assessing failure monitor indications is something of a science it self. On-board computers are now available and being used to assist trouble-shooting and performance degradation analysis.

The Life Cycle Costs for gas turbine engines, especially the industrial ones, are strongly influenced by maintenance and fuel costs. Additionally, penalty costs associated with non-availability and catastrophic failure can be of utmost severity. Any system that can help to increase the thermodynamic efficiency, reduce maintenance costs and minimise the probability of catastrophic failures, especially in critical service, would have a very significant impact on reducing LCC. The modern gas turbines are very reliable though complex and costly. Hence the diagnostic systems have become more cost effective. The key word in diagnostics is the accuracy. This is effected through increased sensor reliability, hardware reliability and software systems.

Diagnostics are likely to change the maintenance philosophy, in that the operators, instead of going by a schedule, will carry out maintenance only when the diagnostics demand it. Another value of diagnostics is at the time an engine visits the repair shop. Through diagnostics it is possible to know in advance, the work needed to restore its performance so that parts can be made available in time. The possibility of removing the identified defective (by the diagnostic system) module instead of stripping the whole engine apart, saves time of trouble-shooting and hence costs. The programs also simulate replacement of the module in the engine without actually doing it, to see how the new module would affect the engine performance.

The current mechanical condition monitoring techniques are complementary to one another, operators are unlikely to take an engine out of service solely on the basis of one, without confirmation by other techniques of mechanical health monitoring. One area where future development is expected to occur is in the field of automatic recording and analysis of the gas path. Performance monitoring determines the economical and the operational capabilities of the engine, it thus can dictate an engine removal even in otherwise "good health".

Hostile Environments and Gas Turbine Maintenance

Gas turbine engines operate in various kinds of environment, ranging from the effects of the drilling dust in off-shore operations, to sand ingestion. In many of the continuous operation processes, it may not be feasible to take an engine out of service even for planned servicing. An accurate assessment of the operating load characteristics of a gas turbine can help extend hardware inspection intervals. Knowledge of the operating load history holds particular significance for a multi-body gas turbine driven chain. The operating logs, start counters, and hour meters have been traditionally used with knowledge of the environment and the unit's service experience.

Modern armed forces operate in highly stringent and less predictable environments, under peculiar distribution, size and quality of threats. This requires future propulsion systems to be more reliable, durable and maintainable. Ease of engine installation and removal enables quick turn around thus increasing aircraft availability and number of sorties flown. Although cannibalisation is a wrong way of maintenance the ability to rapidly cannibalise engine parts, accessories or even modules could be essential when operating limited number of aircraft from remote bases or even from main bases with damaged spare inventories and infrequent resupply. Thus cannibalising modules without knowledge of the module performance could jeopardise complete engine performance.

Better engine diagnostics and monitoring capabilities can reduce turn-around, the time spent trouble-shooting and isolating faults and can enhance confidence in selecting healthy aircraft for deployment or dispersal options.

Depending on the anticipated use, thermodynamic models of differing levels of complexity may be applied. For example by the user in the field or by engineering staff at a central base. Three possibilities may be considered.

(1) Simple models for early warning of engine degradation. This would require minimum sensors

(2) Detailed models used in conjunction with an engine performance test. Additional instrumentation would be required for such a model.

(3) Automatic or semi-automatic systems for online analysis, trending of data which is recorded or tele-metered. This could only be justified in remote operations or on complex stations where computer control is already in use.

Gas Turbine Diagnosis

The problem or symptoms of degradation in the gas turbines appearing as performance deficiencies are really a chain of cause and effect. Trouble shooting works backwards to define these elements of the chain and then proceeds to link the most likely or probable cause. This is quite akin to a failure analysis, the only difference being that the symptoms in trouble shooting appear as performance deficiencies with no apparent failure modes. A thorough knowledge of components and their interaction, operation mode and failure mode is very essential for the trouble-shooter.

Trouble shooting must contain certain diagnostic steps whether the cause of the fault is known, suspected, or unknown. Thus diagnostics can be described as the method of reaching a diagnosis (recognition). The diagnosis could be after a component of the system has failed (failure analysis) or for the purpose of monitoring its health. The health monitoring technique and its application based on performance and condition data for a gas turbine is placed as Appendix A.

All types of machinery (incl. Gas Turbine Engines) give some kind of warning signal before a failure. These signs of the system if analysed properly can lead to the right cause.

Two levels of deterioration normally occur. First occurs suddenly (**instantaneous**) possibly as a result of some transient condition, abuse of operation or because of failure/ingestion upstream of the gas path. Such a damage is normally severe and may give little or no warning eg. fatigue failure of compressor blades or creep/fatigue failure of turbine blades. At other times the damage could be so light that even after the damage has occurred, there may be little or no noticeable change in the monitored parameters and the damage may go undetected for sometime during which further deterioration of the effected part takes place. No amount of monitoring, at any expense, will detect the onset of such failures. These failures could possibly be detected during maintenance or anticipated/predicted from the known history of the engine operation.

The second level of deterioration is **gradual** eg. fouling crack growth, erosion etc. This deterioration can be detected through monitored parameters and an estimate of life/service can then be made. Estimation of the occurance of a failure or of the performance reaching an uneconomical operation status is possible. For known components with a well defined rate of degradation, a very simple ECM system is sufficient. For gas turbines, the rates of degradation are seldom known and normally are non-linear.

There is a stage in between the two, which could be referred to as **delayed time-dependent**. For these failures, there is no detectable change upto some point in service, after which a deterioration is observable. This kind of failures allow some time for corrective action but depend very much on the ability to identify the first appearance of the deterioration symptoms. This requires a very sophisticated system of diagnosis.

Diagnostic systems must monitor such mechanical and aerothermal parameters as are necessary, to analyse the problem [BOYCE,1982] and schedule proper preventive maintenance. For modern gas turbines an effective diagnostics system would involve utilising a set of complex set of parameters and in order to keep track of all these parameters and their inter action with each other, this means a computer based system. The health monitoring and diagnostic systems should accomplish the following:-

1. The Diagnostic information and failure predictions must be well before serious problems on the gas turbine occur.
2. In doing so there should be minimum of spurious warnings.
3. Diagnostics must be precise enough in identification and rectification/preventive recommendations.
4. The program must be user-friendly so as not to involve experts on the system for small problems.
5. The system should be reliable and simple and require negligible maintenance.
6. The system should be flexible enough to incorporate improvements in the state of art of instrumentation and diagnostics.
7. The system should have expansion capabilities to accept increase in the number of gas turbines monitored and/or in the number of channels.
8. The system must be cost effective i.e. should cost less to operate and maintain than the expenses resulting from not monitoring the engine.

Engine Performance Monitoring defines the subset of ECM that is concerned with aero-thermodynamic behaviour of the engine and its ability to produce a specified power, or, for a given fuel input. There is clearly a strong coupling between the thermodynamic behaviour of the engine and its mechanical health. **Gas Path Analysis** is a technique of performance monitoring that uses the instrument readings to deduce other more critical parameters not measurable directly in the field eg. turbine inlet temperature, mass flow, efficiency etc. Relationships of these parameters with the knowledge of their present values are used to determine the present performance level of the engine. This performance can then be compared with that expected from a healthy engine and the fault diagnosed.

Gas Path Analysis

The Gas Path Analysis can hence be conceptualised as a three stage procedure. First, the engine operating variables are obtained (measured and/or recorded). These values are then compared with the operating point variations eg power level and ambient conditions. Finally the comparisons are used to infer the probable cause of the inability of the engine to meet the required performance level.

Gas path analysis may be effective with a very small increase in sensor requirements, but an automated system would require a substantial increase. The present work does not envisage any addition on the existing instrumentation system, and hence all the analysis is developed based on the present sensor technology in use in the gas turbine engines.

Engine Condition Monitoring Systems

Engine Condition monitoring in general can be split into two categories viz ; ground based and aero gas turbines. Many of the ground based gas turbines are aero-derived and since weight is not a major criteria they can accommodate increased number of sensors. The basic industrial gas turbines normally incorporate more instrumentation. The Hour meter does not provide operating time at various loads, hence automatic recording should be incorporated to monitor the speed and the temperature with time [TOLER,1984]. Long life and economics of operation are important. Cost of peak time shut down due to a failure can be extremely high. To ensure mechanical integrity and detect incipient failures well in time, extra sensors for vibration are generally provided. The instrumentations for monitoring a typical ground based gas turbine are given in Appendix A.

Aero-engines condition monitoring is divided into three categories based on the type of gas turbine and its usage. These categories are (1) transport aircraft engines (big engine for long steady operation), whether military or civil airlines.(2) Fighter and Bomber aircraft engines where the power requirements vary abruptly and (3) The helicopter engines (small engines with highly manoeuvrable flights).

For civil transport operators safety and economy of operation are major consideration. Unscheduled engine change especially away from the base is inconvenient and costly. The concept of on-condition maintenance was an out growth of reliability studies and cost considerations of maintaining new commercial aircraft. At the same time high costs of the fuels warranted efficient and economic operation of all the engines. On a 30 aircraft fleet of 3 engined wide bodied aircraft, the annual fuel bill is approximately $200 million [CROSBY,1986]. A 0.5% deterioration in specific fuel consumption will hit profits by around $1 million on fuel alone. Thus to identify the performance shortfall and ensure economical operations, the gas path analysis technique is usually employed on almost all the big engines.

Gas path analysis can be used not only to monitor overall engine performance but also to identify which module is deteriorating, and sometimes even to pinpoint the part of the module responsible for performance shortfall. The application of the concept of engine condition monitoring (both gas path and mechanical health) to commercial airlines resulted in significant reduction of maintenance cost over that experienced under the fixed time overhaul concept at the same time increasing reliability and availability of the aircraft.

Benefits achieved by the commercial airlines attracted the department of defense (DOD and MOD). The requirements of reduction of costs, improved availability and reliability without increasing risk are common between civil and military operations. Engines similar to civil transport eg. TF-39 on C-5A, were put under condition monitoring program and over-hauled based on-condition rather than life. New engines procured, had the maintenance requirement based on the engine condition (on-condition monitoring), as part of the logistics support plan eg TF34, F100, F101, F404 etc.

The military and civil transport aircraft have redundant systems and operate under similar conditions. For these engines gas path trending was accomplished to identify incipient failures. The fighter aircraft may not have a redundancy eg F-16 has only one F100 engine. Moreover the fighter engines are high technology, complex design operating in the supersonic flight range with high pressure, high bypass ratio and consequently changing internal geometry. The aircraft missions subject the engines to high gravitational forces, frequent and extreme throttle excursions and operations over a broad altitude range. These factors together with short engine lives and the fact that efficient regime of operation on earlier engines could not be maintained, inhibited gas path trending on fighter/helicopter engines.

There are two basic approaches to the engine condition monitoring : (1)The short term advantages of analysing flight information immediately after the sortie to improve maintenance decisions and (2) The long time benefits to be gained from providing information on the actual operating environment experienced by engines. Time between overhaul periods for most high performance gas turbines engines used as propulsion systems for defence platforms such as fighters, helicopters and ships, are determined by the operational life times of the High Pressure turbine (HPT) components i.e. the first and second stage blades and stator vanes in the hot end of the engines. The second approach utilises the flight information to determine the exact excursions of loads these components were subjected during the flight and obtain an estimate of life used. Various programs of engine condition monitoring for fighter aircraft engines are centred around the concept of engine usage life. Some of the engine condition monitoring programs in the USA and the UK are included in Appendix A.

Future of Gas Turbine Engine Condition Monitoring

Key future activities involve the use of real-time intelligence to improve propulsion system performance and operability by closed loop control. Some areas where this technology can have significant impact could be :

1. Compressor stall alleviation

2. Active clearance control

3. Secondary flow modulation

4. Active pattern factor control based on blade stresses or temperatures.

On board computational capacity (processing and storage) has increased tremendously and is likely to increase by orders of magnitude by the year 2000. This increase in capacity can be employed to improve greatly the traditional fuel control. The nature of gas turbine components and sub-systems is likely to be influenced by the modern technology computers and new designs of a closed-loop type of operation, resulting in an optimal performance are likely to be evolved [EPSTEIN,1986]. The enhanced computer capability can also be used for failure detection, isolation and accommodation of advanced sensor systems to improve reliability and operability [BEATTIE,1986] incorporating real time decision making (expert systems) logic. Use of Artificial Intelligence systems for effective fault diagnosis, prognosis, and sensor failure detection, isolation and accommodation in real time is imminent.

The present technology instrumentation is aimed at the measurement of: surface flow, rotating frame measurement of flow and stress, hot section measurements (flow and metal temperature, heat flux, temperature stress etc.), on-line assessment of structure (flaw detection, creep etc.) and improved sensor life and reliability. Even though at present this is limited to research instrumentation, it is likely to be used for real time on-line condition monitoring of the gas turbine engines.

The need for an effective diagnostic system and the modern technology make it feasible to have a real time analyser on-board. In accordance with the need for user acceptance, it is clear that, as far as possible, existing instrumentation should be used. Hence the new systems with elaborate instrumentation must be fully justified to the user and may only be considered for new applications without being retro-fitted to existing installations.

Review System identification techniques, for assessing the components in the gas path of gas turbines, have advanced significantly in the past few years. The details of the models and levels of diagnostics possible vary enormously between the techniques. This is a reflection of the management of the gas turbines in different applications, which varies from whole gas turbine down to the module level. Many current condition monitoring systems were initially designed for a supervisory role, especially in aeronautical use where aim was to relieve the crew of the task of monitoring the engines. The economical benefits of engine performance monitoring, for operation as well as for maintenance, aroused interest of all gas turbine users. For the industrial gas turbine the key issue is an avoidance of incidents and costly down time, while minimising the preventive maintenance activities. A brief review of gas turbine condition monitoring has been carried out in this chapter. The effects of performance deterioration are known but causes have to be determined. These causes are the subject of study in the next chapter.

CHAPTER 2

GAS PATH DEGRADATIONS

Introduction

In-service performance deterioration in any mechanical device, such as a gas turbine, is inevitable. Gas turbines operate over a wide range of temperatures, speeds, power and environments. All these cause a deterioration of the gas turbine performance which can be defined as the cumulative effect of the performance degradations of various modules that constitute the engine. These modules are themselves composed of components such as blades, seals casing etc. This chapter describes, qualitatively, the mechanisms that generate microscopic degradations at the component level in each module. The effects of various factors are explained and the methods to determine the cumulative effects of these degradations to generate macroscopic level performance degradations, (module level) are reviewed. The quantities occurring in Figures of this chapter are typical representative values and hence insignificant quantitatively. Even though the chapter is based on the study of performance deterioration of aero gas-turbines, the nature of the deterioration is applicable to industrial gas turbines as well. The difference in the two types of gas turbines is however in the type of environment and hence in absolute level of the degradations.

Nature of Engine Deteriorations

Service use imposes external distortion loads and differential thermal growths which are slightly in excess to those experienced during the post build engine running-in testing. These excesses wear seal clearances and are responsible for the degradations. Analyses of data, from existing aircraft, related to engine performance deterioration show Fig 2.1 [CROSBY,1986] that in-service performance deterioration of gas turbines does not follow a linear path with use but a rate which diminishes. The performance deterioration can in general be broken into two time frames :

(1) That which occurs in the first few hundred flights after entry of an engine into service, called short term deterioration; and

(2)That which occurs more gradually as service usage accumulates, called long term deterioration.

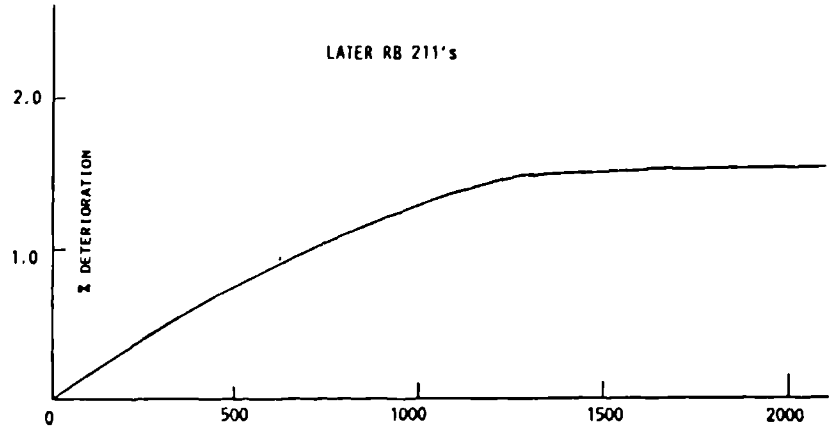


FIG. 2

FIG 2.1 Deterioration of A Gas Turbine In Operation

Engine performance deterioration results from the degradations in mechanical condition of the engine parts. Five causes of this degradation can be identified :-

1. **Flight loads** which are responsible for rubbing contact on any of the seals between the static and rotating parts and account for the major part of deterioration in the early stages of an engine's service life. The effects of flight loads can be :-

   (a) Centrifugal growth of the rotating members
   (b) Distortion of the shape of the engine casing
   (c) Axial movement of rotating parts either due to rotor end losses or "flapping" of the rotor blades due to some induced vibrations.

2. **Thermal distortion** produced by changing turbine inlet temperature pattern resulting in:

   (a) Area changes
   (b) Increased leakages
   (c) Changed clearances
   (d) Relative thermal growth between the static and rotating members.

3. **Engine operating procedures** and operator repair practices and re-build standards that effect cumulative levels of part mechanical damage versus time and the level of pre-repair and post-repair performance.

4. **Erosion** of aerofoils and outer seals resulting in
   (a) Increased roughness
   (b) Increased bluntness of the leading edge
   (c) Loss of camber
   (d) Loss of blade length
   (e) Increased operating clearances

5. **Deposits** The air utilised by the gas turbines brings along a variety of material which can deposit on the compressor blades or even pass down to turbines. A typical example of the deposit is the drilling mud in off-shore gas turbine operations. The drilling mud deposits on a HPT nozzle of a typical gas turbine are shown in Fig 2.2. Fouling of compressor blades in pipeline operations has also been reported [SARAVANAMU TTOO,1985]. There is also a tendency of the dirt to deposit in in the cooling air ports thereby decreasing the turbine blade cooling air flow and causing secondary damage.

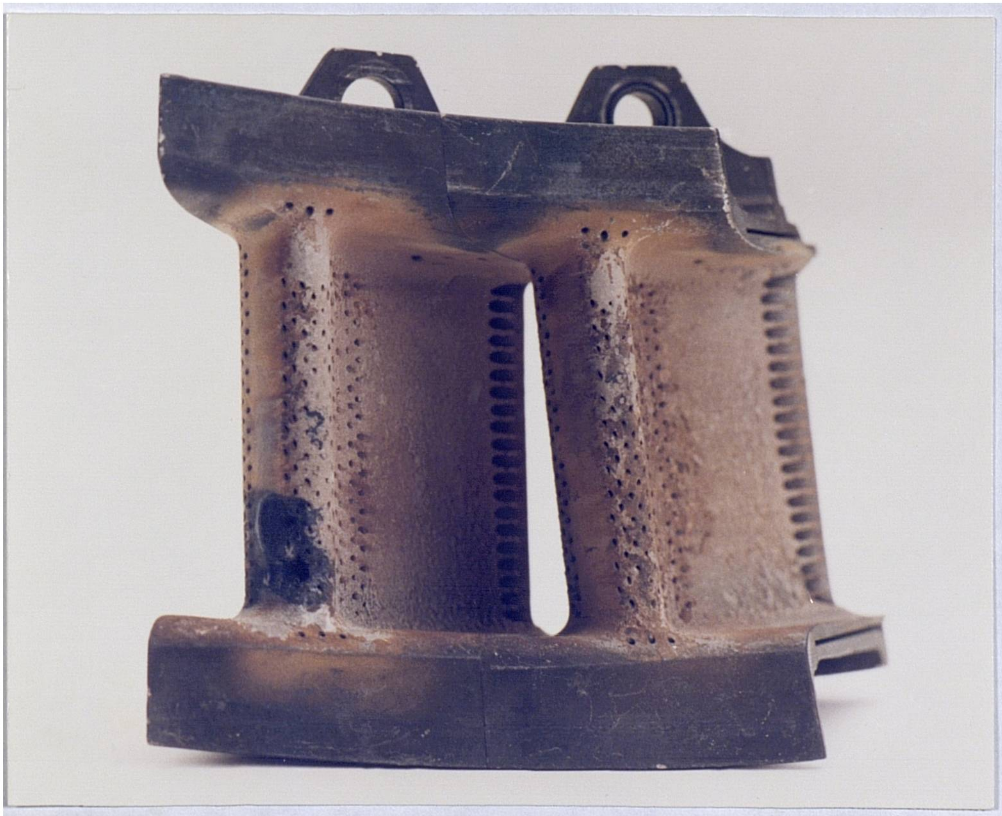


Fig 2.2 Drilling Mud Deposits on The HP Nozzle Guide vanes of a Typical Gas Turbine in Off Shore Operation.

As the engine rub down takes place, there comes a point when no further wearing of the seal, and increase of the clearances occur except under the rare instances of violent manoeuvres. The rate of mechanical deterioration diminishes. Erosion of seals and blades due to the ingested particles or depositing of dirt (fouling) on blading and in the cooling cavities however continues along with a random occurrence of FOD. Since the change over from high rate of deterioration (short term) to the very low rate region depends on the throttle movement at high power rather than with hours of running, the rate of deterioration is generally correlated to the number of throttle movements at high power rather than hours of operation. A flight consists of take-off, climb, cruise, descent and landing phases. Civil aircraft spent majority of the flight time at cruise conditions, when, the engine operation is at low speeds, pressures and temperatures, contributing little to the deterioration. For transport aircraft engines usually a flight is a cycle, whereas for fighter aircraft engines a single flight may consist of a number of cycles. Similarly for the industrial gas turbine engines a start-stop sequence is one cycle. Thus for all gas turbines the correlations are normally with respect to number of cycles.

Flight load induced losses

The increased diameter and tighter running clearances of current high bypass ratio engines have increased sensitivity to the effects of flight manoeuvre loads. During the first few flights there is a performance loss which does not exist during the final acceptance tests of the production engines. The most likely cause of this performance loss is the change in the engine running clearances caused by either the thermal or flight load conditions, not experienced under static test conditions.

The flight load induced deterioration occurs in all of the modules; however the major impact is in the fan, LP compressor and HP turbine. The increased gas path clearances are caused by combination of mechanical effects, such as steady state and transient aerodynamic loads, gravity forces, gyroscopic effects and engine transients etc. The design will not in practice be perfect and there will be inevitable axial and radial movements of the blades relative to their seal linings during engine service and particularly so during the transient operations i.e. acceleration - deceleration. All of which tend to move the rotating blades and seals relative to the stationary case mounted seals. The resulting rubs open the gas path clearances. Contact caused by the axial movement will result in greater wear of the blade tips than pure radial movement. The losses for the most part are estimated to occur early in the engine life and shortly after the engine rebuild.

Distortion of the annulus casing which define the aero-dynamic gas path and blade tip clearances, can be minimised by mounting them flexibly to the engine carcase. A carcase composed of short stiff casing with direct supports to bearings on short stiff shafts minimises bending. Tight seal clearances with minimal contact wear can be maintained if such a carcase is coupled with flexibly mounted inner casing. Fig 2.3 shows the distortion effect of the thrust for RB211 engine mountings [CROSBY,1986].

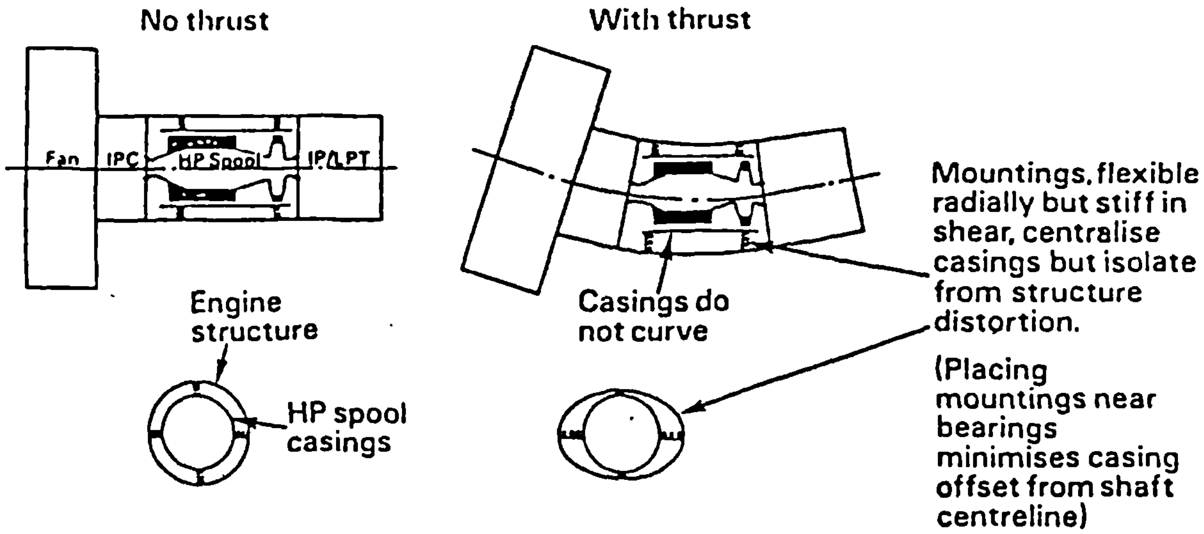


Fig 2.3 HP Spool-Isolation of RB211 Casing From The Engine Structure [CROSBY,1986]

Performance loss due to erosion/deposits

Aircraft engines (commercial and military) are often exposed to foreign objects such as birds, hailstones, ice slabs, runway gravel etc. Erosion can be defined as the wearing away of aerofoil and seal surfaces by the impingement of foreign matter in the gas path and thus occurs primarily during near ground operations Fig 2.4 [PETERSON,1986]. The extent of erosion damage is thus a function of number of take-offs and the conditions at the airports served. At other time they may operate in conditions where the atmosphere is polluted by small solid particles, either the dust blown up by the wind or the industrial dirt and grime, especially in the vicinity of airfields. Some of the mechanisms that can cause foreign object ingestion are: (a) vortex from engine inlet-to-ground during high power setting - Fig 2.4, especially in chin type intake (b) thrust reverser efflux at the runway (c) dust blown by sand storms, even at very high altitude. Helicopters in particular may operate with the inlet air highly polluted with sand blown-up by the rotor downwash. Modern fighter aircraft that fly following the terrain ingest insects, birds, smoke, pollen and grime etc. Sand and salt spreading on the runways during the winter and ingestion of the armament exhaust plumes also contribute to the solid particle ingestion by aircraft engines.

Gas turbines in offshore platforms operations are subject to ingestion of salt and the products of the drilling operation. The industrial gas turbines in general operate in a poor atmosphere, some may be located in the rural or remote areas far from industrial dirt and grime; but in an atmosphere containing insects, pollen and tree sap. Quite often a number of gas turbines operate adjacent to one another and there is a possibility of ingesting the engine exhaust or the oil vent blown by the wind.

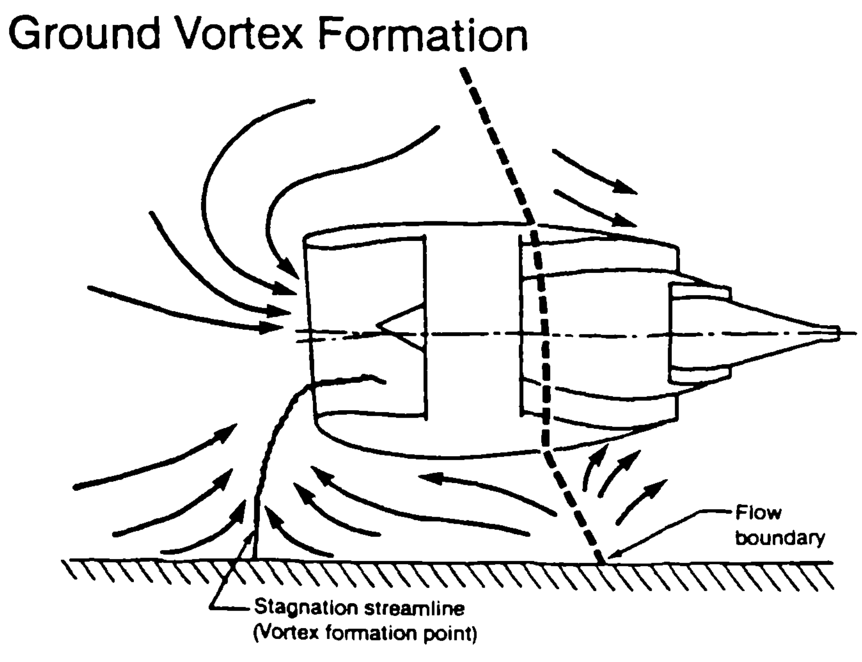


Fig 2.4 Dust Ingestion of a Typical Podded Turbo-fan Engine Due to Ground Vortex Formation [PETERSON]

In many advanced fuels, solid particles are formed as by-product of the combustion. Previous attempts to directly coal-fire a gas turbine experienced operational difficulties due to erosion, corrosion and fouling of the turbine which led projections of the limited turbine lifetimes. The renewed interest in the technology has been kindled by recent advances in corrosion resistant metal alloys, blade cooling techniques, [AHLUWALIA,1986], coal preparation (grinding and cleaning) and coal gasification. The use of pulverised coal as fuel in many power plants and industrial establishments is attractive both at present and in the future. Serious erosion of the nozzle and the turbine blades edges (leading and trailing) is caused by the suspended fly ash in hot combustion gases when coal is the fuel.

The presence of solid particles in the working media lead to performance deterioration of these engines both structurally and aerodynamically. Depending on its nature, the suspended impurities could cause erosion or deposition in gas turbines and degrade its performance.

Erosion

The solid particles, either ingested along with the air flow or by-product of combustion, along with the air flow, form a two-phase flow condition. Under this flow conditions the gas and particles experience different degree of turning as they flow through the blade channels. This is mainly due to the differences in their inertias. The major interacting force between the gas and the particles is the viscous drag. The ratio of the viscous forces and the inertia forces experienced by the particles determines the degree of turning, acceleration and deceleration. Depending on their size and weight, the solid particles tend not to follow the flow in the blade passage, and to impact the blade surface and the inner and the outer annulus.

Two effects arise because of the particles. The first is a change in the blade surface pressure distribution, which alters the engine performance during the period of particle ingestion. Recently several serious incidents have been related to jet engine failures due to operation in particulate environments. Example are, a British Airways Boeing 747, on 23 June 1982, had to switch off all its four engines when encountered a cloud of volcanic ashes in cruise at 36,000ft and also a Singapore Airline 747. The second effect of the particles is the severe erosion due to the impact of particles on the blade surface causing permanent loss of performance and can lead to structural failure [TABAKOFF,1986]. This damage is manifested in the pitting and cutting at the blade leading and trailing edges, a decrease of the blade length, bluntness of leading edge and a general increase in the blade surface roughness. This increases coefficient of friction increasing boundary layer thickness, changes the flow characteristics and decrease surface area. Fig 2.5 shows a typical bade erosion of a J57 turbofan compressor blade [BATCHO,1987]. The overall effect of this is an increase in the total pressure loss across the blade row. In case of severe erosion damage, the blade life can be adversely affected and structural failure of the blade might result.

The erosion problems are generally recognised in aviation (military and commercial). The operating life for sandy area operation in helicopters is very short [TABAKOFF 1986]. Erosion in current commercial turbofan engines primarily attacks rotor blades, stator vanes and outer shrouds in compressors. Refurbishment of these components is typically required at any time within 3,600 to 14,000 hours of operation depending on the axial position of the aerofoil within the compressor, the aircraft route, and the cycle usage of the engine. Separators are commonly used in sandy operations, but particles of small size may not be separated out and can cause erosion damage.

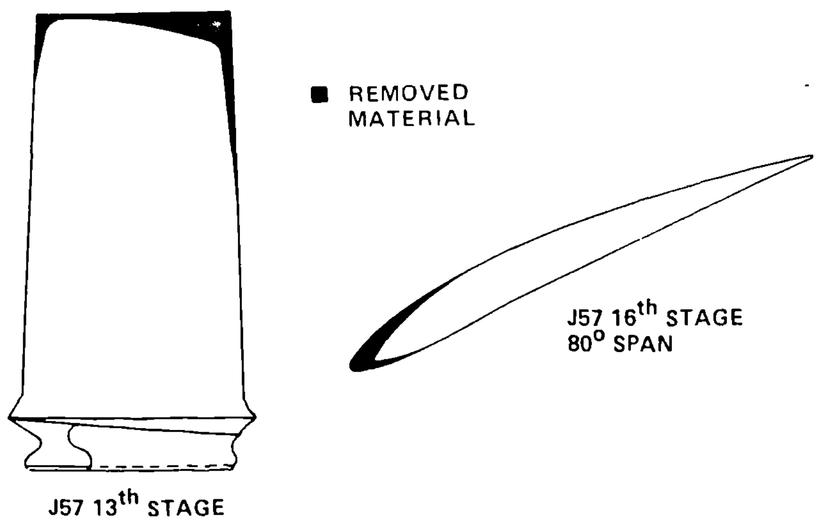


Fig 2.5 Typical Blade Erosion of The HP Compressor of a Two Spool Turbojet Aircraft Engine.

The erosion rate is affected by the impacting velocity, impingement angle, the blade and gas temperatures and by the particle and target materials. The particle dynamics are affected by the blade passage geometry and the operating conditions. Even though the trajectories and erosion effects of the particles can be predicted by applying the experimental erosion data, this would involve knowledge of particle impact location as well as their impacting velocities and impingement angle relative to the blade surfaces. The particle trajectories and their radial and circumferential distribution is altered after every blade row. The ratio of the rebounding to impact velocity and angle are generally different for different particles and target materials, these rebounding particle characteristics affect subsequent trajectories. Drastically different patterns of particle blade impacts, associated with different particles, have been found experimentally [HAMED,1986a]. Thus in a multistage turbomachinery, repeated impacts with different stationary and rotating blade rows make the particle dynamics complex.

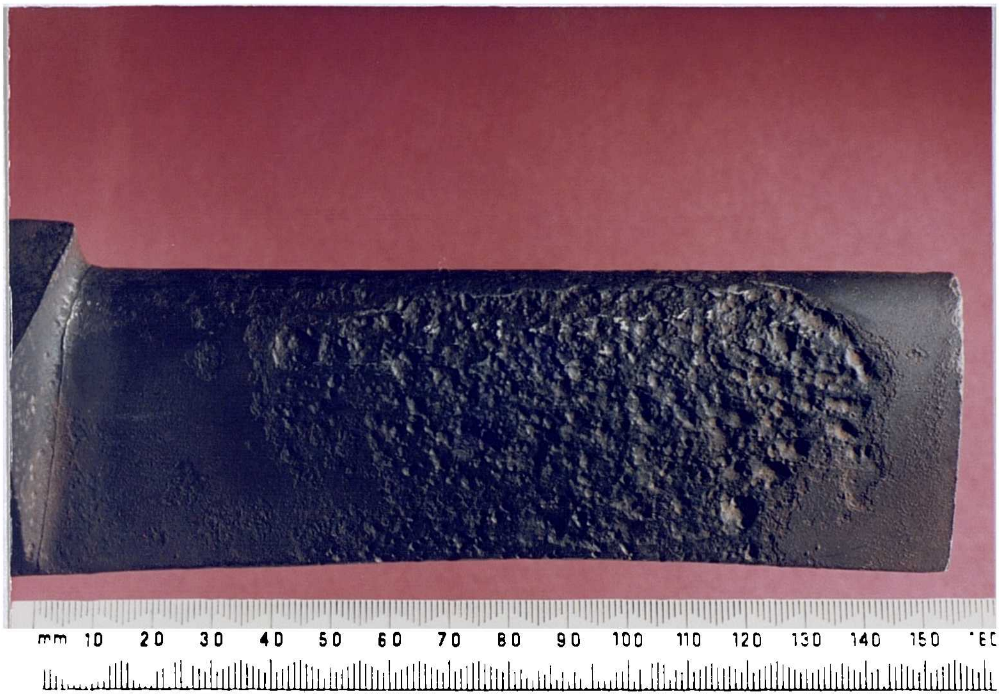


Fig 2.6 Erosion of a Typical Industrial Turbine Blade

Erosion effects of particles on multistage turbines have been studied by Hamed [HAMED,1986b]. In the turbine, the solid particles present in the flow, can produce pitting and cutting of the blade edges and increase the blade tip clearance and surface roughness. In multistage turbine, the erosion damage primarily occurs at the leading and trailing edges of blades and is usually confined to the pressure surfaces [MENGUTURK,1986]. Erosion is more severe on rotor blades than the nozzle vanes [BEACHER,1986]. The location of the blade row influences not only the magnitude of the blade erosion but also the erosion pattern and the location of maximum blade erosion. The first rotor represents the most critical blade row erosion both the maximum local and the overall. In the first stage the maximum nozzle vane erosion is at the trailing edge and the maximum rotor blade erosion is located instead at one third of the blade height from the tip and is concentrated on the leading edge and pressure surface. Fig 2.6 shows a typical turbine blade erosion pattern.

It is not clear whether critical erosion indeed occurs in the first stage of a turbine or in the subsequent stages. It is possible for the following stages to be exposed to higher rates of erosion due to increased deflection of particles from the gas streamlines after repeated impacts with the blade surfaces. The rest of the blade rows in the multistage turbines suffer the maximum erosion at the outermost radial location. The erosion pattern is quite similar to the impact frequency distribution over the blade surface. Erosion rates at the trailing edge are generally lower than the leading edge. This erosion of already small blade thickness at the trailing edge, can present a serious problem. The maximum blade trailing edge erosion are generally at the blades outermost radius in all blade.

The useful life of the machine appears to be dictated by the thinning of the first stage rotor trailing edge. However accurate assessment of the multistage turbine erosion is dependent on the availability of the basic erosion and the impact rebound data for the specific particle and the blade materials involved and the complete range of typical operating temperatures and velocities.

The prediction of blade erosion in multistage turbomachines presents a very difficult problem. The blade erosion pattern depends on many factors such as the blade row location, the blade geometry, the particle characteristics (material, shape, size etc.), the blade material and the conditions of flow. The pattern hence is complex and the prediction of erosion is quite difficult.

<u>Compressor</u>

The overall effect of compressor blades damage, from aerodynamic viewpoint is an increase in the total pressure loss across the blade row [TABAKOFF,1984]. In view of the complexity, the prediction of erosion, as well as the change in cascade performance, represents a difficult problem. Compressor performance deterioration by particulate environment can be represented in terms of pressure distribution and efficiency variation as shown in Fig 2.7. Similar change in compressor characteristics due to deposit in the compressors in pipeline operations is shown in Fig 2.8 [SARAVANAMUTTOO, 1985].

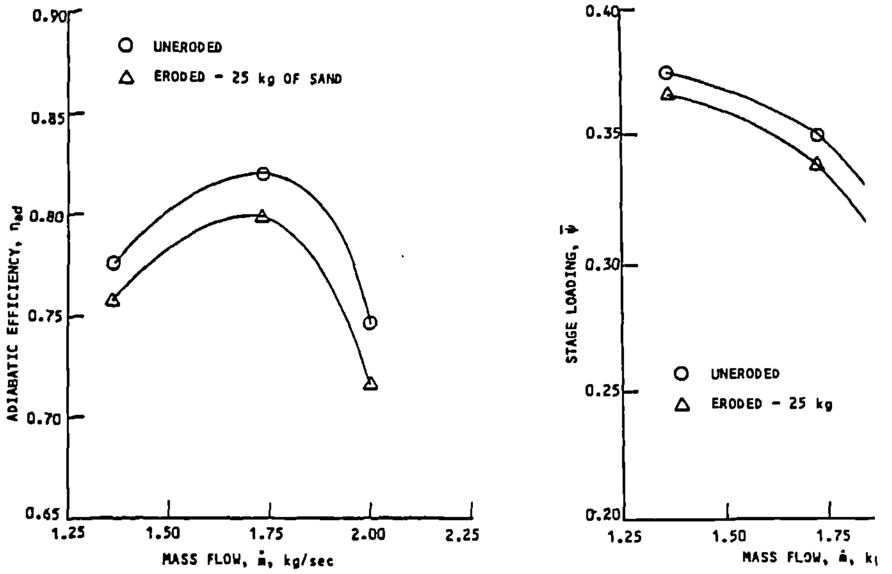


Fig 2.7 Changes in Compressor Characteristics Due to Erosion [TABAKOFF,1984].

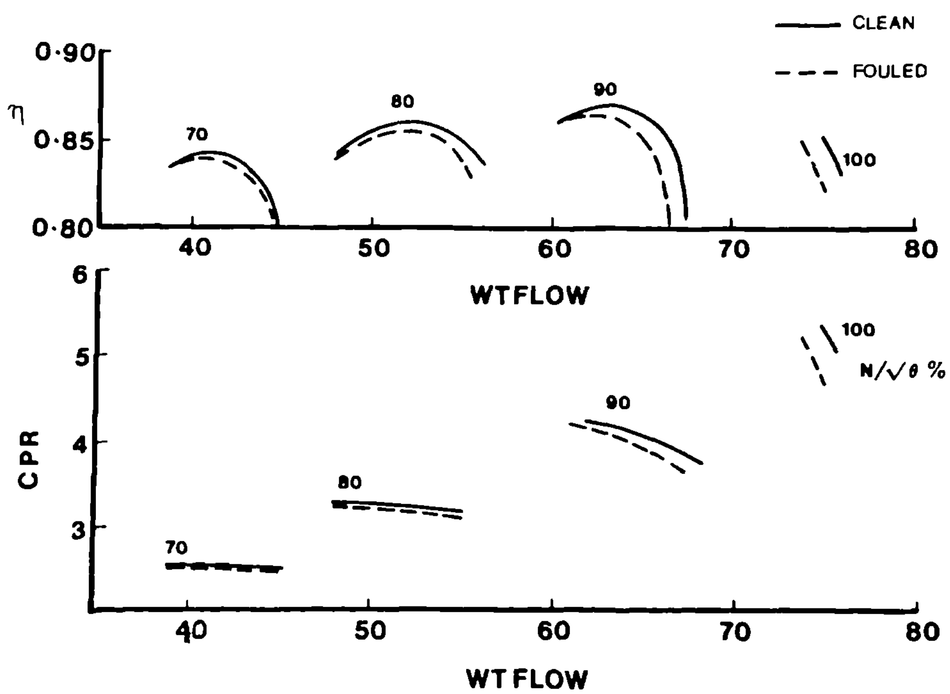


Fig 2.8 Effects of Fouling on the Compressor Characteristics [SARAVANAMUTTOO,1985].

Turbine

The overall effect of the erosion at the turbines is to increase the nozzle area and lower the efficiency of the turbine The solid particles in turbine cooling air can cause plugging of cavities, reducing the cooling flow and causing higher turbine blade temperatures. For example in GE CFM56 the amount of ingested dust in the cooling air supply and its accumulation in the cooling dust, in some cases led to blade tip and leading edge distress. Fig 2.9 shows the effect of overheating on the turbine blades. A larger diameter hole was added in the CFM56 turbine blade tip cap at the end of an internal passage leading to the blade leading edge cavity [PETERSON,1986].

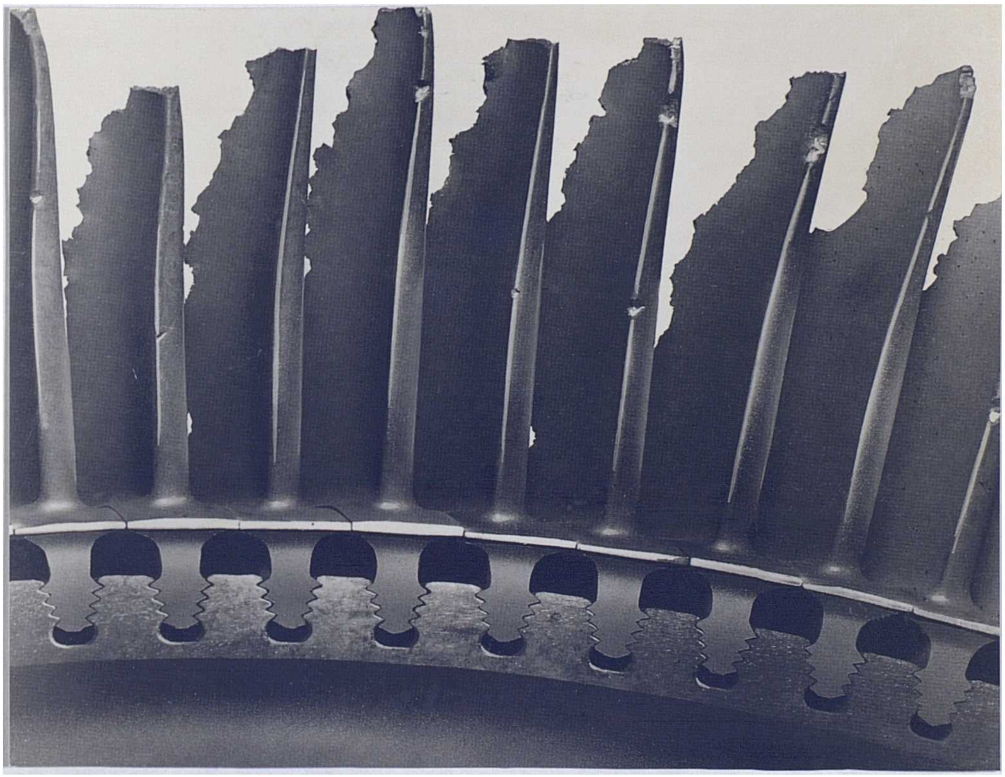


Fig 2.9 Overheating Damage on Turbine Blades.

Fouling

The impurities ingested along with the air can have a tendency of sticking to the surface (deposit) of the blades or stator vanes resulting in both a reduction in the flow area and a change in the blade aerofoil. Because of the mixed nature of the ingested material, the deposits occur mainly on the compressor stators and rotor blades. The oil-seal leak in the compressors allows the oil to escape onto the aerofoil where it forms a sticky surface attracting dirt particles from the air flow.

Another possible cause of the fouling are the exhaust gases from other plants at the same location and the oil vapours from the vents. The effect of local winds may be critical in some locations, with adjacent gas turbines [SARAVANAMUTTOO,1985], affected to a markedly different degree. The fouling of the compressor leads to a decrease in the compressor mass flow and isentropic efficiency. The turbine deposits mainly arise from by-products of modern fuels. Deposits on turbine nozzles and blades arises from molten ash (Vanadium, Sodium and sulphur contents of fuels) at high temperatures. The effects of the deposits is to decrease the nozzle areas and lower the efficiency.

The decrease in the mass flow results in a decrease in the power output necessitating an increase in the compressor speed to maintain a required power level. A decrease of efficiency causes higher turbine inlet temperature thus decreasing the engine life and increasing cost of operation.

Particle separators and cyclones can remove large percentage of damaging particles, but significant amounts of small particles ranging in the sizes between 1 and 20 microns still pass through and enter the engine. On high by-pass engines such as RB211, centrifuge effect of the fan deflects heavy particles down the fan duct. This separation is aided by the spacing between the fan exit and core inlet [CROSBY, 1986].

Microscopic degradations

Erosion, corrosion and deposits on blades are in general responsible for changes in the aerodynamic characteristics, changes in the blade strength and its dynamic characteristics, notch effects associated with erosion and accelerated material fatigue due to change of material properties caused by corrosion. Erosion also effects the attrition lining of the casing which form the blade tip seals thus increasing the tip clearances. Increased friction losses change the aerodynamic characteristics of the flow and thicken the boundary layer. This causes a shift in the transition point and flow separation. The increase in aerodynamic and frictional losses decrease the efficiency and increase total pressure loss.

Aerofoil Erosion

The ingested foreign objects strike the fan blade causing bluntness of the leading edges. This leads to changes in the airflow stagnation point and incidence, resulting in a flow disturbance around the leading edge with performance loss. Fig 2.10 [JASPAL,1984], shows the fan blade leading edge deterioration. Apart from the leading edge curvature change the chord length is reduced, because of erosion of material from the leading and trailing edges of the aerofoil. This results in increased local aerodynamic loading of the aerofoils and eventually effecting the stage efficiency. Fig 2.11 [JASPAL,1984] shows the HP compressor chord erosion rates for various types of environments. The third effect is on the surface finish, when increase in surface roughness causes fall in the efficiency.

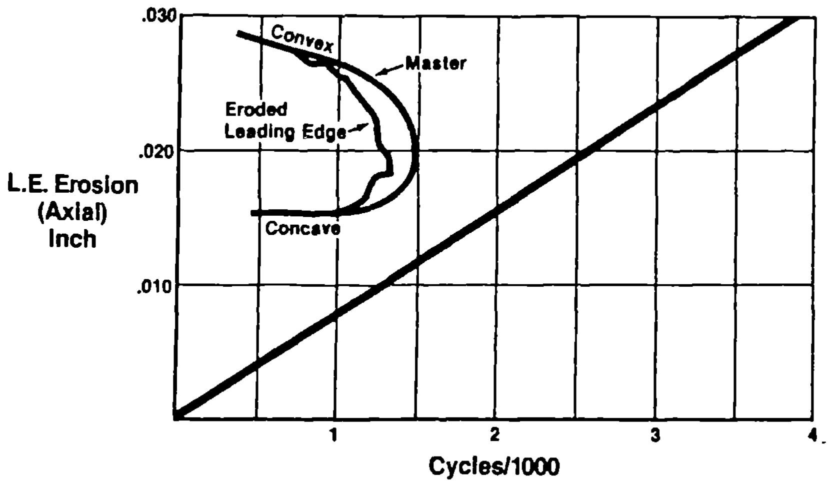


Fig 2.10 Fan Blade Leading Edge Erosion

Shroud Erosion

Fan stator shroud erosion increases the effective blade tip clearance. The vortex generated by tip leakages entraps dirt. If the tip clearances are low then quantity of dirt entrapped in the vortex will be low and cause little erosion.

Aerofoil Surface Finish

The surface coating can be eroded by the impingement of the particles. Effect of increased roughness on the aerofoil has been discussed earlier. The LP turbine aerofoils are susceptible to corrosive action, which may be non recoverable if allowed to deteriorate beyond a certain limit Fig 2.12 [JASPAL,1984]. The surface finish on the suctions surface of aerofoils is more critical than that of the pressure surface because the accelerating pressure surface flow is less likely to separate than the suction surface flow where some diffusion can occur.

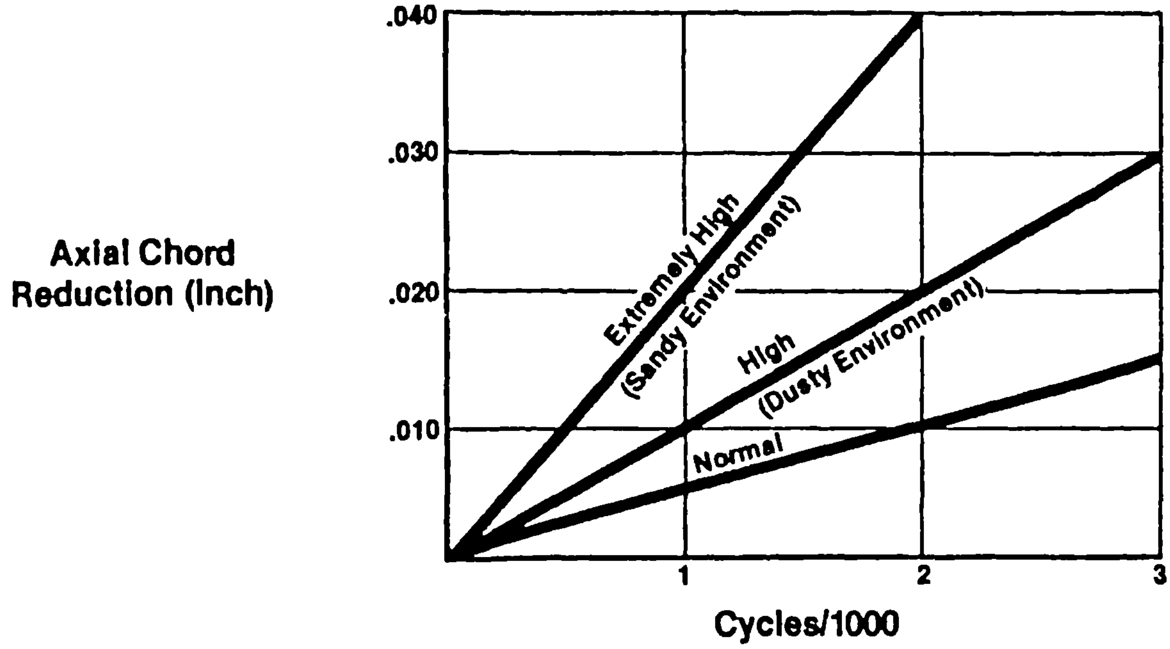


Fig 2.11 HP Compressor Blade Chord Reduction Due to Erosion [JASPAL,1984].

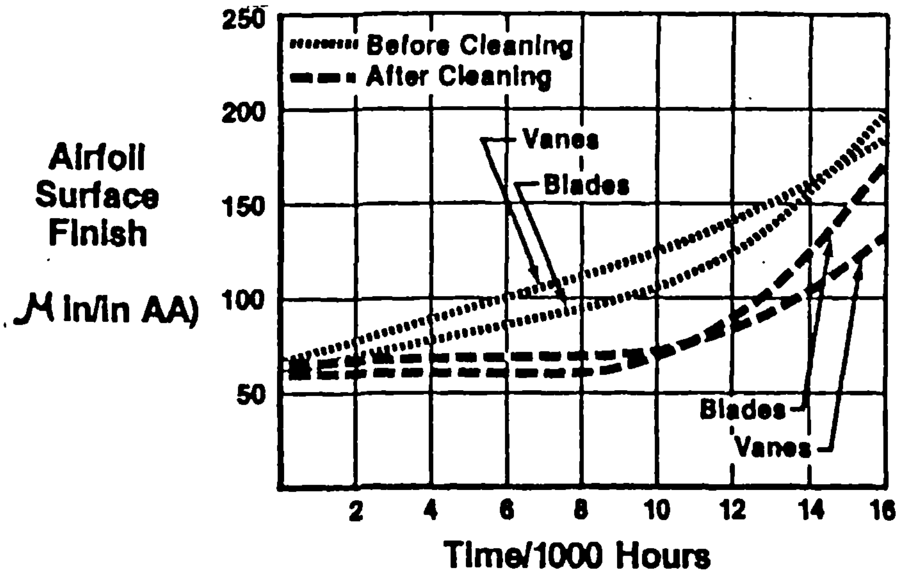


Fig 2.12(a) Deterioration of LPT Airfoil Surface Finish and Effects of Surface Corrosion.

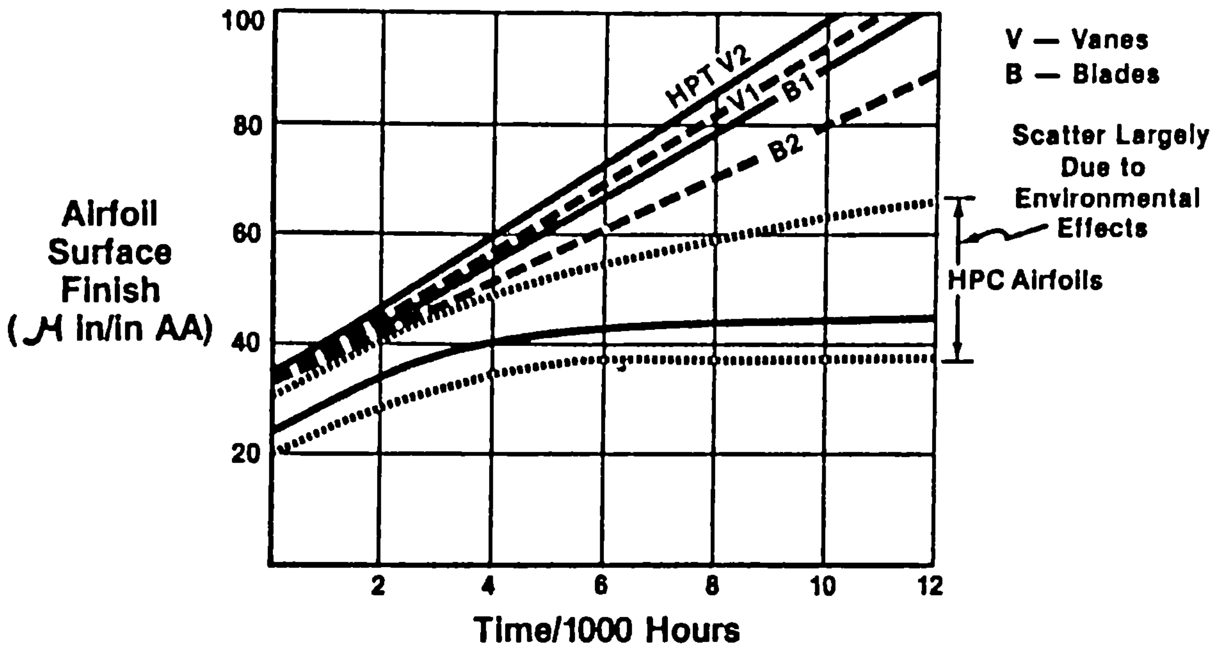


Fig 2.12(b) HP Turbine/Compressor Airfoil Surface Finish Deterioration by Erosion.

Spalling of HP compressor Casing and spool rubcoating

The HP compressor and rotor spools are coated to protect them from rub damage. However during operation these coatings have a tendency to spall under thermal cycling causing an increase in aerofoil tip clearances. The spalled material splatters on the downstream aerofoil surfaces and increases aerofoil surface roughness. The HP compressor aerofoil surfaces are affected by the spool and casing rub coating spalling. The contribution to performance loss due to HP compressor aerofoil surface roughness is normally more significant than the increase in clearance resulting from spalling. Engine derate effects the HP compressor spalling rate as shown in Fig 2.13. High derate and therefore low engine temperatures reduce spalling rate.

Seal clearances

Most labyrinth seals are designed to accommodate rub during the transient conditions. The tolerances in the seal clearances are minimised to reduce the leakage losses. The seal clearances normally change only in the break-in period and are constant thereafter. The rub depth rate could be, in certain cases, dependent on the engine derate. The seals that can affect the engine performance significantly are the compressor discharge pressure, mini nozzle, HP turbine and LP Turbine interstage seals.

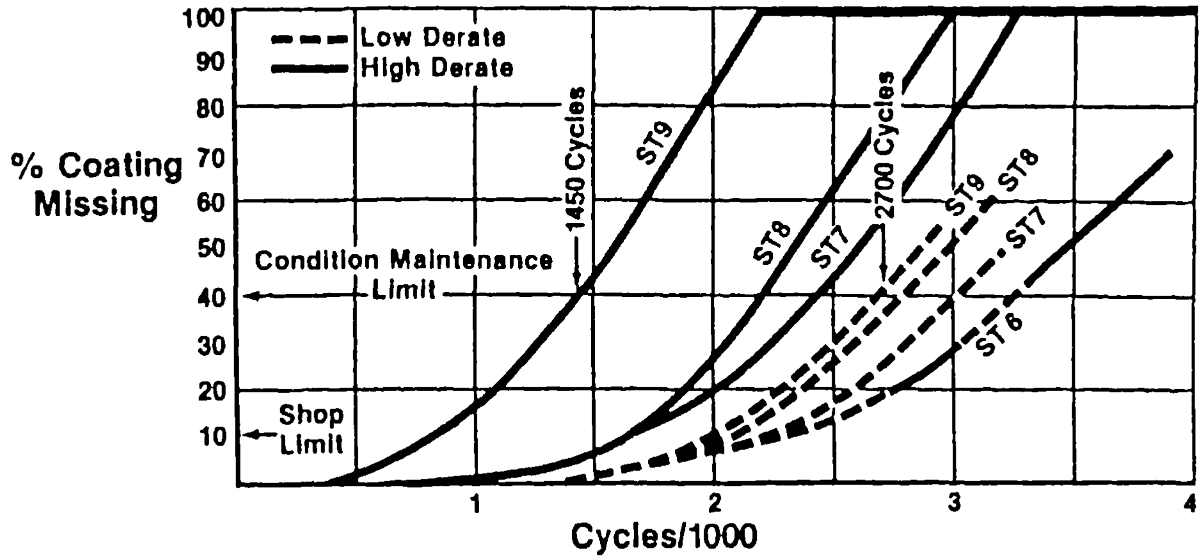


Fig 2.13 HP Compressor Rotor Coating Spalling

Aerofoil tip clearances

During engine transient running conditions, the aerofoils tips either rub or just touch the shrouds. Sometimes the fan blade minimum tip clearance is set to give a uniform rub over the shroud eg. CF6-50, and this rub depth is established during test cell run. Erosion also effects the attrition lining of the casings that form the blade tip seals. Rubber compounds, used earlier, in compressor lining were particularly prone to erosion [CROSBY,1986]. This has been minimised by use of composite materials for lining eg. RB211.

The turbine blade tip seal linings, usually of a honeycomb material can be prone to erosion particularly if there are Carbon particles produced during the combustion. Filling the honey comb with material can decrease the tip erosion. The LPT blades to shroud for CF6-50 are interference fit and run-in in the shop so that stationary seals are effectively pre-groved. The effect of HPT and HPC tip clearance changes, on the performance are significant. HPT clearances increase during service as a result of the shroud erosion, shroud material swelling (causing rubs), bowing of the turbine nozzle assembly and as a result of constraining effects of the compressor rear-frame and turbine mid-frame.

The dust that gets into the turbine cooling flow can deposit in the cooling passages and cause plugging of the cavities. This can reduce the cooling flow capacity, hence the cooling effectiveness of the turbine blades. CFM5 had blade distress because of blockage for the cooling air passages and exit hole at the turbine blades had to be increased.

Thermal growth

Clearances are set, during engine build-up, normally at temperatures very different from operating temperatures. At high temperatures of operation, there is a possibility of axial movement between various parts thus disturbing the radial and axial matching of the static and rotating seal members.

Axial and radial thermal growth can occur on the engines. It is essential that the fundamental design of the engine ensures close radial an axial matching of the static and rotating seal members under all normal running conditions. The difference in operating temperatures and build-up temperatures is equally important. The diameters of the segmented tip seals of the IP and LP turbine stages of RB211 are related to the turbine casings. These casings are often cooled by a controlled amount of fan air to match the growth of the turbine blades. Thermal control ring is also used to control tip seal diameter on HP turbines when the capacity of the ring retards the static members growth to match that of the disc.

Thermal distortion effects

Thermal distortion effects are primary twisting, bowing and soldiering of the turbine vanes which results from the basic temperature and stress environment of the turbine and changes to the environment. These turbine environmental changes are caused by changes in the compressor performance, combustor dimensional changes and the fuel nozzle coking with usage which produce changes in combustor exit temperature levels and profiles. The resulting increase in the turbine aerofoil losses and increased leakages reduce the high and low pressure turbine efficiencies.

Based on turbine part mechanical condition, compressor and combustor deterioration appear to cause radial and circumferential changes in temperature pattern into the turbine and cause elevated metal temperatures above the design levels, resulting in thermal distortion of turbine parts. Turbine vane bow results in flow area changes which control the operating lines of the compressor system. Platform curl and vane twist increase the secondary flow losses and reduce efficiency. High temperatures near the annulus walls increase running clearances due to differential growth of rotor, seals and cases.

Engine Handling

The rubbing contact of seals between static and rotating parts accounts for the major part of the deterioration especially in the early stages of service. If the static the rotating parts just touch each other there would be no wear and the seals would remain perfect. But in service the some of the manoeuvres require abrupt throttle movements which causes unequal growth of the two parts. The degradation is thus dependent on the handling of the engine. Normally the engine is run on test bed to ensure that the seals are worn in gently with minimum wear.

Macroscopic degradations

As discussed above, each of these degradations, such as increased tip clearances, increased surface roughness, nozzle bowing, deposits, loss of the blade material and bluntness of the aerofoil etc, in the components of a module can be manifested in the flow capacity change,, change of pressure loss across the module and change in the module efficiency. Since the effects of the influencing factors on module level degradations (macroscopic) of flow capacity, pressure ratios and efficiency are quite similar, it is not possible to identify the component level changes (microscopic) from the knowledge of the former alone.

Each of the detectable faults whether caused by normal wear, degradation, FOD or abnormal use affects one or more modules in one or more of their basic performance parameters eg. Fan or compressor blade erosion can manifest itself as change in mass flow or the adiabatic efficiency or both. Similarly a turbine fault may manifest as a change in:

1. Turbine effective nozzle area (affecting absorption capability or
2. Adiabatic expansion efficiency or both

Module Degradations

The condition of the modules that make an engine can hence be represented by several independent parameters such as efficiency, flow capacity, area, mass flow (fuel). The influence of each of the constituent factors to generate cumulative effects at various module levels of a gas turbine are discussed in the succeeding paragraphs. The change in level of the damage mechanisms with usage depends on the local flow conditions, material used and the design. The modules and degradations described are for Pratt & Whitney JT9D engine [SALLEE,1980]. These could be generalised by similarity of design and operation to any of the existing gas turbine of similar operation characteristics [CROSBY, 1986, PETERSON,1986].

Performance Loss Mechanism

FAN

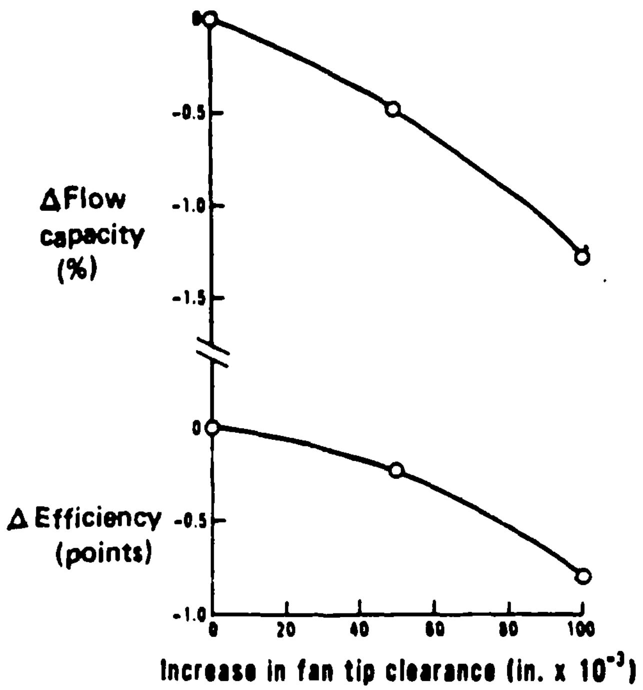


Fig 2.14 **Fan Tip Clearance Effects - An Increase in Fan Tip Clearance Causes a Reduction of Efficiency and Reduced Mass Flow [SALLEE,1980].**

Fan performance deterioration is caused by increasing tip clearance, aerofoil surface roughness and aerofoil leading edge contour changes (bluntness). Since the fan blades are in direct contact with all kind of ingested matter, the wear rate and effects depend strictly on design. Fig 2.14 shows the effect of fan **tip clearance** on performance can be established through engine testing [SALLEE,1980]. **Surface roughness** caused by dirt accumulation and pitting also affect fan performance. Correlations of aerofoil loss coefficient as a function of Reynold's number and roughness indicate that a 10% increase in aerofoil roughness loss coefficient will result in a 1.0 point loss in fan efficiency.

Visual inspection of service fan blades has shown that the fan blade leading edge erodes, becoming blunt and pitted with increasing usage..Almost all the ingested particles (of all shapes and sizes) strike the fan blade leading edges. This causes the aerofoil leading edge contour changes, affecting adversely the air flow, and decrease in fan efficiency. The losses due to the bluntness of fan blades are tentatively estimated to be the major contributor to the fan performance deterioration at high cycle part age.

Tip clearance changes

Tip clearances will increase as a result of blade length loss, blade rub strip trenching during engine transients and aircraft manoeuvres, and rub strip erosion. The blade tip is generally thick and little centrifuging of ingested solids occur in the fan. Hence the particles are generally concentrated near the root and in middle section and the fan blade length loss is insignificant. The fan is in general accessible (in pod type installation atleast) and measurement of the blade tip clearance is easy to determine. The blade length loss due to rubbing was also found to be negligible The rub strip trenching due to engine transients and flight loads is significant as shown in Fig 2.15 [SALLEE,1980]. The trench is fully established in 1000 cycles or so and is almost a constant thereafter.

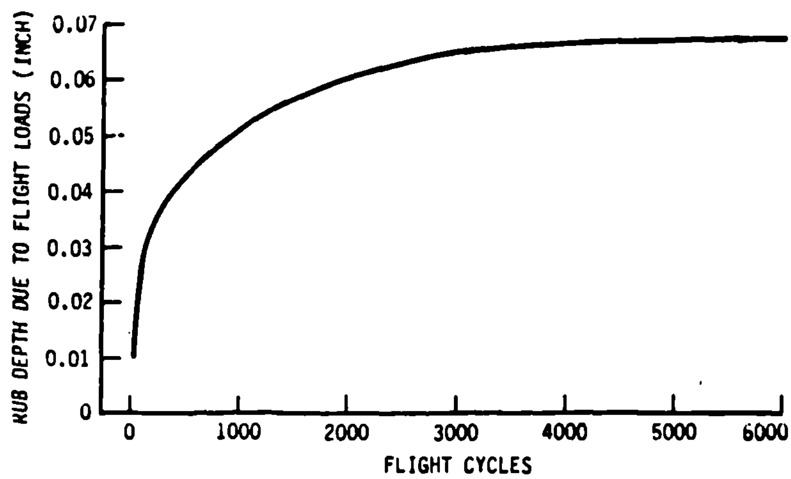


Fig 2.15 Predicted Fan Clearance Changes From Analytical Studies of the Flight Load Effects on Performance Deterioration.

Aerofoil roughness

The surface roughness builds up rapidly and then remains constant as shown in Fig 2.16 [SALLEE,1980]. The effect of surface roughness is through thickening of the boundary layer over the blades and is difficult to be isolated and determined.

The combined effects of all the above mentioned parameters is to decrease efficiency and flow capacity. These effects for JT9D engine are shown in Fig 2.16. Even though the deterioration would be expected to be constant after initial rub-in period, tests show it not to be so. The difference can be associated with the tendency to repair FOD and with the leading edge changes brought about by erosion.

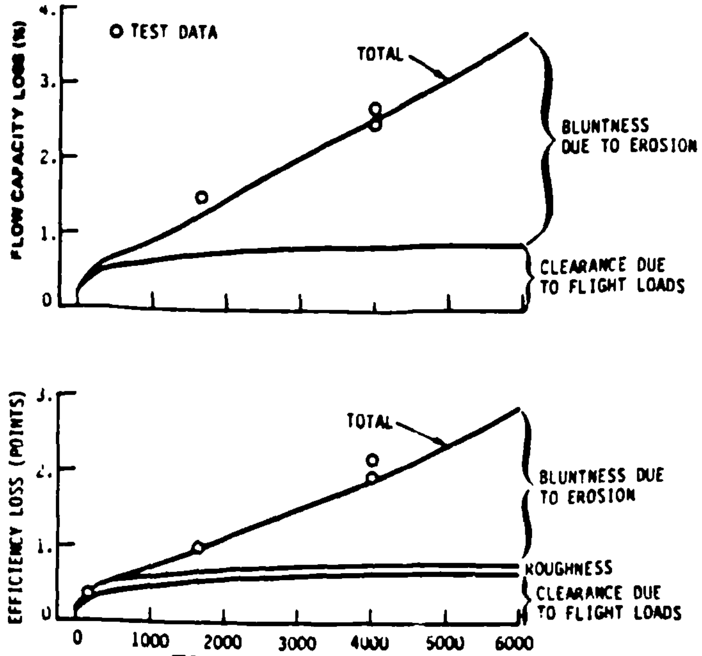


Fig 2.16 **Level of Deterioration of an Average Fan Module Typical Combined Effect of Degrading Factors.**

Low Pressure Compressor

Low pressure compressor performance deterioration is caused by blade tip clearance, aerofoil surface roughness increases and aerofoil contour changes. In estimating the performance loss caused by the tip clearance changes, some consideration must be given to the condition of the rub strip upstream, underneath and downstream of the blade. Blades running over a smooth wall have higher losses than those running over a trench. Trenching the rub strip thus decreases the tip clearance loss. The trench itself is prone to erosion thereby increasing the clearance. The total increase in clearance would now be sum of : decrease of blade length, erosion of rub strip and erosion depth of the rub trench. Tip clearances can be affected by : (1) loss of blade length, (2) rub strip trenching due to rubs during engine transients and aircraft manoeuvres, and (3) by rub strip erosion. The rub strip trenching and erosion have quite significant effects on loss of effective blade length as shown in Fig 2.17 [SALLEE,1980].

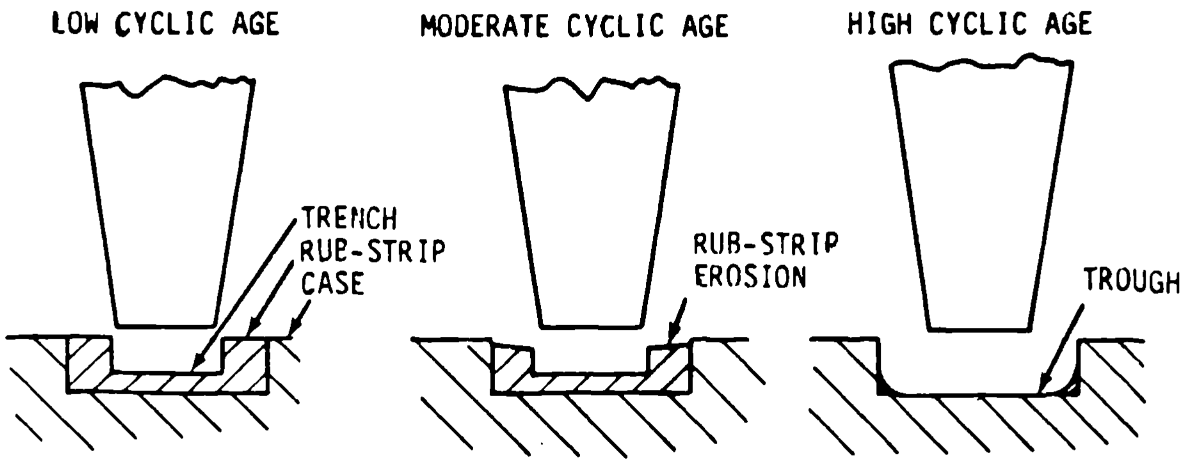


Fig 2.17 Tip Clearance Changes of Typical LPC blades

Surface roughness, caused by pitting and accumulation of dirt negatively affects the performance of low pressure compressor. Largest increase in roughness occurs in stators.

The aerofoil contour changes are negligible and have negligible performance penalty in the LP compressor. This arises from the fact that most of the bigger particles causing blade are centrifuged out by the fan.

Overall deterioration of the low pressure compressor is dominated by the rub strip trenching due to flight loads, rub-strip erosion and aerofoil surface roughness. The effects are shown in Fig 2.18 [SALLEE,1980b]. As can be seen for both efficiency and airflow, the losses due to rub-strip erosion continue to increase with flight cycles, while efficiency loss resulting from aerofoil surface roughness remains constant after initial set-in. Majority of the LPC losses are estimated [SASAHARA,1986], to be as a result of tip clearance increase.

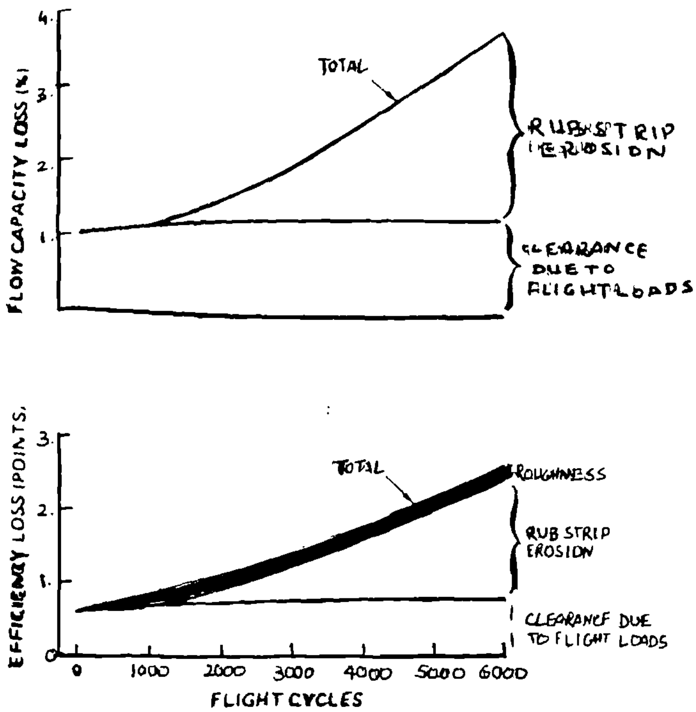


Fig 2.18 Deterioration of LPC : Loss Attributed to Blade Tip Clearances and surface roughness.

High Pressure Compressor

Three factors cause performance deterioration of the HP compressor viz. blade tip clearance, aerofoil surface roughness and aerofoil contour.

Tip clearance The tip clearance wear of HP compressor is made-up of three parts : (1)The trench dug in the rub strip during engine transients and aircraft manoeuvre, (2) erosion of rub strip and (3) loss of blade length. All of these cause significant effects on performance of the HP compressor.Fig 2.19 shows the wear process with usage. At low cycles due to rubbing a trench forms, while there is no erosion of blade and the rub strip. At moderate cycle age blade and flow path wall, ahead and aft of the blade tip, erode. The blade is shortened by the time it reaches high age, at the same time flow-path wall has been eroded to the extent that the trench is no longer visible. The extent of erosion and hence tip clearance caused by these erosions depend on the stage of the compressor. This is so because of use of different material for fabrication of stages of the compressor. The effect of tip clearance on compressor performance deterioration must consider the radial clearance between the blades and the rub strip with considerations given to the condition of the rub strip upstream and down stream of the blade.

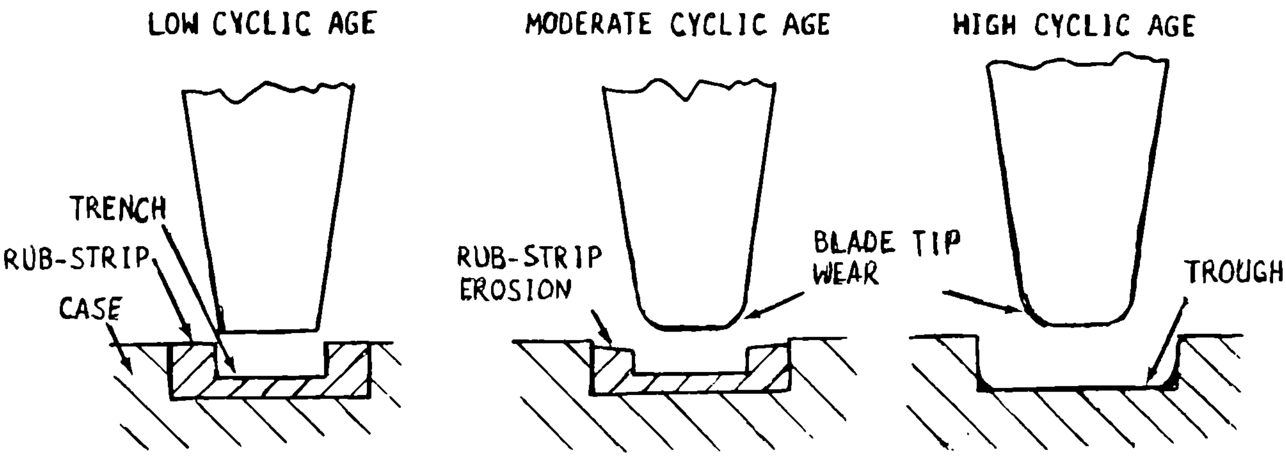


Fig 2.19 Tip Clearance Increase Meachanism of HPC Blades in stages of Trenching, Rub-Strip Erosion and Blade Erosion - [SALLEE,1980b]

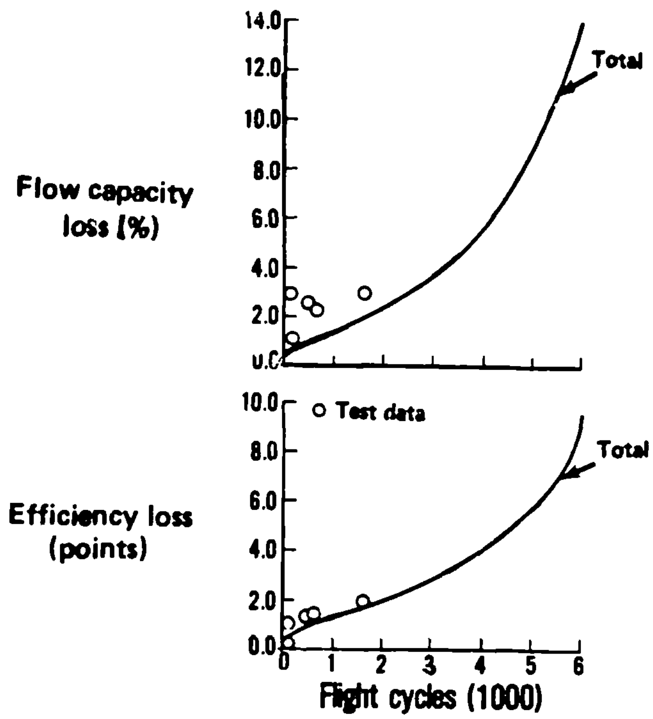


Fig 2.20 High Pressure Compressor Performance Deterioration - Rub strip wear dominates Initially and at high age airfoil Contour changes Dominate [SALLEE,1980b]

Surface roughness effect is similar to the LP compressor and the Fan. Contour change effects in the HP compressor are same as the LP compressor. The **combined effect** of the tip clearance, surface roughness, contour changes is shown in Fig 2.20 [SALLEE,1980]. At low and moderate usage the majority of the deterioration is caused by rub-strip trenching and erosion. At high cycles, aerofoil contour erosion and blade length loss become increasingly dominant.

Combustion system

Combustion system hardware deterioration involves coking of the fuel nozzles, which results in non-uniform fuel spray distribution, and changes to critical dimensions of the combustor, in particular the cone angle. Combustion efficiency and burner pressure drop directly affect the engine performance. variations of inlet temperature and pressure do not differ significantly from the expected value, it could be said that the pressure loss across the burner is constant as a function of usage level. Combustion efficiency is essentially 100% at all power settings except idle and does not appear to be dependent on fuel nozzle or combustor conditions except in the most extreme cases of deterioration. Thus the combustor does not have a significant effect on engine performance deterioration. What is of importance, is the combustor exit profile which is determined by the structural contours of the combustor. The combustor does, however, have an indirect effect on the performance of the turbine, primarily as a result of changes in the combustor exit temperature profile. The temperature profile is affected by : (1) fuel nozzle coking, (2) combustor hardware dimensions as influenced by combustor repair practices, (3) compressor discharge pressure profile, and (4) changes in cone angle.

The parts of the combustors affected are, the combustor liners, the combustion baskets, the transition pieces and the fuel nozzles. The common defects observed on the liners and the combustion baskets are due to shaking caused by the turbulence in combustor, combustion flame impingement and differential pressures between the multiple liners and the basket. Normally the stresses are low because of low pressure drop, but the shaking wears the support brackets, crossfire tubes, fuel nozzle to liner fit, transition side seals and transition to nozzle seals. The flame impingement, because of disruption of the flame pattern, on the combustor liner or the basket may burn through. the transition pieces suffer from shaking, corrosion, seal movement and creep. Sulfidation is common on transition pieces walls usually at the exit area to the nozzle on the convexing curve. The cowl cap fuel nozzle mating rings, crossfire tube collars, outside locating clips and cooling skirts normally wear while cracks may develop between louvers and around cross file tube collars.

Turbine deterioration depends on this profile. Three possible radial temperature distributions are shown in Fig 2.21 [SALLEE,1980]. Distribution I is combustor discharge profile of a new or overhauled combustor. Distribution II is heavily weighted to the outer portion of the gas path and can cause turbine cases to expand radially outward, increasing blade tip clearances with a loss of turbine efficiency. Distribution III is heavily weighted to the inner portion of the gas path and can cause blade platform curling and subsequent aerodynamic penalties. The radial shrinkage for distribution III could excessively reduce running clearances, causing blade tip and knife edge seal wear.

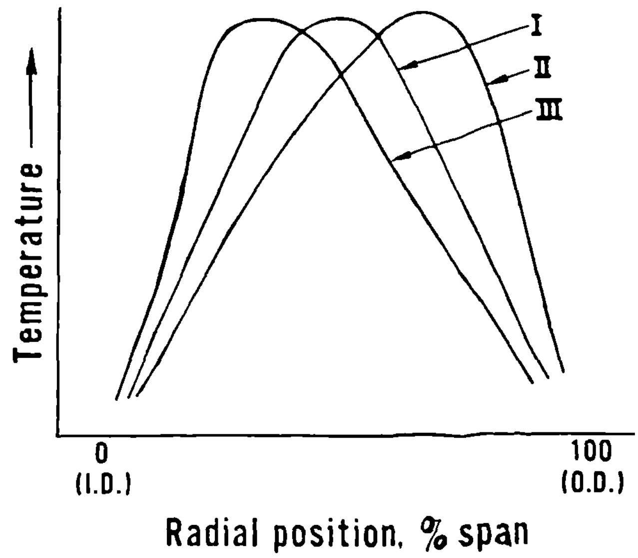


Fig 2.21 Combustor Radial Temperature Distribution

These changes in the combustor exit temperature profile may be produced by deterioration of combustor as well as the compressor. Decreased compressor exit pressures disturb flow in combustor causing inward shift of the profile.

HP turbine

Increased tip clearances and vane bowing and twisting cause deterioration of HP turbine performance. The aerofoil surface roughness also increases but the performance penalty is significantly lower than with other mechanisms. Increased turbine clearances occur as the result of engine transients and flight loads and the interaction between the blades and outer seals. Loss of efficiency as a result of the tip clearances increase is shown in Fig 2.22.

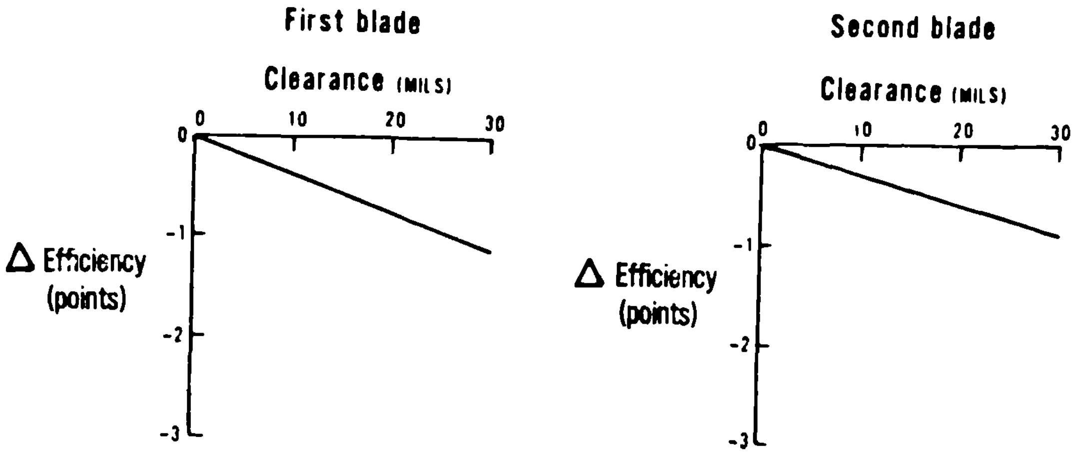


Fig 2.22 Effects of HP Turbine Blade Tip Clearance

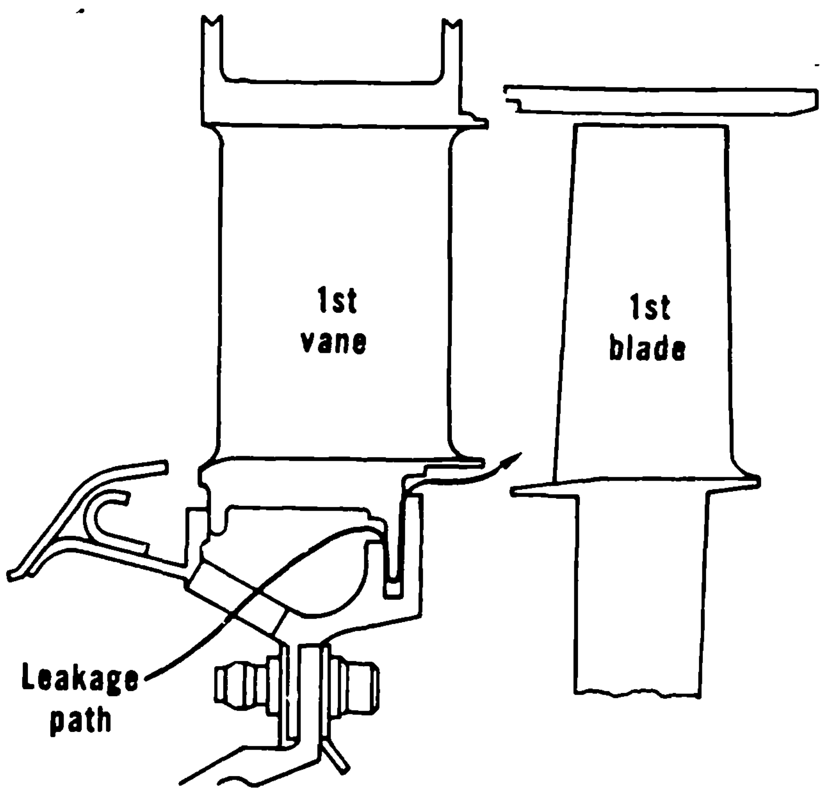


Fig 2.23 HP Turbine Vane Leakage Path Because of Distortion

Vane distortion results when inner platform twists and tilts relative to the vane support because of both aerodynamic bending loads and the temperature environment. The resulting mismatch of the platform creates a leakage path for cool flow into the hot main stream. This changes the flow velocity (in magnitude and direction), reducing the turbine efficiency as shown in Fig 2.23. Trailing edge bowing in a turbine causes the gas path flow area to change resulting in a change in high-pressure turbine flow capacity which in turn changes the engine cycle pressure ratio and the specific fuel consumption. The effect of Vane Bowing on flow capacity is shown in Fig 2.24 [SALLEE,1980b].

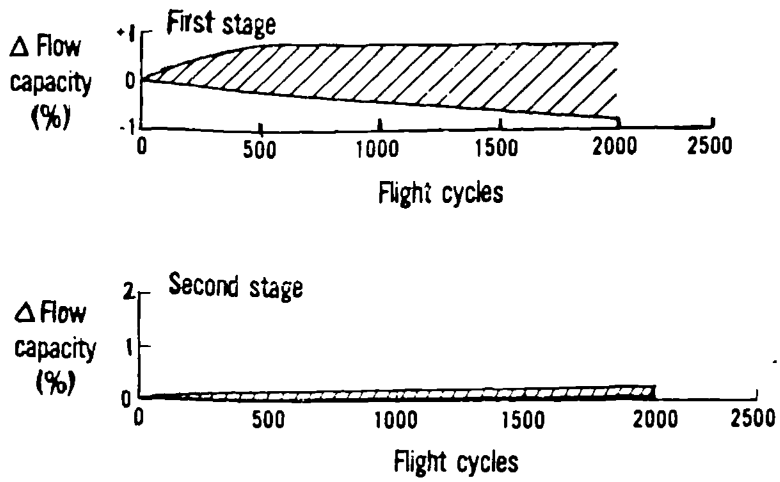


Fig 2.24 Effect of Vane Bowing on Flow Capacity HP Turbine

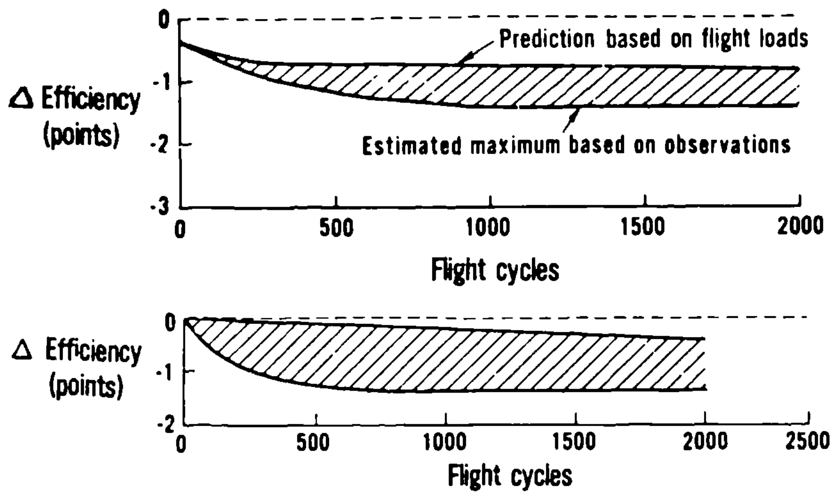


Fig 2.25 HP Turbine Efficiency Loss Due to Tip Clearance (upper) and Vane Twist (lower) [SALLEE,1980b]

The vane twisting or distortion is generally very small in first stage but substantial in second stage. However vane bowing is considerable in the first stage but negligible in second. The combined effect of the two gives almost a constant degradation of efficiency across the stages.

Particulate matter deposited on the surface of the aerofoil especially the first stage turbine blade surface, where many deposits from combustion chamber coatings exist, increase the surface roughness. It is possible that erosion of surface instead of deposition takes place. The effect of the two is to increase friction coefficient causing an increase in boundary layer thickness and pressure loss. The net effect is to decrease turbine efficiency. since the flows are accelerating the effect of increased surface roughness on performance is negligible.

The **overall effect** of tip clearance changes and vane twist and bow on HP turbine is shown in Fig 2.25. The gradual increase with cycles is primarily due to the accumulating effect of vane twist. Fig 2.26 shows the effective area changes of the first stage turbine vanes.

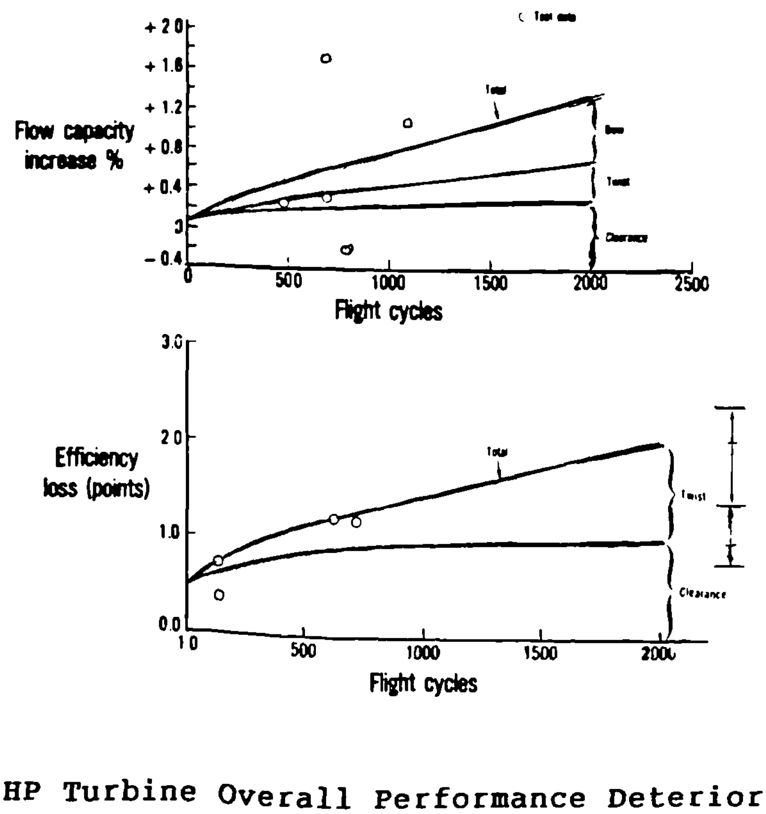


Fig 2.26 HP Turbine Overall Performance Deterioration

LP turbine

Deterioration of LP turbine performance is caused by increased tip clearances, vane bowing and twisting and vane inner diameter "soldiering". The aerofoil surface roughness also increases but the performance penalty is significantly lower than with other mechanisms. Increased turbine clearances occur as the result of engine transients and flight loads and the interaction between the blades and outer air seals. Loss of efficiency as a result of the tip clearances increase is shown in Fig 2.27 [SALLEE,1980b].

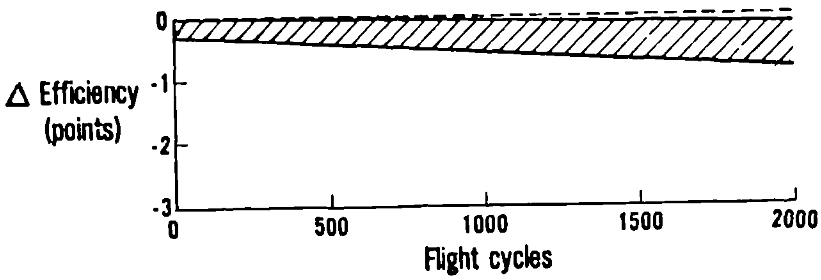


Fig 2.27 Effects of Tip Clearance Increase LP Turbine

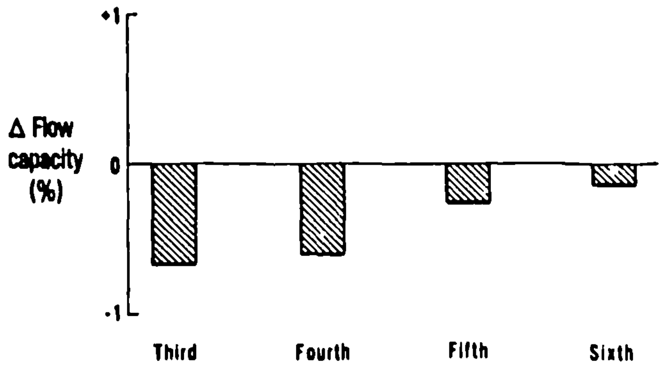


Fig 2.28 Effects of Vane Bowing and Twist in LP Turbine

Misalignment of vane inner platform is termed "soldiering". It creates steps in the inner flow-path surface which cause aerodynamic losses. This causes loss of turbine efficiency. Twist effect is negligible since leakage flow levels are very small. Vane bowing and twisting decrease the effective vane flow area causing a decrease in flow capacity. The roughness effect is negligible for LP turbine. The effects of vane bow and twist are shown in Fig 2.28 [SALLEE, 1980b].

Combined effect on low pressure turbine performance is shown in Fig 2.29 and is similar to HP turbine. The effect is due to clearance and soldiering. Both, the clearance effect and the soldiering effect change with cycle, hence the LP turbine has continuous degradation through out its life.

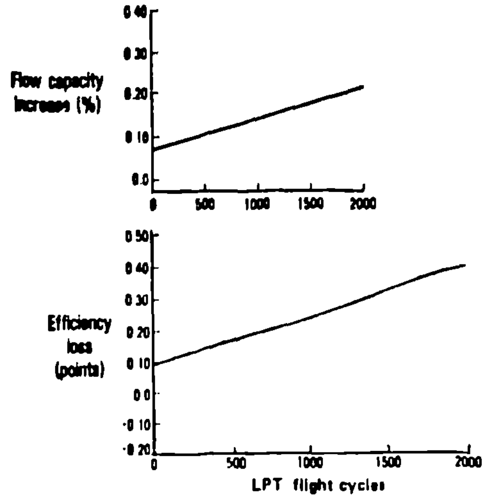


Fig 2.29 Overall Deterioration of LP Turbine

Intake

The intake is likely to be effected by the solid particles when the lips can become blunt and surface roughness of the annulus increase causing higher pressure losses in the intake and distortion of the flow. The effect of the distorted flow is to reduce pressure recovery and inlet mass flow [QIUTING,1983]. There is further effect of fall in compressor efficiency, shift of constant corrected speed line to the left and flatten in shape with virtually no pressure ratio loss across the compressor. The stall limit is however is lowered while thrust and specific fuel consumption deteriorate.

Water ingestion

Presence of moisture in the intake air has two types of effects. Firstly there is direct aerothermal effect on the performance of the engine, secondly there is mechanical effect due to condensation and impact. Water ingestion into aircraft-installed jet engines can arise during take-off from a wet run-way or during operation in rain. The nature and magnitude of effects depend upon the type of air-water mixture ingested [MURTHY,1986], design of each of the components of the engine and control, and engine matching scheme utilised for design point and other operational conditions of interest. The extent of effects under steady state are reduction of mass flow of air through the hot parts of the engine, increased compressor losses, decreased compressor delivery pressure at higher temperature.

Industrial Gas Turbines

Corrosion

Although power loss provides a high incentive of cleaning the gas turbines, especially the compressor, avoiding corrosion is an equally important reason to keep the machinery blades as clean as possible. Moisture settles on blades in the first two or three stages of the compressor and tends to form an electro chemical active solution with the particles of the fouling substance on the blade. This results in pitting due to contact-potential corrosion. Hairline cracks propagate from the bottom of the "pit" which reduce the strength of the blade material. The result is change of the aerofoil contour and increased surface roughness, causing decrease in the compressor flow capacity and compressor efficiency. If pitting is allowed to go too far, the performance cannot be recovered by washing.

In gas turbines fired with alternative fuels,such as heavy oils or coal, there is high risk of corrosion on the vanes and blades of the combustion turbine. The corrosive effect of Sodium and Vanadium is very detrimental to the life of blades. Low cost residual fuels but produces high amounts of ash, the material remains after combustion has taken place [BOYCE,1982]. The metallic compounds present in the ash cause corrosion when sulphur content reacts with alkaline metals. Corrosion damage on vanes is characterised by thinning of metal sections, pit causing initiation and distortion due to weakening of the material. This causes increase in turbine area and decrease of efficiency.

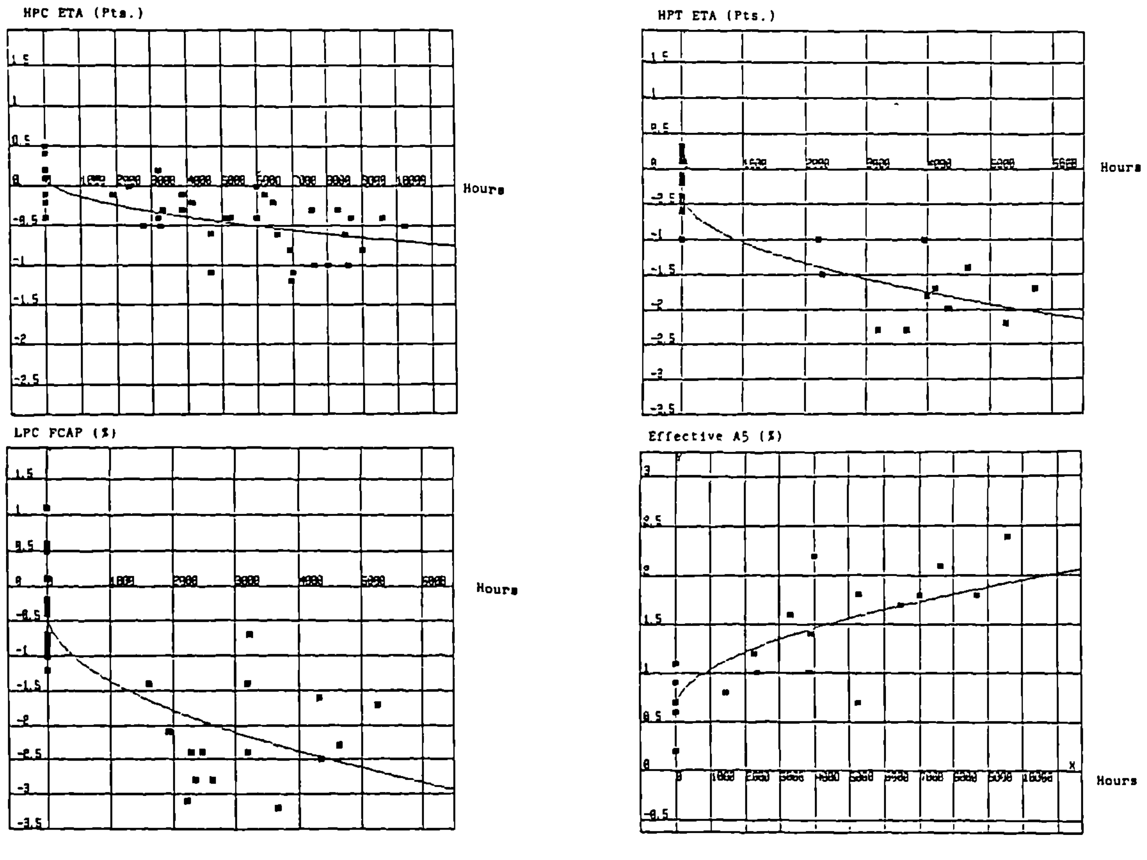
In general the industrial gas turbine performance deterioration could be summarized as :-

1. Clogged air filter - Causes increased pressure drop across the filter.
2. Compressor Surging - Detected by instability of compressor delivery pressure and increase in the vibration.
3. Compressor fouling - A decrease in pressure ratio, mass flow through the compressor and fall of efficiency. Change in vibration occurs if fouling is critical.

4. Plugged nozzles - Causes an increase in fuel pressure (monitored in industrial applications). This is a common problem with residual fuels.
5. Cracked or Detached liner Indicated through a large spread in exhaust temperature and acoustics.
6. Turbine fouling - Detectable by increased turbine exhaust temperature. Vibrations increase only in extreme of fouling.
7. Damaged turbine blades Detectable by increase in the turbine exhaust temperature and vibrations.
8. Bowed nozzle The exhaust temperature will increase, may be accompanied by turbine vibration.
9. Cooling air failure Problems associated with the blade cooling system may be detected by increase in the turbine exit temperature (due to overheating).

The module level effects of microscopic level degradations are similar for aeronautical and ground based engines. The primary difference being the flight loads, design and the environmental effects.

<u>Dependent Parameters</u>



LPC Performance Deterioration HPT Performance Deterioration

Fig 2.30 **Overall Deterioration of a Compressor and a turbine with Flying Hours as life reference [SASAHARA,1986].**

The component degradations of clearance increases, aerofoil contour changes, surface roughness increase, vane bowing and twisting etc thus can be combined at each module level to generate variations in flow capacity, pressure loss, efficiency decrease and changes in the area. All these module level degradation variations have usage life (cycle) as the common base or the reference. Knowing the average cycles per flight and average duration of the flight each operator may, for convenience of reference, represent, these parameters with respect to flying hours as shown in Fig 2.30.

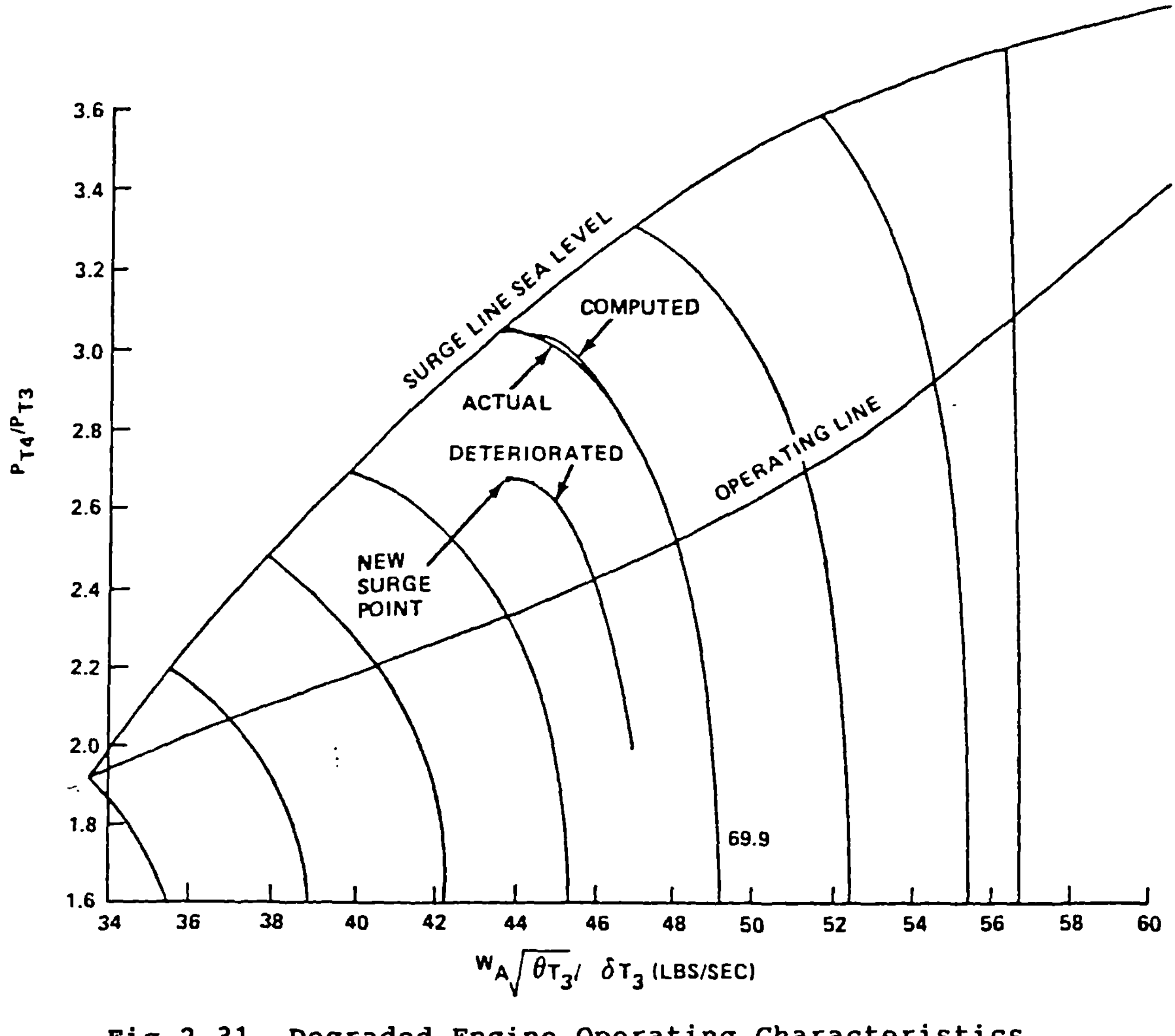


Fig 2.31 Degraded Engine Operating Characteristics

These primary independent parameters although fundamental in nature and leading directly to the detection of engine faults are not readily or practically measurable. The parameters typically measured are temperatures, pressures, speed of rotation and fuel flow, known as dependent variables whose absolute values depend on those of primary independent variables. Thus at first sight it can be seen that a change in independent parameter, resulting from degradation, will cause a change or deviation in dependent parameter from its expected value. The two key words viz. change and expected value are explained in detail in the next chapter.

The degradations at module level will combine to form the complete engine degradations. Fig 2.31 shows the effects of erosion, due to dust, on the engine performance [BATCHO, 1987]. Similar results have been obtained for the degradations caused by deposits [SARAVANAMUTTO,1983,1985].

Conclusions

The deterioration of the gas turbine performance can be broken down to the component level. Various factors that cause the changes at the component level are loads, thermal effects, erosion and deposits. The effects are to change the profile, roughness and the clearances. Qualitative effects of these factors on gas turbines for industrial and aeronautical use have been studied in the chapter. The cumulative effect of these component changes is to cause changes in the module characteristics.

The performance degradations, in general, are dominant in the compressor and the turbine modules. The combustor module faults are normally mechanical in nature and effect the combustor exit temperature pattern. The performance characteristics of the combustor, viz. the pressure drop across and the combustion efficiency change negligibly. In the compressor and the turbine modules, the degradations exhibit themselves in the module flow capacity, pressure ratios and the efficiency. The general effect of the degradations is to decrease all of these.

CHAPTER 3

GAS PATH ANALYSIS

Introduction

This chapter reviews the generation of the engine base_line and the techniques of Engine Performance Monitoring. The theory of Gas Path Analysis technique of the Engine Performance Monitoring has been built up in the second part of the chapter. The effects of the engine module degradations reviewed in the previous chapter, have been applied to the engine and the likely performance degradations are visualised.

General

Deterioration or ageing as described in the previous chapter, causes changes in component characteristics. These changes may be small but their cumulative effect on engine performance can be appreciable. Fig 3.1 shows component breakdown for CF6-6D and CF6-50 engines before overhaul as compared to the new engine performance levels [STICKLIN, 1981].

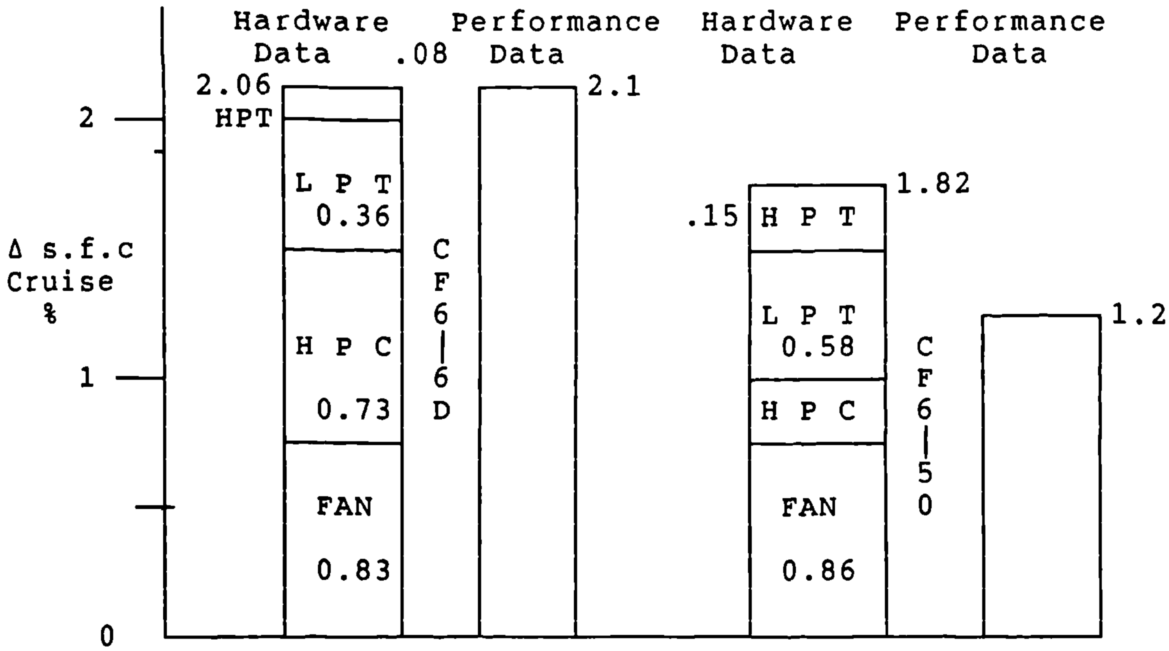


Fig 3.1 Component Breakdown CF6-6D and CF6-50

Major part of the performance loss is due to the fan and the HP compressor. The HP turbine also undergoes a deterioration in its performance, but this loss of performance is restored through refurbishment during shop visits. If the fan, HP compressor and the LP turbine performance is also restored, the saving in terms of fuel would be enormous. The module degradations, which result from module component degradations, described in the previous chapter, can be determined through the engine performance monitoring.

Detection of Performance Shortfall

To determine the changes, two sets of values must be available, the present values and the expected values. The change is then merely the difference of the two. Detection of the performance loss or deterioration can be two fold viz, identifying the module(s) responsible for the degradation and quantifying the loss of performance.

For the purpose of comparison with expected value certain parameter must be used as a basis or reference. Since the interest is economical, fuel consumed to carry out a particular task, could be the basis. For example fuel consumed to travel a given distance. Distance travelled depends on environmental changes such as altitude, wind, weight of the aircraft, temperature etc and hence is not determinable directly. The thrust parameter is independent of aircraft drag and weight. Hence quantity of fuel burnt to generate a given thrust (or power) is generally used for comparison.

The purpose of an aircraft powerplant is to generate thrust. It follows, therefore, that indications of the actual thrust produced should be included among the instrumentation describing the engine performance. This would aid in direct diagnosis of the engine health and at the same time allow the crew to know the "reserve of power". A direct measurement of thrust is hence desirable, but it is not possible. Therefore indirect measurement of thrust is resorted to through parameters of LP shaft speed or Engine Pressure Ratio (EPR). LP spool rpm measurement is simple. But in a multi-spool engine, at a given LP spool RPM, different thrust is generated for different values of HP spool RPM. Thus as the engine deteriorates LP shaft speed/Thrust relationship may change - often in a direction which masks true deterioration [CROSBY,1986]. Nozzle pressure ratio or Engine pressure ratio is hence used as a measure of thrust. This is more difficult a parameter to measure than the LP spool RPM but its fundamental relationship to thrust which is insignificantly affected by engine deterioration, makes it an attractive parameter for comparison. Quite often multi-probes (pressure) located around the ducts are used to eliminate susceptibility to pressure profile changes.

The EPR and thrust relationship is quite smooth and almost linear. It appears to be very satisfactory at all "dry" power settings. However in the after-burning regime the engine controls maintain all parameters essentially constant, and hence an EPR/thrust relationship does not exist and EPR alone no longer gives any indication of actual thrust generated.

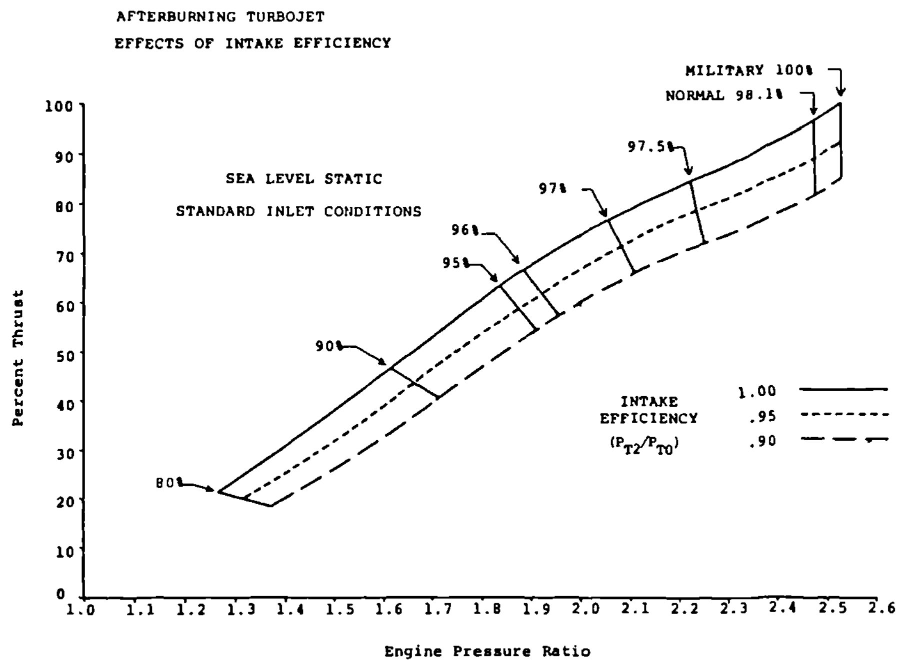


Fig 3.2 The Relationship of an After Burning Gasturbine Thrust With its Controls [CHAPPEL,1974]

The thrust available, is a function of not only the environment and speed, but also the engine health. Fig 3.2 [CHAPPEL,1974], shows the effect on the EPR/thrust relation, of decrease in intake efficiency. Lines of constant power setting or the EPR are essentially constant at their standard values for the after-burning engine even when the intake efficiency has reduced by 10% causing a 15% loss of thrust. The only means of knowing such a shortcoming to measure the thrust or compute it from aero-thermal relations.

The fuel consumed is dependent on the total energy (heat) released in the engine. The quality of fuel, i.e. its calorific value or the heat content, is difficult to measure and is not usually precisely known. There is around a 1% of variation in calorific value of fuel supplied at different airports through out the world. Knowledge of the accurate calorific value of fuel is necessary for accurate performance diagnostics.

One of the easiest way to compare performance of different engines or of a particular engine is to test the engine in a test cell. This involves taking the engine out-of-service for sometime, hence is very costly. On wing testing is generally resorted to as an alternative.

Baseline of an Engine

The comparison of the measured performance is against an expected or specified reference value. This reference level is typically obtained from the manufacturer who generates baseline values through either a computer "matching deck" simulation or some statistical average of actual production engines as shown in Fig 3.3 [FRITH,1985]. This expected value is the nominal baseline, which by definition states how the nominal or average engine will behave in a loss-free environment with nominal exhaust areas when measured with perfect measurement system. These are ideal conditions and can never be realised. Real systems therefore must be corrected for the effects of non-standard exhaust nozzles; installation losses, instrument calibration errors, quantity of bleeds, non standard atmospheric conditions, effects of Reynold's number etc.

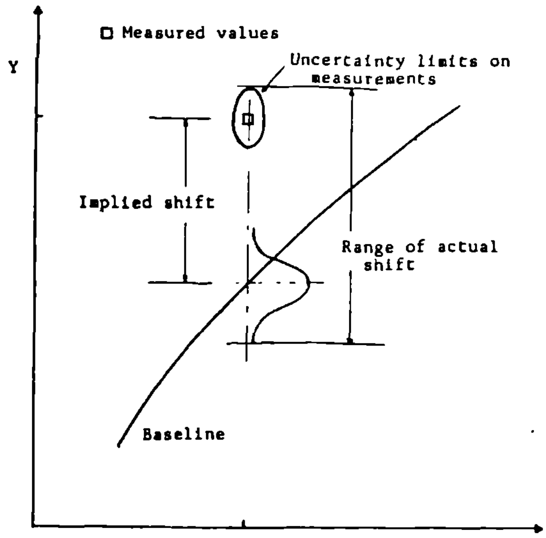


Fig 3.3 Base Line of an Engine and Shift in Operating Point due to Deterioration of the Engine.

Since there exists a relation, for the mass flow through an engine, of the form :

$$m = f(R_e, M, \gamma, \frac{P_2}{P_1}, \mu_N) \qquad ..... (3.1)$$

For a given gas (γ = const) and for a given engine and inlet conditions (R_e = const) we can write this relation as

$$\frac{P2}{P_1} = f(\frac{m\sqrt{T_1}}{P_1}, \frac{N}{\sqrt{T_1}}) \qquad .... (3.2)$$

For the compressors and the turbines these relations are represented as characteristic maps, as shown in Fig 3.4 [BENSIMHON,1986].

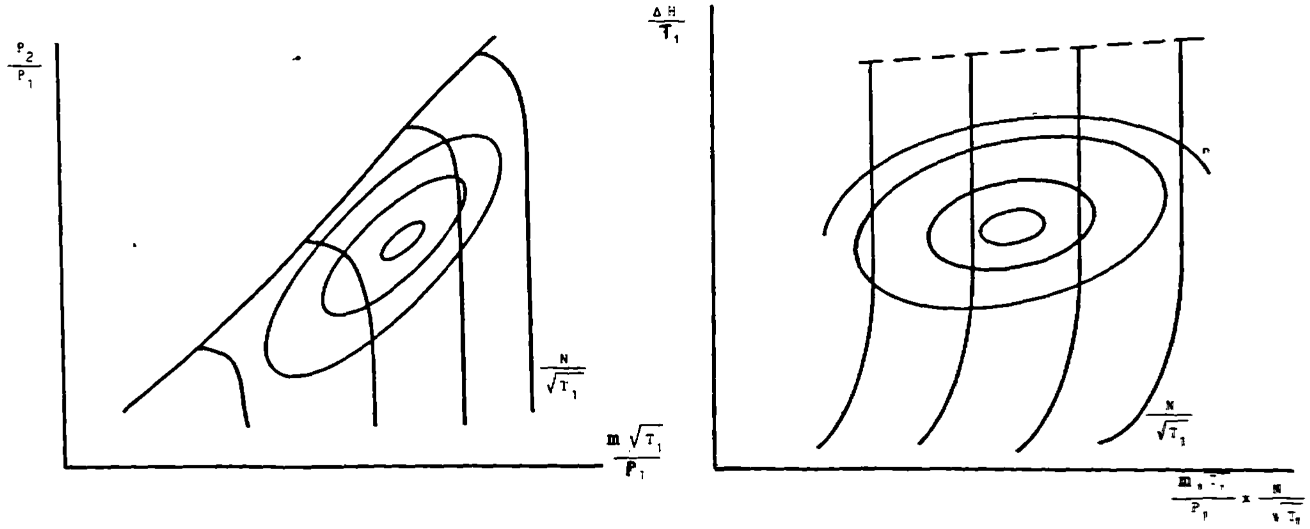


Fig 3.4 Compressor and Turbine Characteristics

It is thus possible to represent the engine working line on compressor characteristic. To reduce the influence of process noise, the base line should account for such second order effects as bleed, auxiliary power extraction, Reynold's number effects etc, across the range of engine operating conditions covered by the capture window.

The engine performance is determined by environmental operating conditions of temperature and pressure. Simplest model for comparing the values under non standard inlet conditions is display of the operating line referenced to standard atmospheric conditions. The operating line being determined from measurements on a new engine or from thermodynamic equations. The base line models can be experimental models for a particular engine (called custom models) or generic models, analytically determined for a nominal or representative engine.

Engine manufacturers normally provide users with performance specifications for a nominal engine; information provided would usually include the variation of power output or thrust and heat rate or thermal efficiency with ambient conditions, along with suitable limiting values for safe operation or long life [SARAVANAMUTTOO,1983]. The information is essential to the user, to ensure that the gas turbine is capable of meeting the anticipated power requirements. in the event of engine deterioration, however, the information provided is of minimal help and the operator has no capability of identifying the cause of the problem; the severity of the problem could range from atmospheric fouling of the modules to severe mechanical damage. Before the user can make informed decisions, it is necessary that one is able to predict the performance of the gas turbine over its expected running range.

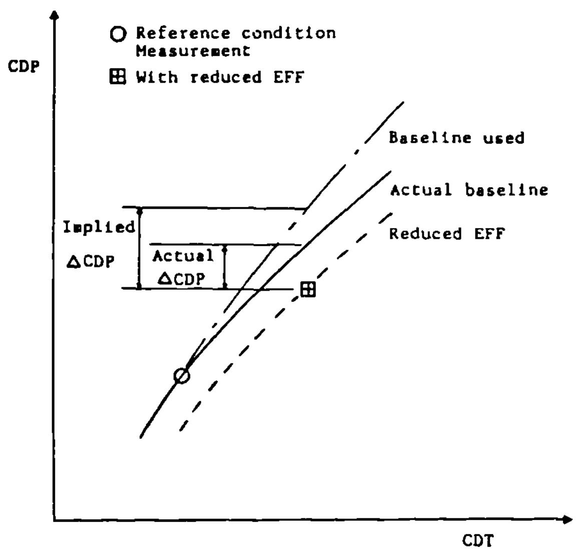


Fig 3.5 Error Induced in Evaluating Compressor Performance due to error of Base_line Assessment [FRITH,1985]

Since the deteriorations of an engine's performance are evaluated by comparison against the base or nominal line, accuracy in determining the base line is very important. An inaccurate base line can imply contamination by an error dependent on the operating conditions at which measurements were made. Fig 3.5 [FRITH,1985], shows the error introduced in evaluating difference in compressor delivery pressure

(CDP) because of an error in assessment of the base line. Normally the "matching deck" models and post build acceptance checks are carried out at design or max power condition. The base line therefore is reasonably accurate at this point. It is for this reason that to-date most of the performance deterioration analysis has been confined to "max power" condition (point representation).

Gas Turbine Engine Modelling

Equally important as the base line determination for a type of engine, is the determination of actual working line of the engine. For example, the base line may be representative of acceptance level of performance of the engine type, whilst the actual engine may be 5% (say) above this level. This difference is represented by stationary condition parameters whereas non-stationary condition parameters are indicative of the deterioration occurring in the engine. Further the base line may have been determined in a test cell where the engine is isolated. Due to the interaction of flows the performance "on-wing" is quite different [COVERT,1985]. Hence determining the base line under installed condition is necessary.

By specialising the general solutions a generic methodology is evolved which is applicable to a wide class of engines, instrumentation, and processing hardware configurations [SKIRA,1981]. In general linear models provide a large percentage of engine type independent processing software that can be flexibly altered, modified and updated without significant programming impact, but the linear models do not accurately model installed engine performance.

The thermodynamic cycle monitoring approach uses a generic baseline and fault parameter mode combined into a class of algebraic equations known as quasi-linear regression (QLR) models. These models are non-linear in engine operating variables of the form :

$$z = g_o(x,u) + g_\theta(x,u)\theta + g_w(x,u)w + h_\phi(x,u)\phi + v \qquad \text{....(3.3)}$$

where

- z is a vector of measured values eg. N_1.
- x is the engine state vector
- u is the control vector
- θ is the deviation of linear fault parameters

w is the deviation of disturbance parameters from normal

v is random noise

ϕ is the instrument error parameter

g_o is the non-linear polynomial baseline model

g_θ is the fault model

g_w is the disturbance model

h_ϕ is the instrument error model

In the absence of engine degradations all terms except $g_\theta(x,u)\theta$, which represents the fault model will be present. Thus if faultless state was defined as z_o, or the initial state, then the faults at the engine level could be specified as $z-z_o$. This has the advantage that all terms except fault and noise disappear. The absence of instrument error parameter shows that absolute accuracies of the instruments are not very important. The term v does not disappear as the noise produced is not identical. The fault model $z = g_\theta(x,u)\theta + v$ can now be linearised.

Linearisation of The Model

Let us consider noise free model (for simplicity) where z is a function of two variables, say x and y. That is,

$$z = F(x,y) \qquad \ldots\ldots \quad \ldots \qquad (3.4)$$

If z_o is the value of z when $x = x_o$ and $y = y_o$ then z can be expanded in a Taylor series as :

$$F(x,y) = F(x_o,y_o) + \left.\frac{\partial F}{\partial x}\right|_o (x-x_o) + \left.\frac{\partial F}{\partial y}\right|_o (y-y_o) + \text{H.O.T} \qquad \ldots\ldots\ldots \quad (3.5)$$

H.O.T representing higher order terms of expansion. For small $(x-x_o)$ and $(y-y_o)$ H.O.T can be neglected. and we have

$$F(x,y) = F(x_o,y_o) + \frac{\partial F}{\partial x}\bigg|_o (x-x_o) + \frac{\partial F}{\partial y}\bigg|_o (y-y_o) \quad .. (3.6)$$

or in terms of z from equation 3.4 we get

$$z = z_o + \frac{\partial z}{\partial x}\bigg|_o (x-x_o) + \frac{\partial z}{\partial y}\bigg|_o (y-y_o) \quad .... \quad (3.7)$$

or writing in a different form

$$\frac{z - z_o}{z_o} = \frac{x_o}{z_o}\frac{\partial z}{\partial x}\bigg|_o \frac{(x - x_o)}{x_o} + \frac{y_o}{z_o}\frac{\partial z}{\partial y}\bigg|_o \frac{(y - y_o)}{y_o} \quad .... (3.8)$$

Defining a value Δ as the change in the variable per unit percent change in an independent variable, we get

$$\frac{\Delta z}{z_o} = \frac{x_o}{z_o}\frac{\partial z}{\partial x}\bigg|_o \Delta x + \frac{y_o}{z_o}\frac{\partial z}{\partial y}\bigg|_o \Delta y \quad ...... (3.9)$$

OR

$$\frac{dz}{z} = \left(\frac{x}{z}\frac{\partial z}{\partial x}\right)\frac{dx}{x} + \left(\frac{y}{z}\frac{\partial z}{\partial y}\right)\frac{dy}{y} \quad ..... (3.10)$$

the subscript has been dropped because coefficients in the parentheses are evaluated at an arbitrary steady state operating point.

Performance Monitoring

These variables in the context of the gas turbines could be the microscopic degradations such as erosion, corrosion, fouling, excessive tip clearances etc or they could be module level degradations such as flow capacity, efficiency. The object of the engine performance monitoring is to implicitly detect as many of these as is accurately and economically possible. This is carried out through measurement of judiciously chosen dependent parameters eg. pressures, temperatures, speeds and fuel/mass flow. To be implicitly detectable (i.e. implied from their effects on the measured parameters) the problems or faults clearly must be of a nature and magnitude that will produce an observable change. Thus certain problems such as fatigue cracks in rotor discs or blades, or corrosive attacks on the metallurgical structure are undetectable [URBAN,1972], by analytical technique and must be detected through mechanical monitoring techniques.

The absolute values of the dependent parameters depend on the absolute levels of all the primary independent engine variables. Therefore, since the changes in the values of the dependent parameters are brought about by changes in the primary independent variables, differences in these parameters from their baseline expected values can be used to implicitly determine which elements of the gas path have undergone distress or departed from their initial or expected condition. Any parameter by itself does not necessarily indicate a fault in any particular module.

Techniques of Performance Monitoring

Two approaches viz. "Top-Down" and "Bottom-up", can be used to analyse the measurements. The top down analysis begins with definition of parameter deviations from a production base line. This requires correction of test data to standard test cell conditions (i.e. including installation and the bleed effects).

Bottom-up analysis requires knowledge of the module age vs cycle age at the start. From the cycle age at the time of the analysis, the module degradation is worked out. Prior knowledge of module level or component level degradations with cycles is implied. Thus for this technique to be effective the cycle life variation with hours of operation and variation of degradations (microscopic or macroscopic) with cycle age must be built up. Having built the microscopic degradations, the macroscopic degradations are built up as explained in the last chapter. The engine simulation program can then be run to generate the degraded working line. The differences between this calculated performance and the measured performance determine the accuracy of estimation of the component degradations. With this approach one can accurately determine the microscopic degradations, but for this approach to be effective a good knowledge of the cycle usage with service life and the variation of microscopic degradations with cycles is very important. This approach does not depend on the engine base line, but an accurate engine model is essential to establish the working point.

The top-down approach does not depend on the prior knowledge of the cycle life with service or of degradations variation with cycles. But what is important is, the establishment of a very accurate base line. A comparison of the two approaches supports each other [SALLEE,1980b]. Since the bottom-up approach requires enormous data to the build up the hour-cycle and cycle-degradation algorithms, top-down approach only shall be considered in this thesis.

Three possible methods of performance analysis are:- (i) **Trend analysis,** (ii) **Trend analysis with base lines,** (iii) **Gas Path analysis.** At its simplest level, **trend monitoring** merely allows the operator to keep track of the directly observed readings. One of the basic problems with simple trend monitoring is that if different power settings are used from day to day there can be considerable scatter in the data even for a perfectly healthy engine. The diagnosis through trending the parameters measured is an important secondary process of analysis. The majority of the trend monitoring performed today uses the baseline data in order to determine when engine performance is deviating from the norm; it is usually more convenient to plot the differences (between the measured values and baseline values) against time. Automatic trending requires smoothing of the data scatter while manual plotted trends may be identifiable. The accurate quantification of the trend embedded in the data scatter can be linked with life usage. While the level of component performance is a function of the engine build, the change in performance can be associated directly with deterioration. Trending parameters to measure changes as a function of usage and to predict when an allowable level is exceeded is an extremely attractive aid for maintenance policy formulation.

While trend analysis is a useful and essential technique, it is somewhat limited in its capability. Thus it may be possible to detect engine deterioration, but may not be able to identify the cause of the problem. The judicious use of gas path analysis, however, can help in focusing attention of the likely causes of the problem. For this reason trend analysis is regarded as a complementary rather than competing systems. This has remained an activity at the base level rather than in the field.

Gas Path Analysis

Gas path analysis uses the instrument measurements to deduce the independent, more critical cycle parameters that cannot be measured directly in the field eg. mass flow, Turbine Inlet Temperature, thrust etc. The process of transforming the measurements from an engine to health assessment indicators could be a direct comparison method or an inferential. The former detects consistent deviations in the engine measurements; hence the name. Applicable in the steady state of operation, the measured values are compared directly against nominal engine values under similar conditions. Changes are the indications of a malfunction while arithmetic sign and magnitude of consistent deviations can be used to isolate common failure modes. This requires little modelling and computation of data.

For this approach, it is sometimes argued that individual or customised base lines are required for individual engines [SARAVANAMUTTOO,1983], but establishing the base line in the field is a problem. The approach does not involve large-scale computing systems, which are required for individual base lines. Use of common base line is often made and initial difference from this common baseline at the beginning is noted. Since the change with time, is of interest, the initial deviation is of no consequence.

The second method uses fault coefficient model to invert the measured deviations and calculate an estimate of the deterioration parameter. The changes in the modules being small, modern estimation theory is used to assess these from the measured overall performance of the engine. The fault coefficient model is determined by varying each deterioration parameter and observing the change in each of the outputs. For this purpose it is assumed that (1) The parameters affects the output in direct proportion to their values, and (2) The effects are independent of each other. The resulting equations are defined as a linear fault coefficient model.

Gas path analysis techniques are based on some or all of the following **assumptions** [SMETANA, 1974] :-

(1) The gas flow (air or air-combustion products) is essentially one-dimensional, that is it has substantially same pressures and temperatures at every point in a plane normal to the flow of gas. These temperatures and pressures are in effect averages of the conditions across the gas path. In case the pressure or temperature pattern in the plane is determined by means of mult-probes complex instrumentation, then this assumption can be lifted off.

(2) The engine is in a steady state i.e. constant mass flow rate, fuel flow rate, thrust,weight inlet pressure, inlet temperature, engine temperature distribution, and engine speed. Hence equilibrium thermodynamics can be performed provided accurate

gas state condition is available through measurements.

(3)The gas flow through the engine is adiabatic.

(4)The ratio of specific heats of the gas, before and after each of the major engine components is constant and known beforehand. As a result, thermodynamic processes can be computed in closed form.

(5)By comparing measured changes in enthalpy across major engine components or even the entire engine with those expected for the same conditions of operation of the engine (air mass flow and/or fuel flow rate), it is possible to compute thermal efficiencies of these components or the engine as a whole. Presumably, a given change in efficiency is indicative of deterioration of health and of the need to perform maintenance.

(6)By comparing measured changes in the work done in compressing the gas and expanding it through the turbine with new engine or theoretical estimates, an efficiency, based primarily on pressure rather than on temperature measurement, can be computed.

(7)Measurements of the exhaust gas velocity and mass flow can be used to determine a factor related to engine thrust. If the engine thrust so determined falls off with time for a given power setting, then it can be assumed that at some point maintenance will be required. Similarly shaft power generated by the power turbine could be used as the deciding criteria.

(8) The engine components operate in an interdependent fashion. Thus work done by the compressor, the accessory drives and the frictional work absorbed by the bearings cannot exceed the work done by the turbine. Such measurements can be used as part of overall effort to isolate faults.

(9) Malfunctioning transducers can be identified individually by comparing the quantity calculated using the measurements from different transducers.

(10)Sensor indications can be combined to form parameter values which are characteristic of engine performance.

(11)"Healthy" engines have a particular set of parameter values for each operating condition. Each significant fault causes at least some of the parameter values in a set to change. Hopefully each fault displays a unique pattern or "signature" in a set of parameter values which makes it possible to identify the fault.

Based on these assumptions and with the knowledge of thermodynamic laws with in a component level control volume, the macroscopic effects are modelled. Conservation of energy and mass flow relate these macroscopic effects to observable parameters such as temperature and pressure. Verification of such data is usually accomplished in component test rig.

Module Degradation Identification

The inferential method of analysing data was introduced earlier in the chapter. A group of p measurements, z, are recorded. An additional abscissa variable, u, is also measured. Curves or functions, f(u), are used to represent normal engine operation as determined from a fleet average or from a particular engine's running levels. A set of p deviations in y, is calculated as the difference in the measured and the baseline performance values. A linear coefficient mode relates the deviations to engine parameter shifts, the q values, i.e. fan efficiency or pumping capacity changes.

If a single set of measurements is used the parameter estimates are determined from snapshot calculations. This gives an indication of the engine status at a particular instance of time. The number of accurately detectable parameters must be smaller than the number of measured variables. Also the random and deterministic instrument errors can cause significant inaccuracies in the estimates. The measured data can be filtered to eliminate the severity of errors either through hardware or statistically.

The basic premise underlying GPA is that the performance of an engine is directly related to the condition of its modules and that these can be mathematically interrelated to measureable parameters. The baseline performance of an engine is a direct outcome of the module interaction, the deviations can be described as the results of degradations of the engine. Thus the simplest fault model described above, in the absence of noise (i.e. v = 0), becomes

$Z = g(X,U)$ which can be represented as

$$[Z] = [H]\,[X] \qquad \ldots(3.11)$$

where

$$Z = \text{Column vector of dependent measured deltas} = \begin{bmatrix} \Delta\ T5 \\ \Delta\ N1c2 \\ \Delta\ N2c2 \\ \Delta\ T7 \\ \cdot \\ etc \end{bmatrix}$$

$$Y = \text{Column vector of independent measured deltas} = \begin{bmatrix} \Delta s.f.c \\ \Delta OLS\ hpc \\ \Delta Tburner \\ \Delta Power \\ etc. \end{bmatrix}$$

$$X = \text{Column vector of independent measured deltas} = \begin{bmatrix} \Delta\Gamma comp \\ \Delta\eta comp \\ \cdot \\ \Delta Aturb \\ \Delta\eta turb \end{bmatrix}$$

$$\begin{bmatrix} He \\ \hline Ge \end{bmatrix} = \text{matrix of engine fault coefficients}$$

A mathematical solution assuming the fault coeff He to be "invertible", is :

$$[Xe] = [Hs]^{-1}[Z] \qquad \ldots. \quad .. \qquad (3.12)$$

$$[Y] = [Ge][Xe] = [Ge][He]^{-1}[Z] \qquad .. \ (3.13)$$

Various assumptions made in deriving the above equation can be summarised as :-

1. The engine model is accurate with the base line and correction procedures allowing accurate assessment of measurement deltas and influence coefficients that truly reflect how potential module problems are represented by measurements

2. The fault coefficients are an accurate engine model descriptor; the faults occurring in the engine are among those being sought.

3. The fault coefficients are "invertible" i.e. the changes in the unknowns are adequately manifested in the observations.

4. The measurements are repeatable and noise free.

The model considered (for engine base line and analysis) and effect of repeatability have been discussed in chapter 8 and chapter 5 respectively.

<u>Review</u>

Deterioration, the slow degradation of gas turbine performance is caused by cumulative effects of the module degradations. Quantitative determination of these effects is gas path analysis. The top down and bottom up approaches of evaluating these effects across a module yield similar results. Often, in the absence of data, top down approach is followed. This requires an accurate estimation of a base_line for the engine. The performance monitoring could be through trending the data, trending the independent critical cycle parameters or with the help of a sophisticated computer program. There is a strong coupling between the thermodynamic behaviour of the engine and its mechanical health, and through monitoring the performance of the gas turbines an accurate estimate of time dependent failure can be made. But there are components of the gas turbine that either cannot be monitored through performance, or which have instantaneous failures or both. Also to be detectable by the analysing technique, the faults must be implicit.

Certainly some faults are too minor to be detectable by gas path analysis. This requires implementation of other techniques of condition monitoring. Some of these are considered in the next chapter.

CHAPTER 4

MECHANICAL CONDITION MONITORING TECHNIQUES

Introduction

Monitoring techniques that determine the mechanical condition (health) of the gas turbines and ensure safe operations are reviewed in this chapter. To be cost effective the engine condition monitoring system must be a totally integrated diagnostic system, with a proper balance of emphasis on all of the condition monitoring techniques. It is the intention of this chapter to describe these techniques and their interaction with the GPA. Techniques of (1) oil condition and debris monitoring, (2) vibration monitoring (3) engine life usage and (4) visual inspection have been explained.

General

The purpose of any gas turbine engine condition monitoring system, is, to permit meaningful conclusions on the engine status to be drawn from measurable data in a cost effective manner. Certain faults occurring in the gas turbine are not possible to be implicitly detected by the analytical technique because of the negligible effects caused by these on the measurable parameters of the engine. Detection of these faults, such as fatigue crack, corrosive attack, bearing failure, combustor liner crack, fuel injector coking etc, is important. Similarly determination of the engine life used, problems of rotating components and condition of accessories are necessary.

A failure can be defined as a state when the machine is unable to yield the same performance as when new. Failures occur mainly because of design deficiencies, material defects, processing and manufacturing deficiencies, assembly errors, unintended service, maintenance deficiencies (eg. neglecting some of the procedures), improper operation or abuse. Various stages of a failure can be classified as, damage, deterioration, distress, incipient damage and incipient failure. The gas path analysis is an analytical technique, capable of detecting only those degradations that imply measurable changes of the measured variables. Most of the faults arising in the modules of the gas path do generate detectable changes of temperatures and pressures which permit the GPA to identify the faulty modules. Hence a large portion of the potential faults related to the engine performance parameters are amenable to detection by the GPA.

This ensures an efficient and an economical use of the engine but the concept of "safe operation" is equally important. Symptoms of the mechanical condition (and failure) may be present in the gas stream, but the complexity of the flows, limited number of sensors, errors and uncertainty of the measurements have inhibited their identification by the GPA. Detection and prediction of the failure of these components that are present in the gas path, but do not induce detectable changes in the measured parameters, is as important as the determination of the deterioration of the engine performance. In addition to these, there are a few components that are not washed by the gas, and hence may not influence any changes in the measured parameters .The GPA cannot predict behaviour of such components, that are not washed by the gas, eg. bearings, shafts, auxiliaries, support system etc until their deterioration has reached such a level so as to cause a noticeable change in the measured parameters.

Certain monitoring techniques that determine mechanical integrity of the engine to ensure safe operation must be installed on the engine along with the GPA. A totally integrated diagnostic system must serve the measured data from gas path, rotating parts and accessories, in a fashion, mutually complementary to each other to diagnose the problem. For example rear end vibration coupled with gas path information changes might be indicative of lost or damaged turbine rotor blades, whereas the rear end vibration coupled with a high lubricating oil temperature might be indicative of a damaged main rear bearing [URBAN,1972].

As the gas turbines have become more capable, complex and costly, sophisticated maintenance has developed. When the engine goes for maintenance, complete knowledge of the engine health, its performance and the scope of the work needed to restore its performance, is required to be known without stripping the engine. This involves monitoring the mechanical condition of the engine by other techniques in addition to the gas path analysis. Detectable faults due to wear, component degradation, corrosion, erosion, abnormal use etc. can be determined by these mechanical diagnostic methods.

Following are the current prominent mechanical monitoring condition techniques for the gas turbine engines.

- **Oil system monitoring technique**
- **Vibration monitoring techniques**
- **Engine usage monitoring techniques**
- **Visual condition monitoring techniques**
- **Exhaust gas spread**
- **Limited transient monitoring**
- **Acoustic monitoring**

A detailed description of all these techniques has been included in Appendix B. Some of the techniques that aid in the diagnosis of the cause of the engine performance loss are reviewed in succeeding paragraphs. It is emphasised that all the techniques are equally important. There is no one technique that can satisfy the requirement of fault detection for all the components and the faults arising in the gas turbines. Inference drawn from observations of one technique is usually confirmed, for traces of the fault hypothesised, in the other techniques. Thus all the techniques of the engine condition monitoring are complimentary to each another.

Turbine Exit Spread Monitoring

Turbine Exit Temperature spread monitoring, under steady conditions, is an established technique of condition monitoring the gas generator combustion system and HP turbine gas path components. During commissioning of industrial turbines, it can be used as a tool for making fuel adjustments. A set of equi-spaced thermocouples, with one thermocouple per burner is necessary for effective spread monitoring. The monitoring is carried out continuously (manually or automatically). Typical problems that could be detected by use of T.E.T spread are :-

1. Buckling and cracking of combustion chamber, eventually resulting in pieces becoming detached and lodging against NGV's.
2. Partially or Fully blocked burner
3. Asymmetric distribution of the fuel to the burners.

Limited Transient Monitoring

During start up and shut down limited monitoring of the gas generator transient condition gives useful information not necessarily shown by other methods. During start up the parameters monitored are the Maximum Gas Temperature (MGT) and the time to light. MGT is recorded on each engine to monitor hot start occurrences and trend analysis which may indicate fuel system drift, starting system shortfall or gas turbine combustion system deterioration [EHLER,1984]. In some cases, in the absence of required electric supply, eg. field starting of helicopters, remotely placed gas turbines etc, the value of MGT might have to be input by the operator.

Gas generator Coast-down Time

The time to reach a specified speed for each spool from idle, during a shut down, is also recorded in most of the cases. Trending this time can give useful indications about the faults in the fuel system, bearings, seals or the rotating blade tip rubs. This also generates complete range spectra for vibration analysis. Here again when automatically recording the data, and, in the absence of an electric supply source, the supply should be run on one engine and the last engine data has to be provided by the operator. While this can be easily accomplished for aircraft, industrial engines have to be specially shut down to check the vibration spectra in that region. The operational requirements may not permit this, and hence the coast down time is recorded only when the engine is taken off line for maintenance.

LP cooling air temperature

The LP cooling air temperature on some engines, eg Avon, provides an important indication of internal air and oil leakage within the gas generator and also provides a check of the turbine entry casing which may be deteriorating due to burner malfunctions.

Usage monitoring

Monitoring the cycles of the rotating components especially in the hot zone is at present applied primarily in the military aircraft engines (fighters and helicopters). The logs of start-stop cycles and the hour meters, traditionally employed on the industrial engines do not provide complete life cycle history of the engine. The usage monitoring allows the life of each engine to be assessed separately, thus ensuring that no engine is used beyond its normal assessed life, nor is the engine removed before it has completed such life until and unless its performance has deteriorated below acceptable level. Since the module level degradations are evaluated in terms of the cycles completed this aspect of monitoring is closely associated with the GPA.

Review health Various techniques of monitoring the mechanical health have been reviewed in this chapter and the supporting Appendix B. These techniques together with the gas path analysis form an integrated diagnostic system. Even though a few of the techniques are beginning to appear on-board, most of these techniques are still off-line techniques. No one technique is 100% informative about the complete engine. Hence, each of the fault is normally confirmed by two or more techniques before the engine is taken out of service. Almost all the users agree that even with the most sophisticated technique of the gas path analysis or other monitoring techniques the decision to remove an engine from service, is always based on the visual inspections.

CHAPTER 5

GAS TURBINE MEASUREMENTS FOR GAS PATH ANALYSIS

Introduction

Effectiveness of the gas path analysis depends on the effectiveness of the measurement system. Only those faults can be implicitly detected, the effects of which can be accurately measured. Accurate observation of judiciously chosen parameters with minimum of disturbance to the engine and its systems, minimum weight and at a minimum of the cost is the aim of the measurement system. This chapter reviews various measurement errors and effects of the basic measure parameters on deduced values (of interest to GPA). Finally techniques of measurements for various parameters of the gas path are explained.

General

Propulsion instrumentation is required for several functions eg. control of the gas generator (including geometry) and interaction between the gas generator and, the intake and the nozzle; control panel (cockpit) display of monitoring instruments, propulsion output (thrust/power functions) information for interfacing with fuel management, flight control, weapon system and of course engine diagnosis or maintenance purposes. Performance parameters of the gas turbine engines and its components are rarely measured directly. These are generally deduced from the measurements of basic parameters such as temperatures, pressures, rotational speed(s) and the fuel flow.

The simplest way to monitor the performance of a gas turbine engine is to read the engine instruments and compare these with a reference data (under similar conditions of operation eg. load or flight). In fact this is done by the flight crew or the operator. Modern complex engines in a single crew aircraft require the data to be separately recorded and/or analysed leaving the pilot to look after operational flying. Similarly for the operation and performance monitoring of remotely controlled gas turbine engines, recording the data is a necessity. The recording of the basic parameters should however be without disturbing the other indications even in case of the recorder mechanism mal-function. A disturbance in the wrong direction can lead to a limit exceedance, and in a severe case can cause in an engine failure. There is hardly any scope for additional sensors to be installed on the engines and even if it was plausible too many sensors could lead to a disturbance of the gas path in the engine.

Measurement Chain

The chain of measurement, whether for display or for recording, is shown in Fig 5.1 [BENTLEY,1983]. In general the chain consists of four elements or blocks.

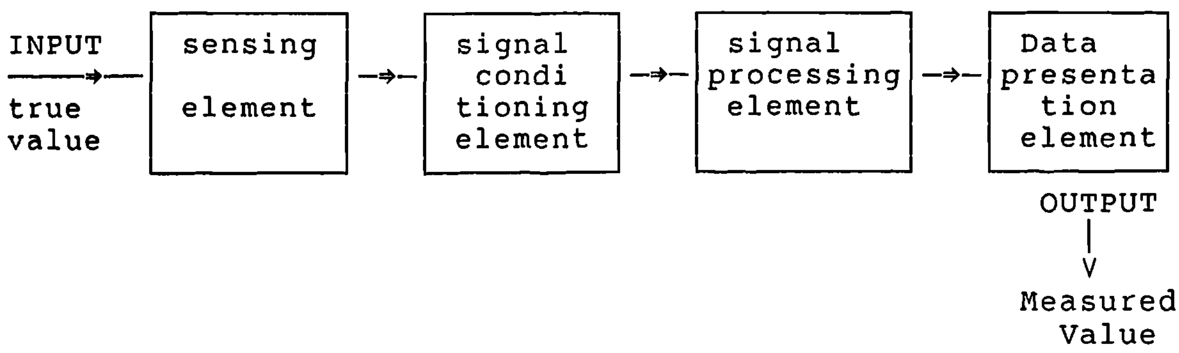


Fig 5.1 General Structure of a Measurement System

Sensing Elements This is the contact with the process and gives an output which in some way depends on the variable it measures. In the system with more than one sensing elements, the element in contact with the process is called the primary sensing element and others, secondary.

Signal Conditioning Element converts the sensing element output into a form more suitable for further processing. The output is usually a d.c. voltage, an a.c. voltage, or a frequency signal.

Signal processing element conditions the output of the conditioning element into a form more suitable for presenting or recording. For example an analogue signal may be digitised for manipulation by the computer or for the purpose of storing the data.

Data presentation element presents the measured value in a recognisable form. This could be conventional display unit or alpha-numeric display.

The commonly used word **'transducer'** is a manufactured package which gives an output (usually voltage) corresponding to an input variable such as pressure or temperature. The transducer thus incorporates sensing and signal conditioning elements.

ERRORS

All measurements have measurement errors, defined as difference between the true value and the measurement. Uncertainty is the maximum error which might reasonably be expected in a measurement and is a measure of the accuracy, i.e., the closeness of the measurement to the true value [ABERNETHY,1975]. A detailed description of the types of errors of a measurement, characteristics of measurements and measuring systems and analysis of the uncertainty of the deduced parameters is given Appendix C. Hence only a brief reference to these is made here.

There are two types of systems involved and the errors can be classified according to the system.

Measured System Errors

In addition to the errors originating in the measured system, there can be an error due to imperfection in modelling the measured system (eg. gas turbine exhaust) which underlies the measurement process. The temperature of the exhaust gases, for example, may not be uniform, and a result of the measurement that assumes uniform distribution will be in error.

There can be an error that arises due to the changes in the configuration of the measured system produced by the introduction of the sensor [FINKELSTEIN,1983]. The increase of back pressure of the engine, because of the thermocouple in exhaust duct, can cause increase in the fuel flow and in turn an increase in the EGT it is measuring. The sensors absorbs certain amount of power, however small, thus causing an error. The heat exchange between exhaust gases and the sensor alters the heat content of the gases and hence its temperature.

Integration of a new sensor on the engine involves the probe, position error estimation, averaging system, type of transducer, environment (Pressure, loading, temperature, vibration etc.), signal transmitivity, signal conditioning, filtering and data recording. For flight, the equipment must satisfy the safety regulations. Mounting the sensor on structure surrounding the engine gives the sensor a longer life and is desirable. But this may not always be possible. When mounted on the engine the temperature and stresses of the engine parts can cause considerable relative movement that must be taken into account. The involvement of the manufacturer is hence considered very essential.

Measurement System Errors

Whatever be the parameter measured, its measurements incorporate an uncertainty. This uncertainty is due to certain errors depending on the type of system used. For a gas turbine engine system these could be :-

Calibration Hierarchy Errors
Data Acquisition Errors
Data Reduction Errors

A detailed error analysis has been worked out in Appendix C, where the types of errors and their propaggative effects on the deduced parameters have been reviewed. The absolute error as derived in the Appendix can in general be written in terms of the constituent errors as

$$\Delta Q_{abs} = \left| \Delta M_1 \frac{\partial f}{\partial M_1} \right| + \left| \Delta M_2 \frac{\partial f}{\partial M_2} \right| \;\ldots\; + \left| \Delta M_n \frac{\partial f}{\partial M_n} \right| \quad ..(5.1)$$

In order to eliminate the effects of opposite signs the root mean square (RMS) value can be written as

$$\Delta Q_{abs} = \sqrt{\left(\Delta M_1 \frac{\partial f}{\partial M_1} \right)^2 + \left(\Delta M_2 \frac{\partial f}{\partial M_2} \right)^2 \ldots + \left(\Delta M_n \frac{\partial f}{\partial M_n} \right)^2} \quad .\ (5.2)$$

The cumulative effect of the errors is thus a weighted root mean square of the individual component errors. This technique of determining the uncertainty of deduced parameters will be used for the analysis in later chapters.

Error reduction techniques

The errors in a measurement system because of non ideal characteristics of the constituent elements can be identified through calibration of the system. Once the element with most non-ideal behaviour has been identified, compensation strategies to eliminate or minimize such errors can be devised. This would produce significant reduction in the error of the overall system. Various methods of error reduction are :-

- Hardware redundancy
- Compensating non-linear element
- Zero environmental sensitivity
- Opposing environmental inputs
- High gain negative feed back
- Computer estimation of measured value

The characteristics of measurements, the errors in the measurement system and the propagation of the error to the values of the parameters deduced from them is included in Appendix C.

THE INSTRUMENTS FOR A GAS TURBINE

During the design and development of a gas turbine engine numerous, precise and complex instruments and measurement systems are used on the test bench to determine the critical parameters and validate the assumptions of modelling. However, when the engine enters service, the instrumentation used is restricted to a minimum, simple, inexpensive, light weight and as necessary for the safe operation of the engine.

Gas Path Analysis and Instrumentation

For an effective performance monitoring system, through data storage, the measurement system normally consists of transducers, signal conditioners, signal processors, recorders, and readers. Conditioning the signal output could involve conversion from analogue to digital, modulating, amplifying, filtering noise (high band-pass and low bandpass) and coding. The recorders could be analogue or digital. For the analysis the recorded data has to be read, decoded and reconditioned before it could be interpreted sensibly by the operator or the computer.

In the gas turbine engines the parameters principally measured for performance evaluation are the static pressures, total pressures, temperatures, running clearances, positions and air angles. In addition rotational speeds and the fuel flow are measured to determine the stress and strain in the rotating parts and the engine thermal condition. These measurement of rotational speed and fuel also serve as a basis for comparing the performance of the engine and for its control. Many of the control sensors additionally supply signals to the control-board indicators which inform the controller of the engine condition when adjusting the controls to vary power. It may be necessary to measure certain parameters for monitoring mechanical health of the engine. This could include - Vibration (frequency and amplitude), lubrication oil pressure, chip accumulation in oil etc.

The sensors are mounted either on the engine or inside the engine and consequently experience very severe environmental conditions which deteriorate their performance can cause failures. This puts the measured data in doubt, both of accuracy as well as validity. The importance of the reliability of the measuring system for gas path analysis cannot be over emphasised.

Pressure Measurement System

Pressure in gas turbines is measured for the purpose of the engine control and for the GPA. The pressure transducer converts the gas pressures into usable output form. To measure steady state pressures (static and total) the transducers should have low frequency response while for measurement of pressure fluctuations or turbulence, the response should be high. Pressure transient measurements are of interest in research instrumentation and has not been so far utilised for GPA.

Operational measurements of, both, static and total pressures are in the steady state only. The basic sensing element of the instruments is a capsule with a bellow that responds to changes in the pressure. This movement of the bellow changes either the inductance or flux distribution thereby causing a change in emf output voltage. Accuracies of the order of 0.05% with range upto 3.1 Mpa have been achieved. Vibrating element type transducers make very precise measurements of pressure and are particularly suited to engine control [SCHLUMBERGER,1987], and monitoring due to their high reliability and stability characteristics.

Static Pressure Probes These are based on the assumption that the variation of the static pressure across the boundary layer is of the second order. Thus the pressure measured in a cavity at the wall is the same as the static pressure at a point across the plane where the velocity is a maximum. The shape and size of the hole affect the measurement and are important for accuracy [ARMENTROUT,1979]. The effects arise because of turbulence and compressibility. Sometimes the static pressure measuring hole may be combined with the total pressure probe which is protruding into the flow. These measurements are used to determine flow rates and to establish the thermodynamic state of the gas.

Total Pressure Probes measure the pressure of the flow by bringing the flow to stagnation condition isentropically. These are normally protruding into the flow so that the measurement is away from the boundary layer effects. This causes disturbance of the flow which travels both, upstream, causing measurement errors, as well as down stream, causing flow distortion. The total pressure probes are influenced by flow direction, turbulence, compressibility, pressure gradient and the probe geometry. Protrusion of the probe into the flow causes stresses at the base of probe attachment failure of which can be catastrophic if such a probe was used in front of a rotating component. Thus there is a reluctance to measure total pressure before compressors and turbines.

Total pressure in the jet pipe varies considerably with location, requiring up to 6 probes circumferentially for an accurate assessment of the average. Total pressure in jet pipe is altitude dependent and as such difficult to use as a measure of thrust. Total jet pipe pressure and the fan/compressor inlet pressures are measured separately, their ratio, the Engine Pressure Ratio (EPR), is used as an engine control parameter. The EPR representation is used mostly on multi spool engines. The probe measures pressure ratio across the gas generator (turbine exit to compressor inlet). Electro- mechanical and electronic type of transducers are used. In electromechanical the movement of the bellow shaft is sensed by a linear variable differential transformer which converts this mechanical property to current. The electronic EPR system utilises two vibrating cylinder pressure transducers that vibrate at frequencies relative to the pressures. EPR is then calculated through electronic measure of these frequencies.

Measurement of inlet total pressure avoiding the boundary layer is possible using one or two probes provided the probe(s) are with in 10 degrees to the local flow angle [VLEGHERT,1981]. Compressor Delivery Pressure is measured at exit to the diffusor or inlet to the combustion chamber. Since Mach numbers are very small normally a static pressure tapping is used to estimate CDP when the error is less than 3%. The CDP to inlet pressure ratio is used as a fuel flow control function.

Pressure indicators or switches are also used to sense oil pressure, lube oil filter pressure differential, fuel filter pressure differential and main burner fuel pressure.

Temperature measurement The thermodynamic state of the engine can be determined from the measurement of the gas temperature. To measure the gas temperature thermocouples have been used for quite some time. The underlying principle is of generation of an electromotive force in two dissimilar metals when their junctions are maintained at different temperatures. However the cold junction is simulated by incorporating a temperature compensating device in the circuit. The accuracy of thermocouples is affected by temperature distribution, recovery factor, radiation to and from the environment, heat conduction from the probe by the leads and thermal inertia. The thermal inertia makes the measurement a low frequency response and hence basically a steady state phenomena.

The thermocouples are very simple, but, they are (1) subject to calibration drift above 550 K, (2) unable to average out temperatures in transonic flows and (3) unable to survive very high temperatures. Temperature at all stations, except at the exit to the combustor, in an engine can be measured through thermocouples . So far measurement of gas temperature at exit to the combustor has been limited to research instrumentation only. For this purpose shielded thermocouples, refractory metal thermocouples, cooled thermo couples, optical method and sample gas analysis have been used. Also the dynamic temperature measuring sensors to measure gas temperature transients for study of unsteady flow effects and heat transfer to the engine parts has been a research [ALWANG,1980], instrumentation work only. Operational utilisation of these methods is still quite far.

Because the combustion gases are swirling around, the measurement of temperature at one point only, in the plane of flow down stream of the combustion, is not a very good representative of temperature at other points in the plane. To determine temperature accurately, especially at the hot end, multiple probes (up to 20) in a plane around the engine periphery, are generally used. This allows us to scan temperature spread and infer condition of the combustor.

The predicted durability of the engine components depends on the accurate prediction of the temperatures, the temperature gradients, and the stresses under steady state and transients. Typically, in high temperature turbines failure is dominated by creep rupture, low cycle fatigue, creep fatigue interaction, corrosion or erosion. Creep failure prediction and corrosion are dependent on steady state temperature whereas low cycle fatigue is determined by transient temperatures and stresses. Thus measurement of turbine blade metal temperature is very important. The most effective method of metal temperature measurement involves the use of optical pyrometry. The blade metal temperature is deduced from the radiant energy emitted by the blade surface. Other methods used for measurement of the metal temperature are thin film thermo couples, Imaging pyrometry and coherent anti-stokes raman spectroscopy.

The engine performance is non-dimensionalised with respect to inlet conditions and then standardised to ISA conditions. These include IGV scheduling, computing corrected N1 or N2, corrected EGT, determining corrected fuel flow and correction of the thrust specific fuel consumption. The influence of accuracy of measurement of the inlet temperature hence affects greatly the uncertainty of performance determination. The need for inlet total temperature measurement accuracy has increased with the development of full authority digital engine control systems [EDWARDS,1984]. The sensors are exposed to solid particles ingested with the flow. The water and ice particularly cause "cold shift" in the temperature measurements and sensors read lower temperatures. Shielded sensors are slow in response and the measurement is not accurate. The error are further aggravated by use of anti icing air.

<u>Gas Path Clearances</u> To obtain desired performance the gas path clearances must be carefully controlled. To achieve this active control, as on XG-40 engine for European fighter aircraft, the gas path clearances must be measured. Since minimum clearances and the accompanying seal rubs frequently occur during the engine transients, the measurements must be made in steady state as well as in transients.

At low temperatures, the clearances can be measured by electrical proximity probes (inductive, eddy current and capacitive types). But because of zero point drift and calibration drift it is not possible to use these at high temperatures. Optical proximity probes have been used upto temperatures of 1385 K in the steady state as well as in transients.

In test beds X-radiography can be used during an engine run to determine these clearances accurately. This has advantage of study of any internal location without special case penetration and sensor bosses but are expensive, complex and require special methods for thin blades [PAULON,1981]. Inspite of these accuracies, in the absence of the ability to simulate flight manoeuvres in the test bed, they cannot substitute the measurements in flight . The desire to develop highly fuel efficient engines has greatly increased the requirement of in-flight measurement of the gas path clearances.

Rotational Speed

Measurement of rotational speed is carried out using either a tachogenerator or a pulse probe. The underlying principle of a tachogenerator is generation of current proportional to the rotation. The chief advantage is independence of external power source, capacity to withstand high temperatures and loading and long life.

The pulse probe is basically an e.m.f. generator and a frequency counter system. The e.m.f. is generated in a coil by the rotating shaft in such a way that one pulse per rev is generated. These pulses are counted at the other end. The probe has no moving parts (long life), simple in design and does not require a special drive (as tachogenerator). Low spool rpm has been used as an engine control parameter and because of the reliability of the instrument and the accuracy of its measurement, it is still a preferred control.

Fuel Flow Measurement

Measurement of the fuel flow enables the performance analyst to know exactly, the amount of thermodynamic energy input to the engine, enabling energy balance to be carried out accurately. Commonly used fuel flow meters are the turbine-type. The fuel flowing axially in a duct turns the multi-bladed, free spinning rotor that obstruct its path. The instrument is so designed that the speed of the rotor is nearly linearly proportional to the flow velocity and hence to the volumetric flow. For thermodynamic performance of the engine, mass flow of the fuel is normally used. Hence using such a fuel flow meter, the temperature of the fuel is required to be measured, to determine the fuel density and hence the fuel mass flow.

Mass flow meters, based upon the inertial properties of the fluid, are used in some aircraft to measure the amount of the fuel burned and the fuel remaining. These are inaccurate, more complex mechanically [JAPIKSE,1986], than the turbine meters and are expensive. But they eliminate the problem of measuring the fuel specific gravity, or the density.

For ultimate accuracy the flow meters must be corrected not only for the density but for viscosity as well. The lack of information of exact low heating value of the fuel, viscosity limits the value of on-line density meter for thermodynamic analysis. Working accuracy of about + 0.1% is achievable through positive displacement calibrator. Despite the simplicity and importance of fuel flow measurement, it is usually the least reliable of all [VLEGHERT,1981]. A problem of accurately measuring the fuel flow is the error because of the longitudinal vortices set up by the bends in the fuel pipes, practical fuel flow meters do not have flow straightners. Sensitivity to fuel contaminations and the requirement of protection against ice accretion are a few more of the problems that affect the accuracy of the measurement. From gas path analysis view, volume fuel flow is not as important as calorific input. Most of the industrial engines use fuel of a known calorific value and both density as well as viscosity can be determined. For jet fuels (AVTUR) on the other hand the calorific value of the fuel correlates closely to the specific gravity, and in turn to the temperature of the fuel, fuel temperature is hence measured separately and fuel flow is corrected correspondingly.

Mass Flow Measurement

Accurate determination of the mass flow in gas turbines is very much desired since the fouling and erosion of the compressors are directly related to the mass flow. The simplest technique of mass flow could be the use of a manometer utilising the intake depression. In the gas turbine test beds the mass flow through the engine is determined by a calibrated venturi flow measuring device. For initial flight tests the inlet is similarly calibrated. This however requires corrections when the ambient conditions are non standard and non-nominal or non calibrated intake is used.

An alternative method is to determine the mass flow with the knowledge of the compressor flow capacity. Knowing the pressure ratio and the referred speed the mass flow can be determined from the compressor maps applying corrections for circumferential and radial pressure profiles, Reynold's number, radial tip clearances and humidity. This method of mass flow determination has certain draw backs. The compressor may now be operating in series rather than singularly and this will have interference effects requiring corrections. Variable geometry guide vanes/stators, change of characteristics due to erosion/deposits, change of clearances further induce complications. However when calibration is possible it may not always be necessary to refer to the compressor maps. The flow is then determined by correlating to the engine referred speed and the pressure ratio.

The mass flow in the core can be determined using the turbine flow parameter, which is a constant in the choked region. The choked value may be determined from rig tests and modified for the turbine nozzle area in the test engine. Calibration is possible during ground test using engine instrumentation when the mass flow is determined by another method [SAE AIR 1703]. Corrections for turbine pressure ratio, referred speed and gas properties may be necessary. Since turbine inlet pressure and temperature are not measured they are estimated from compressor and combustor characteristics depending on the fuel flow rate. This is however iterative and in off-design conditions, the choked condition may not exist.

The engine mass flow can be obtained through measure of internal static and total pressures. The measure of pressures in rake (with number of probes to cover the annulus) is correlated to the mass flow determined by other methods. Since the instrumentation is quite large, can introduce disturbances and could also effect safety this method is not a favoured one.

Mass flow could also be calculated from the knowledge of nozzle conditions such as nozzle entry total temperature and pressure, nozzle pressure ratio, nozzle area and flow the coefficient. This requires instrumentation similar to thrust determination. This however is possible only in the core section of bypass engines. Hence the mass flow through the fan must be calculated by the energy balance. This method may not be possible in afterburning engines because of high temperatures.

Thrust measurement

The knowledge of thrust in aircraft engines provides a straight forward estimation of the engine state. But the thrust of the engines is affected by the ambient conditions, flight speed, gas generator speed, reheat, bleeds etc and in flight determination has not been possible so far. In test beds and on the wing, the measurement of the thrust using strain gauges has been possible. several types of strain gauges could be used eg. wire strain gauge, thin film strain gauge, thin film capacitive strain gauge, double core fibre optic strain gauge etc. Unfortunately, under the hostile environmental conditions as in the path of the the gas, some problems arise in their use. These are :-

(a) Excessive drift with time, especially at high temperatures, requiring frequent calibration and hence a factor of uncertainty is always present in the measured data.

(b) Low temperature operation.

(c) Unpredictable temperature effect on coefficient of resistance.

(d) Large and non linear correction factors.

(e) Poor fatigue strength and flexibility.

(f) Susceptible to corrosion and oxidation.

Because of these shortcomings of the strain gauges, the thrust is measured directly only in test beds. Operationally it is represented either by the LP spool rpm or by jet pipe pressure. Since jet pipe pressure is altitude dependent ratio of gas generator pressures known as Engine Pressure Ratio (EPR) is used as a measure of thrust.

Knowing average total pressure in the jet pipe and the nozzle flow area, gross thrust is determined. Flow around the nozzle is important for gross thrust but not the engine type and the gas temperature. Determination of net thrust is deduced subtracting intake momentum drag which is intake mass flow times intake velocity. As intake drag is about 66% of gross thrust on a fan engine in cruise flight, the EPR method is not very accurate measurement of the net thrust. Influences like pre-entry drag aft-body drag etc. are quite large in transonic and supersonic flight [COVERT,1985].

<u>Torque measurement</u>

In shaft engines (turbo-shaft and industrial) the power available on the shaft is the output and is measured by the torque on the shaft. The torquemeter is a planetary gear system with one or more helical pinions driven by the shaft in a oil filled case. The helical gears produce axial force on the enclosing oil which pressurises the case. The measure of oil pressure is thus the indication of the torque applied.

For a known modulus of elasticity of the shaft material, use is made of the amount of twist in the shaft to determine the torque. Speed and torque in such a system, known as total system, are measured simultaneously. The non contacting system [SCHLUMBERGER,1987], measures relative movement between tips of teeth of two wheels mounted on the shaft transmitting power. This requires use of a micro processor based electronic signal conditioner compensating for temperature and other factors.

It is desirable to know the torque on the shaft(s) rotating compressor(s). This determines the work done on the compressor and hence its efficiency. But the size and calibration requirements have been a problem in the development of the same.

Electrostatic exhaust probe measure the charge on the striking particles in exhaust gases and output as voltage. It consists of a low impedance probe protruding into the high temperature exhaust gas. This measurement in the gas path allows the mechanical condition of the gas washed components, especially the hot zone (including combustor), to be ascertained.

Fibre Optics are used in gas turbine engine measurements for various purposes. Gas path clearances measurements, flame diagnostics, determination of temperatures, holography, detection of flutter and double core fibre optic strain sensor are a few applications in the development stage and under laboratory (test bed) environments.

In field, fibre optic based endoscopy that allows internal viewing of engine components without disassembly is becoming very popular. Modern engines have numerous endoscope view points that allow regular inspection and recording (video or film) of inaccessible components such as compressor or turbine blades, combustor lining etc.

This permits the visual condition to be trended and/or diagnosed by experts away from site. In old engines the boroscope points can be used for limited endoscopy.

TELEMETRY IN GAS TURBINE ENGINES

As designs and material are pushed nearer to their limits, accurate measurements of stresses in components become increasingly important. The actual conditions of stresses, strains (dynamic and static), temperature in an engine are only when it is run on a test bed or in operational use. Most of these measurements exist on the rotating shaft, discs, and blades. In addition the vibration modes of these rotating parts is also important. These measurements on the rotor of an engine have to be brought out for reading and/or recording. Mounting conventional slip rings is often impossible [JAPIKSE,1986], because of restricted space, or undesirable, because of inaccuracy and unreliability.

This requires an electronic system to transfer the essential measured data to outside the engine for reading and recording. This is telemetry.

Some of the problems associated with the use of telemetry are :-

1. The measured signals are corrupted by spurious engine rotational signals. Improper antennae, close proximity of engine metal work, rotating parts, and electric interference on long wiring involved are the primary causes.

2. Failure of electronic components due to high loading.

3. Hostile environment featuring oil, water, high temperatures and temperature variations.

Recent advances in electronics however have a good scope of making telemetry of important data not only for development engines but also for operational monitoring for diagnostics and life assessment. This can be achieved through

1. Increased accuracy through the use of digitised modules.

2. Reduction in construction costs, weight and increased reliability through use of thin film wiring technology.

3. Increased resistance to hostile environments and variations.

4. New applications for telemetry techniques such as acoustic emissions.

Instrumenting Small Gas Turbines

Small gas turbines have additional problems where space for installing the sensors, high rotational speeds and complexity of flows presents formidable measurement problems [ALLAN,1983]. Quite often these engines are mounted on small platforms eg. helicopters, trucks, remotely piloted hovering platforms, tanks etc. which generate vibrations. The small size and weight of the engines prohibit using elaborate instrumentation which could have been acceptable for a large size engine.

Other Measurements

In addition to these measurements there is the measure of **oil temperature, oil pressure, fuel temperature, fuel pressure** and **vibrations.** Oil system measurements and vibration measurements have been included in Appendix B. The fuel temperature provides useful data of the calorific value of the fuel, whereas the pressure measured in the low pressure side, monitors the fuel filter clogging.

Position measurements to determine the flows and variables of geometry are very important. These measurements are used either for control of the engine or for determining the bleed flows. Linear variable differential transformer displacement transducers can be suitably packaged for position monitoring. Encapsulation and correct material ensure reliability of use.

Sensor Characteristics For the GPA

Effectiveness of the GPA depends on the reliability and the accuracy of the measuring equipment. Unreliable engine sensors can cause long out-of-service time of an engine, in that not only have the sensors to be repaired, but undetected failures of the sensors can lead to stripping down and rebuilding an engine. The sensors must have long term stability of measurement thus providing accurate measurements not only when new but over whole of the engine's life. For this, the sensors should use as few moving parts as possible, magnetic materials should not lose their strength, the coil winding insulation should not degrade. The probes that are mounted right inside the engine, such as speed and torque probes, it is especially important that they do not fail in service. Interchangeability of the sensors with identical signal output and design with zero maintenance requirements is preferred.

It is a fact that an engine is more reliable than any single instrument; this means that a trend can only be taken seriously if it is supported by a special pattern of deviations of a number of different instruments, for example relative to a base line.

In choosing a measurement system for gas turbine performance analysis, the reliability of the system is as important as the accuracy itself. It is no good having an accurate measurement system which is constantly failing, thus rendering the diagnostic system ineffective and requiring repairs.

Reliability of a measurement element or the system can be defined as "the probability that the element or system will operate at an agreed level of performance, for a specified period, under given environmental conditions." Thus the agreed level of performance could be the specified accuracy. In case the accuracy deteriorates beyond the specific value then the element/system is considered to have failed. Reliability of the system is the product of reliabilities of its components. **Unreliability** is the probability that the element or the system will fail to meet conditions specified above.

The simplest and most obvious method of improving the reliability of a measurement system is to choose material of the components that will not fail the hostile environments. For the system this would mean to use components with higher reliability.

Normally use of hardware **redundancy** is made to increase reliability. This would mean providing more than one system or more than two elements of a type in a system. This ensures that failure of a single element does not result in the loss of the measurement. Here the reliability has been improved at a higher cost, weight and complexity. Modern processors can make use of real time analytical redundancy to detect, isolate and accommodate a sensor failure.

The Total Lifetime Operating Costing of a measurement system is defined as the total cost penalty, incurred by the user, during the lifetime of the system. This includes cost of installing the system, cost of repair and maintenance and cost of measurement error over lifetime of the system. This cost must be minimised. This also helps the user in deciding whether to install the measurement system at all or not. The cost of not installing the system means no measurements and hence a large measurement error.

Instrument Failure Detection and Calibration

Inspite of all the design care, the environments in which the sensors have to operate (viz. high temperatures, large variations of temperature and pressure, hot corrosive gases, an oil spray or even drenched in oil, shock or vibration etc.) do degrade sensor performance. Sensors with magnetic materials generate different output voltages for a given input while the coil winding insulation degradation also cause different output. Maintenance and calibration of some of the sophisticated instrumentation system required for health monitoring, much of which these days is electronic, can be both a nuisance [VESSER,1977], and an expense to the gas turbine users. Yet the cost of neglecting maintenance can be excessive if breakdowns under peak demand results. Certain sensors can be calibrated during use. A good variety of the calibration problem stems from the wide variety and sheer number of transducer signals and their individual specialised test sets. Calibration eliminates bias error and thus is recommended to be undertaken frequently for an effective Gas Path Analysis programme.

Since the modern gas turbine control systems are FADC (Full Authority Digital Control) the reliability of sensors has to be very high. However their failure during operation can never be ruled out. Increase in reliability can be achieved through hardware redundancy or by an algorithm that could detect sensor failure in real time. A lot work has been carried out for sensor failure detection, isolation and accommodation. This has been through analytical redundancy

[MERRILL,1985] technique as well as hardware.

What to Measure for Gas Path Analysis

For gas turbine diagnosis the requirement of instrumentation has to be carefully chosen between too many and too few. On one side is a "measure-a-mania", who thinks of measuring everything that can change, believes that he can find a microminiature transducer that can measure anything accurately, reliably, in any environment and also that he can take any output no matter how imperfect, no matter what the temperature coefficient and obtain perfect data for use in the diagnostic system. On the other hand, too few instruments can render a good performance diagnosis technique, ineffective. Modern engines have so much of instrumentation for control and integration with other systems that often all the measurements performance analyst requires are readily available, for example, to utilise COMPASS system on V2500 engine, Rolls Royce have obtained all the required data from AIRINC 429, except 3 parameters. Judicious utilisation of available data could be paying.

The level of instrumentation required is dependent on the type of performance analysis to be carried out. The primary purpose of monitoring the engines is to maintain its safety, availability and performance at low cost of operation. EHM hence can be regarded as a tool to improve the operator's ability to interpret the information obtained from the instruments. Escalations in fuel prices make performance monitoring more important than in the past, hence the need for better and accurate instrumentation.

Future of Gas Turbine Instrumentation

Most of the gas turbine components are open looped eg compressor, turbine, combustor etc. The limitations of on-board computation, relatively poor sensor technology, overriding concern for reliability favouring mechanical sensors have inhibited complications of closed control looped components. But the microelectronic revolution has made it possible to have high capacity onboard computations which should be used to move gas turbine components and sub-sytems from open- to closed-loop operation, making them self adaptive to local conditions i.e. subordinate to a master engine control. These engines will be optimised for each off-design operation, will be less expensive to develop, will have increased damage tolerance and reliability through dynamic reconfiguration of the engine subsystem and will be able to fulfil efficient multi-functional propulsion requirements of the advanced high speed aircraft with variable- or mixed-cycles.

This "smart" engine technology applies feedback control to adapt to the local conditions using sensors, processors and actuators. Active control of turbine-blade tip clearance based on the real time measurements rather than open-loop scheduling, active exhaust nozzle position, active inlet distortion control etc are near term applications of this category. Reaching this goal will demand development of highly reliable sensors completely revolutionalizing the present sensor technology. The increase in onboard processing power should reduce number of sensors used in the engine, not increase it. Both the reliability and the operability may be eased by incorporating sophisticated signal processing within the measurement system, with transducer, signal conditioning, control and data reduction elements all on the same chip. Fibre optics and opto-electronics also hold promise.

Review

It is evident that for Gas Path Analysis to be effective, the measurements must be accurate and precise. From the GPA point of view, there is a need to measure as many parameters as possible. Restriction of high temperatures, low weight and minimum disturbance to the engine or its systems requires a judicious selection of the parameters to be measured. New technology sensors can revolutionise the measurements but have to prove their reliability.

CHAPTER 6

FILTERING THE NOISE OF MEASUREMENT AND THE STATISTICAL APPROACH TO THE GAS PATH ANALYSIS

Introduction

The uncertainty of measurements, limitation on the number of measurements and the endeavour to obtain maximum information about the degradation of the engine modules justify the use of the best estimate techniques. The level of degradations in a gas turbine does not change too abruptly, but follows a typical pattern, which can be defined as the probability density function of the failure. Use of stastical techniques can then be mde to estimate the faults witin the restrictions described above. Elimination of the noise of measure and of the engine performance is described in this chapter. application of stastical methods for Gas Path Analysis of gas turbines for diagnostics is also discussed. Only the theory and approach is described here. The development of the matrices invoved is described in chapter 9.

General

The signal whose value at any time can be predicted from previous observations, is called a **deterministic** signal. Real processes such as the gas path in a gas turbine, will depend on many factors including the atmospheric conditions, the engine internal flow state, the component characteristics at the time, vibration, external disturbances etc. The magnitude of these influencing factors cannot be predicted exactly. Hence their effects can neither be known in advance nor can be precisely predicted. These input signals (that cannot be predicted) are random (or **stochastic**) in nature. Their behaviour can be estimated, based only on the statistical characteristics of mean, standard deviation, probability density function, power spectral density and autocorrelation function.

The random inputs factors produce corresponding random variations in the engine output and the measured signals. Thus we can have random fluctuations in the current output of a differential pressure transmitter or random fluctuations in the amplitude and frequency of the a.c. voltage output of a variable reluctance tachogenerator, which are caused entirely by the random variations of the engine input parameters. These fluctuations are as a result of changes in the input eg. pressure fluctuation or changes in the rotational speed and would exist even if the measurement system was an ideal.

In addition to these, the real systems (the gas turbine) will have a real measurement system that has its own input (the engine parameter measured) and the noise of the measurement, as discussed in the previous chapter.

The problem is further complicated by the possibility of a failure or the degradation of the main system (engine) with an error probability distribution function, and, may be some additional unwanted signals caused by the coupling to the sources outside the measurement system. The magnitude of the unwanted signals may be comparable or even larger than that of the measurement signal itself. This results in a measurement error of the overall system. These unwanted signals are referred to as noise and are random in nature. The two noises describe above are jointly present in the final output of the measurement system and must be eliminated to obtain the true value.

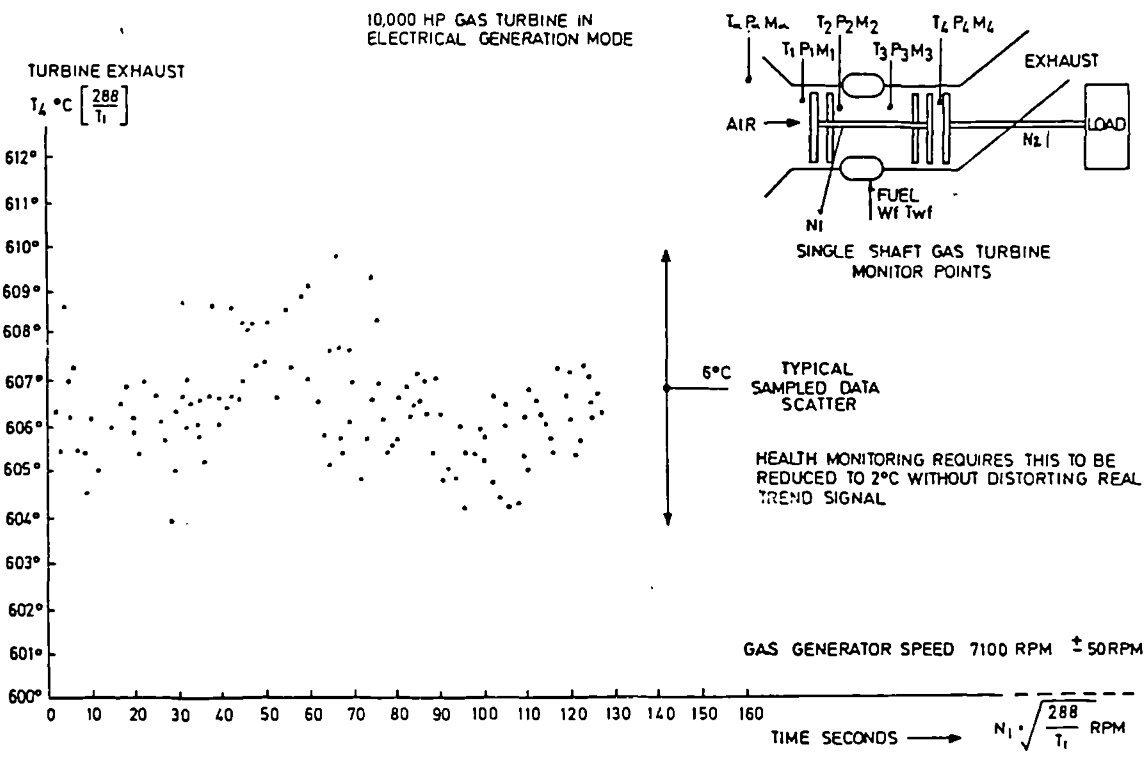


Fig 6.1 Measurement of temerature in a turbo-shaft engine

Uncertainty, as discussed the previous chapter, is a function of the measurement process and provides an estimate of the largest error that may reasonably be expected from the measurement process. For a multi-engine set-up the uncertainty of performance parameters, for similar engines, is a function of bias limits and the precision indices of the individual engines for these performance parameters. Errors larger than the uncertainty rarely occur. On repeated runs within a given measurement process, the parameter values should be within the uncertainty interval. These differences might look like Fig 6.1 [HILL,1986]. Run to run differences between the corresponding values of A should be less than the uncertainty for A.

If the differences to be detected by gas path analysis are of the same magnitude or smaller than the projected uncertainty, the corrective action should be taken to reduce the uncertainty. This could be achieved through (1) An improvement in the instrumentation, (2) Selection of a different function to obtain the parameter of interest and (3) Filtration of the data to retrieve the true value.

Filtering of Measured Data

The measured data is subject to a scatter even during the steady state of the engine. Consider for example the data of variations in EGT with time at a given gas generator rpm. Fig 6.1 One or two of the points of these could be rejected for exceeding a reasonable maximum rate of change credibility check (400°C/sec) whereas majority of the points are normally valid.

Data from other sources on widely differing engine types display a similar pattern and even in "good" condition. Therefore the scatter (which is random) is insignificant as far as condition, type of engine and power setting is concerned.

If the scatter had a meaning in the dynamic sense, then the plant would be running erratically. But the practical observations of prime parameters exhibit a steady and not an erratic state. Further since the scatter is indicated even on a "good" engine, a rapid deterioration of the engine is ruled out, so is the correlation of the scatter to the engine condition.

The scatter is about 6°C in 600°C which from point of performance diagnostics may be considered as too high (a change of 5°C is considered to have condition monitoring importance). It therefore, has to be accepted that the scatter of raw sampled data is in general too high, is meaningless at this level and the scatter must be eliminated or reduced enabling effective performance diagnostics.

The current experience on data scatter (data other than vibration) gives following characteristics :-

1. Forward predictions can be performed only on the data gathered under steady state conditions.

2. Signal scatter is always severe for parameters after

the combustion stage.

3. Smaller engines (in size and power) generate more severe data scatter in gas stream parameter signals as compared to big ones.

4. The signal scatter under steady conditions has a normal distribution as developed in the previous chapter.

5. Prime movers subjected to power changes produce reversible hysteresis effects of gas stream parameter measures.

6. Pressures and temperatures measurement is location sensitive in absolute value terms and speed dependent. Thus a direct comparison between the engines is difficult.

This scatter reduces the immediate usefulness of the signals required for monitoring the engine. The noise in certain parameters measured in the gas turbine engines can exceed the sought for change. To extract vital information this data must be processed eliminating noise. This judgement of the approximate value is the estimation process which can be of three types :

1. **Filtration** When the time at which the estimate is required coincides with the last measurement point.

2. **Smoothing** When the time of interest falls within the span of available measurement data.

3. **Prediction** When the time of interest occurs after the last available measurement.

Our interest of input data scatter reduction is at the present instant (coinciding with last measurement) this allows us to follow either of the first two choices. For smoothing, the instrumentation has to have absolute level of accuracy. Thus the estimation of true value is through through filtration only. The filtration could be in the hardware or the software. In either technique the frequencies of the signal and that of the scatter play an important part in design of the filter.

The **High Frequency** component of the signal are not, in general, of interest except for vibration measurements and can be suppressed. The **medium frequency** component usually include the maximum credible rate of change for that part of the gas turbine which has to be established either, by the previous experience, by design calculations, or through additional data gathering. The capability of measuring such rate of change must be retained for alarm and safety monitoring. When this is done some form of data averaging is usually incorporated to prevent spurious noise triggering off the safety and alarm systems.

The **Low Frequency** signal components are required for performance monitoring. These are however mixed with the engine generated noise, the noise in engine operation explained earlier. The hardware low pass filter is used in most conventional filtering systems for condition monitoring. This filter must suppress high frequency noise but permit the maximum credible rate of change of transducer signal parameter to pass through.

Software averaging is aimed at reducing the data scatter on input data, collected during steady state running of the gas turbine, to an acceptable level. The optimal estimator for this part is a computational algorithm that processes measured data so as to produce a minimum error estimate of the parameter. The **Software Filters** are of two types, recursive or non recursive. In general these have the same effects as the hardware low pass filters, but being from a sampled data source have a recursive frequency attenuation response. The maximum attenuation achievable is determined by the number of samples in the moving average over which the input sampled data is taken. The frequency point of maximum attenuation is determined by the sampling rate set for this input parameter. The sampling rate and the number of samples must, hence, be high enough so that reasonable averaging can be performed, but not too high to impose a penalty in terms of high speed sampling or hardware utilisation. Normal sampling rate of individual parameters is between 0.1 sec and 2.0 sec.

MEAN VALUE

Given a sample parameter time history record x(t) from a stationary random signal i.e. the mean noise about the true parameter value, the mean value U_x of that signal may be estimated by averaging the instantaneous value of the signal over sampling time T as

$$ux = \frac{1}{T} \int_0^T x(t)dt \qquad \ldots \quad \ldots\ldots \quad (6.1)$$

For random variations the short term average value will be the true value of the signal, i.e. the noise is cancelled.

The occasional extreme values however introduces new scatter in data which was not present earlier.This new scatter does not effect the trend and the long term condition monitoring but does affect the alarms, limit exceedance and post failure diagnostics. Two parallel lines of data entry to the computation processor may hence be necessary if the requirement of the engine signal scatter attenuation and the maximum rate of change are incompatible. This gives the required flexibility to the system.

The advantages of software filtering are:-

1. Flexibility, the number of samples in the moving average can be readily adjusted as on the plant experience is gained without hardware changes. The number of samples in the moving average fixes the maximum attenuation.

2. The sampling rate which is also controlled by the software can be adjusted to vary the break point of the software filter.

The disadvantage is that the filter section is recursive at the sampling rate and higher multiple frequencies. To prevent this being a problem, with noise etc, it may be necessary to incorporate a hard ware low pass filter beyond the point of maximum parameter rate of change expected.

Before applying the maximum rate of change credibility check, the sudden rates of change should be allowed to become established. In this manner the averaging technique can be used on all incoming data and spurious noises will not trigger off the credibility check. The maximum rate of change check will need to be rescaled to take into account the effects of sampling rate and the number of samples in the moving average. If an averaging technique is not used on the incoming data, the maximum rate of change checks need to be applied across several individual data samples.

Unless the engine is running under likely conditions of limit exceedance, the data beyond the maximum credible rate of change, will need to be rejected. Separate processing may be necessary in situations where steady state collection of data requires heavy filtering which is not compatible with engine maximum rate of change in signals.

Valid Window of The Data

Defining a valid window for the incoming data, monitored under normal conditions of operation, has two advantages. Firstly, it enables gross plant transducer failure to be detected discarding the information from such a source. Secondly, it prevents large spurious data changes, due to temporary interference, from entering the system. The transducer failure detection may require a decision table formed with other transducer outputs especially when the failure is in the normal working range of the engine and the transducer. The valid window concept however should not interfere with the limit exceedance detection.

Filtering The Measurement of noise

More complex filtering may be required for highly "noisy" data when the simple moving average filtering technique is not so effective in detecting the true signal. The technique of weighted moving averages and auto correlation is successful in dealing with high noise, but does introduce considerable delays and requires more computational power. The success of the filter is dependent on weighting one can give to deviations from the existing signals.

If this type of filter is not adequate then dynamic filters such as "kalman" filter may be employed. The **KALMAN FILTER** is based on the concept of linear feedback of the estimate error and, hence, a recursive filter. Since it varies in time permitting to deal with non stationary error sources, it is an optimum recursive estimator. An important constraint on the estimation algorithm is the high [HILL, 1986], computational requirements especially for small fleet users and the users of remote controlled and off-shore engines. This means that in the context of engine condition monitoring its use is restricted to the manufacturers and the large fleet operators only.

Hence an elaborate dynamic noise filters cannot be used to eliminate noise of measurement without enormous computation facility. However the noise, as discussed in the previous chapter, is random and can be conveniently assumed to be Gaussian with zero mean. This assumption of zero mean implies that the bias error has been eliminated through calibration. One can then average the measured data by sampling at equal number of time intervals and determining the arithmetic mean.

If a single measurement is used in the linear performance analysis procedure, the estimates are determined from a **snaphot** calculation. A snap shot estimate gives an indication of the engine status at a particular instant of time. The number of accurately detectable parameters must be smaller than the number of measured variables.

The Noise of Engine Performance

Since all sensors have a drift in bias, they are likely to be out-of-calibration most of the time. Calibration involves taking the engine out-of-service and hence cannot be carried out frequently. Thus in practice all measurements have bias which have a cumulative effect as discussed in the previous chapter. The engine performance, when calculated from these measurements, will be different for different times even in an ideal state of operation and condition of the engine. This error of performance is random in nature and has a density distribution peculiar to each engine type. The deviation from the true performance can be defined as "noise" in performance determination. These errors and the measurement errors can cause significant inaccuracies in the snapshot estimates. The severe instrument accuracy requirements of the snapshot approach, can be alleviated by estimating the best possible combination of causes and effects. The best solution is to combine previous parameter estimates and new measurements to form both the optimal parameter estimates and estimates of error variance. Filtering the performance noise, is, hence, very important for the Gas Path Analysis to be meaningful.

For several reasons the problem of filtering nonlinear systems is considerably more difficult and admits a wider variety of solutions than does the linear estimation problem. The reasons for not pursuing filtering are the following :-

1. In linear Gaussian case the optimal estimate of the performance parameters can easily be established. But in the non-linear problems, the independent parameters vector is generally not Gaussian rendering the analysis more difficult.

2. For Gaussian random variables, identical results are obtained from estimation techniques of maximum likelihood, weighted least squares, Baysian method etc. For non Gaussian variables however they all yield different solution.

3. The structure of the system non-linearities causes further complications.

Thus representing the gas turbine by linear dynamics, rather than by non linear dynamics helps in reduction of the complexity of estimation algorithms. Hence only a linear model of the gas turbines will be considered. Further the noise density distribution itself is considered to be a Gaussian.

It is important to consider which parameters are to be estimated. The parameters should be physically meaningful [SKIRA,1981], and useful and it should be possible to estimate them accurately. These should not be instrument parameters, cycle parameters or disturbance inputs. As discussed in chapter 2 and 3, the parameters that define the module degradations such as efficiencies, mass flows pressure ratio, burner temperature etc are considered useful [URBAN, 1974], for the Gas Path Analysis.

An important consideration in processing the measurements is the detection and isolation of data scans that include failed or disconnected channels. Also if the uninstalled engine run data is the base line, then, a full data complement may not be available with the operator. In practical operation, sensor channel may remain failed for a long time before a maintenance action could be taken to put the instrument back in service. This requires programs that detect, isolate and accommodate such sensor failures [BEATTIE,1981]. Accommodating such a failure is however the task which gas path analysis can incorporate [SKIRA,1981]. One such method of accommodation could be a simulated valid window at operating point generated by onboard computer. Any reading out of this window range could be considered a failure of the measurement. Analytical methods have been developed [MERRILL,1986], for control systems and are available.

Estimation of The Best Value

Let the measuring devices provide corrupted data functionally related to some variables that are of interest to us, but whose values we do not know. A general **estimation problem** can be to use this data, together with whatever knowledge we have about its relationship to the variables of interest and about the noise of corruption. There are five fundamental components of an estimation problem :

1. The variables to be estimated
2. The measurements or the observations available.
3. The mathematical model or their relationship.
4. Mathematical model of the uncertainties present
5. The performance evaluation criteria to judge which estimation algorithms are the "best".

If we are considering only the static linear Gaussian noise models, then these components can be described as :

(1)The variables to be estimated will be put into the form of the component of the n-dimensional vector **x**. The true values of these quantities remaining constant, but unknown.

(2)There will be **m** measurements available to us and these will be made the m-dimensional vector, **z**.

(3)The set of measurement data **z** will be assumed to be linear combination of the variables of interest, corrupted by an uncertain measurement disturbance **v** of dimension m :

$$\mathbf{z} = \mathbf{H}\mathbf{x} + \mathbf{v} \quad \ldots\ldots\ldots\ldots \quad (6.2)$$

where **H** is a known (m x n) matrix. This equation for the gas turbines has been developed in chapter 3.

(4) Probabilistic models can be proposed in the form of random variables to describe the uncertainties. Thus, our **a-priori** knowledge of the variables of interest can be used in describing the values **x** assumed to be a Gaussian random variable with mean x^- and covariance P^- (**the superscript** $^-$ denotes a value at a time before incorporation of a measurement; and $^+$ will denote corresponding value after such in corporation).

Similarly, a random variable model is used to describe the noise corruption. We let **v** be a Gaussian random variable, characterised by mean zero and covariance **R**, and assume that **v** and **x** are independent. The equation can then be viewed as an equation relating the realisation of random variables: for a particular outcome ω, the realisation v of the random variable **v** is added to the linear combination **Hx** of the realisation **x** of **x** (the particular realisation being the "**true**" value of the variables of interest) to generate the measurement data **z**. This data **z** can itself then be interpreted as the realisation of a random variable, denoted as z. Consequently, a random variable model would be

$$\mathbf{z} = \mathbf{Hx} + \mathbf{v} \quad \ldots\ldots \quad \ldots\ldots \quad (6.3)$$

where **x** and **v** are as defined earlier.

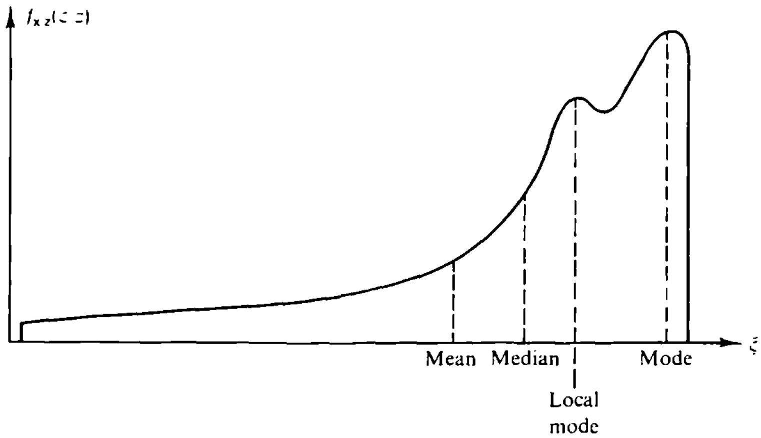


FIG 6.2 The Choice of The Estimator

(5) With respect to the performance criteria, we will adopt the Bayesian approach that the true objective of our

> efforts is to generate a complete description of the probability distribution for values of the variables of interest. Since we are interested in estimating the value assumed by a continuous random variable **x**, knowing the value of the measurement $z(\omega) = z$, we are thus really interested in explicitly generating the conditional density function $f x|z(\xi|z)$. Once such a density function were established, it would provide all the information necessary to define an "optimal" estimate [MAYBECK,1979], regardless of the optimality criterion. In the multipeaked density of Fig 6.2 [MAYBECK,1979], reasonable estimate of an optimal estimate might include the median (having equal probability weight on either side), the mode (maximum likelihood value) or the mean (centre of probability mass estimate)

This gives us the solution as

$$\mathbf{x}^{+} = [H^{T}R^{-1}H]^{-1}H^{T}R^{-1}z \qquad \ldots\ldots \ \ldots \ (6.4)$$

Various theories of estimation for Gaussian variable, Gaussian noise yield similar solution. These include **minimum variance, maximum likelihood, conditional expectation** and **maximum a-posteriori.** The Kalman filter discussed earlier also gives similar equation and hence is an optimal estimator.

Normally in gas turbine engine measurements there are some measurements that are more accurate than others. Hence a different weight is possible to be associated with each of the measurement. This means we want to match certain points more closely than others in the best curve fit. This is known as weighted least squares estimation.

In case the number of measurements equals the number of faults (unknowns), the technique of weighted least squares can, sometimes be used. Let **W** be a general (m x m) weighting matrix, then we have the best estimate x :

$$x_{WLS} = [H^{T}WH]^{-1}H^{T}Wz \qquad \ldots\ldots\ldots \qquad (6.5)$$

In the above solution, the matrix $(H_{T}WH)$ is a (n x n) non singular matrix, hence

rank (HTWH) = n

Since the rank of a product of matrices can never exceed the rank of its factors we have rank H < n. Since H is an (m x n) matrix therefore m > n and also rank H = n

Thus in order to obtain a unique estimate of the n unknowns, we must have at least n (= m) measurements and precisely all the n measurements must be linearly independent. if we have exactly n independent measurements, then H is a (n x n) non-singular matrix and we can carry the solution a step further with the knowledge that the inverse of a product of two or more non-singular matrices is equal to the product of their inverses in reverse order and obtain :

$$X = H^{-1}W^{-1}(H^T)^{-1}H^TWZ = H^{-1}Z \quad \ldots\ldots \quad \ldots(6.6)$$

for a system of measure the weighting matrix can be taken as the inverse of the covariance of the random errors $W = R^{-1}$ and this gives the solution as eqn. (6.4)

We have thus the solution

$$X = (H^TR^{-1}H)^{-1}H^TR^{-1}z = Dz \quad \ldots\ldots \quad \ldots (6.7)$$

where $D = (H^TR^{-1}H)^{-1}H^TR^{-1}$ is called the **Diagnostic Matrix.**

If x_o denotes the expected value (mean) of x

i.e. $x_o = E(x_o)$ .... (6.8)

then the estimation error e is defined as

$$e = x - x_o \quad \ldots\ldots\ldots \quad \ldots \quad (6.9)$$

and the symmetric positive semi-definite covariance matrix of the estimation error is given by

$$P_o = E([x-x_o][x-x_o]_T) \quad \ldots\ldots \quad \ldots \quad \ldots \quad (6.10)$$

An alternate expression for P_o is in terms of the diagnostic matrix as

$$P_o = DRD^T \quad \ldots\ldots \quad \ldots\ldots \quad (6.11)$$

The elements along the main diagonal of the matrix P_o are the variances of the estimation error.

We have assumed that the mean and covariance of v are known and given by

$$\text{mean} = E(v) = 0 \quad \ldots\ldots\ldots \quad \ldots (6.12)$$

$$\text{Covariance} = cov(v,v) = E(v,v_T) = R \quad .. \quad (6.13)$$

where R is a symmetric (m x m) positive definite matrix.

The value of x (denoted x) which maximises the conditional probability distribution function p(xz) (probability of x given that z has occurred, is given as

$$X = X_O + D\ (Z - HX_O) \quad \ldots\ldots \quad \ldots\ldots \quad (6.14)$$

Here
$$D = P_o\ H^T\ (\ H\ P_o\ H^T + R\ )^{-1} \quad \ldots\ \ldots\ (6.15)$$

This requires **a-priori** (known previous to analysis) some statistical information regarding **x** and **v** viz. their mean value and the level of scatter (i.e. P_o and **R** respectively). The matrix **D** relates the independent fault variables to the measurements and thus represents a pseudo inverted set of engine/sensor fault coefficients.

Two kinds of filtering techniques can now be considered. First type is called the "snapshot" technique, when only the measurements at the present are considered. Previous values of the measured data thus have no bearing on the analysis. The estimated values are based solely on the measured data at the instance and the knowledge of the system. Kalman Filter is a filter of this kind and is recursive. The Second type is the the types that depends on a large amount of data gathered from the same system, and the analysis is based not only on the present readings but also on previous. ARIMA (Auto Regression Integrating Moving Average) time series type of filters are of this category and so is the trending technique.

We have seen that for gas turbine diagnostics we have the engine module deviations and sensor deltas as variables and of course a set of measurements. The matrix D relates the independent fault variables to the measurements and thus represents a pseudo inverted set of engine/sensor fault coefficients. The main task of the diagnostic program is to estimate changes in the module performance from some reference point, called the "**base line**", that represents the expected performance of a nominal engine operating in a noise free environment with nominal exhaust nozzles and some assumed level of engine air bleed and power off take. These conditions of operation are unlikely to be maintained in real life when in addition to module deterioration, non-nominal fan and/or core nozzle areas, overboard and cooling bleeds, Reynold's number, engine intake and bed configuration, the instrument non repeatability etc. contribute to the magnitude of the observed gas path parameter. The measured parameters require to be corrected for these effects before they can be used for estimating the module deviations.

The engine deviations have been modelled in vector notation, avoiding the use of [] notations that is implied, and can be represented as :

$$z = H_e X_e \quad \text{and} \quad \ldots\ldots \quad (6.17)$$

$$y = G_e X_e \quad \ldots\ \ldots\ldots \quad \ldots\ldots \quad (6.18)$$

As described earlier, even with highly accurate sensors some kind of errors or "noise" can be expected. The effect of the error of measurement of the independent parameters on uncertainty of deduced parameters has been explained.

Typical non repeatabilities of the measure and their effect on the aero-corrected parameters is worked out in Table I. The gas turbine performance parameters depend on the ambient conditions and are standardised to ICAO conditions of temperature and pressure. The effect of engine inlet temperature and pressure errors on the measured parameters is evident from the relationships of the aero-corrected parameters. In addition to these, the gas turbine output is also dependent on the value of the control parameter (N_1 or EPR). Error of measure of this control parameter called the abscissa also influences the engine performance. This introduces a vector of "apparent" sensor errors X_s which accounts for the main gas path parameters, inlet parameters (used for reducing data to standard conditions) and the base parameters. Thus our basic model (eqn 6.17) then becomes :

$$Z = H_e X_e + H_s X_s + v \quad \ldots \quad \ldots \quad (6.19)$$

$$Y = G_e X_e \quad \ldots \quad \ldots \quad (6.20)$$

The matrix Hs is a (m x (m+n+3)) matrix of "sensor fault" coefficients and other symbols have been defined. This can be simplified to give a simultaneous solution for X_e and X_s by concatenation as :

$$z = H X + v \quad \ldots\ldots \quad (6.21)$$

$$y = G_e X_e \quad \ldots\ \ldots\ldots \quad (6.22)$$

where

$$x = \begin{bmatrix} x_e \\ \hline x_s \end{bmatrix} , \qquad H = [\ H_e \mid H_s\ ]$$

these are composed as shown below. The abscissa parameter Π has an influence on all the parameters as also the basic sensors of non-dimensonalising values.

$$[Xs] = \begin{bmatrix} N1sens \\ N2sens \\ P3sens \\ .. \\ .. \\ Tnsens \\ T2sens \\ P2sens \\ \Pi sens \end{bmatrix} \qquad [Xe] = \begin{bmatrix} \Gamma\ LPC \\ \eta\ LPC \\ \Gamma\ HPC \\ \eta\ LPC \\ ... \\ ALPT \\ \eta\ HPT \\ ALPT \\ \eta\ LPT \end{bmatrix}$$

The column headings of H_s refer to the deviation of the individual "raw" measurements while the row values refer to the aero-corrected component of **z**. The sub-matrix **(m X m)** starting with (n+1)th column is an identity matrix. The identity submatrix indicate that a deviation in main gas path parameter produces a deviation only in the corresponding 'corrected' parameter, whereas a change in the inlet or the abscissa parameter affects all components of z according to the aero-correction relation or the base line generation relation.

The number of problems is now more than the number of equations, we have m measurements and (n+m+3) unknowns. The solution is however possible by best estimate technique explained earlier. In order to use equation 6.14, X_o, R and P_o must be known. The vector X_o is an a-priori estimate of the percent deviations in the engine/sensor independent faults for a particular engine in question. This matrix is developed with the help of the knowledge of the deterioration in service as a function of time or number of cycles etc. In the absence of any information nominal values can be assumed, when X_o can be taken as zero matrix. In that case the system will isolate the deviant modules and measurement errors but will tend to either under-assess or over-assess the actual magnitudes. The matrix R is obtained from instrumentation repeatability statistics and the relations contained in Hs.

Determination of the state vector covariance matrix P_o, is not easy [VOLPONY,1983]. Either a lot of data on engines is gathered and analysed statistically for the most probabilistic occurrence of a fault. The second approach allows equal detectability of each of the engine/sensor faults. This is an ideal, fictituous statistics approach which assumes that all the faults can occur with equal probability. The concept of filtering the noise and its applications in the GPA is further developed in chapter 9, when all the matrices have been derived for a representative two spool turbo-fan engine with hypothetical probability density function distribution of the failures.

CHAPTER 7

APPLICATION OF ARTIFICIAL INTELLIGENCE IN GAS TURBINE DIAGNOSTICS AND PROGNOSTICS

INTRODUCTION

The modern concept of artificial intelligence, the fifth generation computer language, has been successfully applied in the field of diagnostics in medicine and electronics. The rules in these fields are simple and direct. The gas turbines are complex machines with wide range of users and wide range of operation in each application. There are no set laws of deterioration which make application of the artificial intelligence in gas turbine diagnostics quite challenging.

Knowledge based expert systems have already made their debut in ground based diagnostic system of aero-engines. In this chapter the principles of artificial intelligence (AI) are explained, methodology and applications of AI to gas turbine field are reviewed. Languages for the development of a Knowledge Base program for gas turbine diagnostics at CIT are reviewed.

Why AI In Gas Turbine Diagnostics

When the monitored data from a gas turbine is not the same as expected, the operator (the field engineer or the pilot), will try to determine the cause, working through his/her knowledge of the engine and of the likely faults. There can be an occasion when an unusually difficult problem in a specific area involving diagnostics is confronted that cannot be solved, they will then turn to a specialist who has more knowledge about the state of the engine and of the faults that caused the symptoms. This knowledge of the specialist, who with analytical skills and a wealth of experience that he/she has, can draw and integrate the complex data available, form preliminary hypothesis, suggest tests and ultimately diagnose the operating problem. Having experienced the problem once the operator will be able to diagnose the fault next time. Thus diagnosis is a learning process based on past experience and logical deduction of faults from symptoms. **Collection, collation and interpretation** of data (symptoms) are the three levels of diagnosis (condition monitoring) in gas turbines. Manpower expenses at all these three levels have, in recent times, increased because of sophistication and complexity of modern gas turbine engines.

The present day computer technology has enabled a large amount of automated data collection through off-line/on-line monitoring. The operators together with their training and experience use this data to determine the exact fault. These characteristics (viz. the training, experience and intelligent guess work) make the operator an expert. Absence of an expert because of leave, day off, reassignment or change of job causes a **'knowledge vacuum'**. The new engineer can learn from maintenance manuals. This takes time and even if the maintenance manuals contain all the information these may be difficult to consult.

Computer Program vs AI

A computer could be used to store information gathered and programs run conventionally to diagnose the data. Conventional programs are specific and require to be changed (re-programmed) every time a gas turbine or its system is modified. This led to the development of so called Intelligent Programs that are structured around established knowledge problem solving patterns or some logical inferences and man-machine interface. These programs use **Artificial Intelligence** (AI) and learn as they operate and incorporate expert knowledge. They employ human knowledge to solve problems that ordinarily require human intelligence and are hence known as Expert Systems.

The main characteristics of an expert system are :-

(a) Programmed to a significant extent, from an explicit representation of empirical human knowledge.

(b) Readable by those who provided the knowledge and, potentially, by similarly knowledgeable users and managers.

(c) Able to provide explanations of their reasoning on demand.

(d) Quickly alterable with (comparatively) low risk of unwanted side-effects.

The differences between a conventional computer program and an expert system are shown in Fig 7.1. In conventional programs instructions are arranged so that the program follows one path, determined by the programmer, towards the solution. These programs are numeric process oriented and difficult to change because of integration of knowledge base and the control program. AI programs are symbolic with the symbols defining real world objects or concepts. Instead of performing calculations these manipulate the symbols. Using rule of the thumb or heuristics, rather than step by step algorithm, the programs look for new relations among symbols. Inference is logical and programs are easy to read and modify. The knowledge base and the control program are independent and hence the program run could be stopped in mid-execution to see what rules are being used and trace the reasoning process.

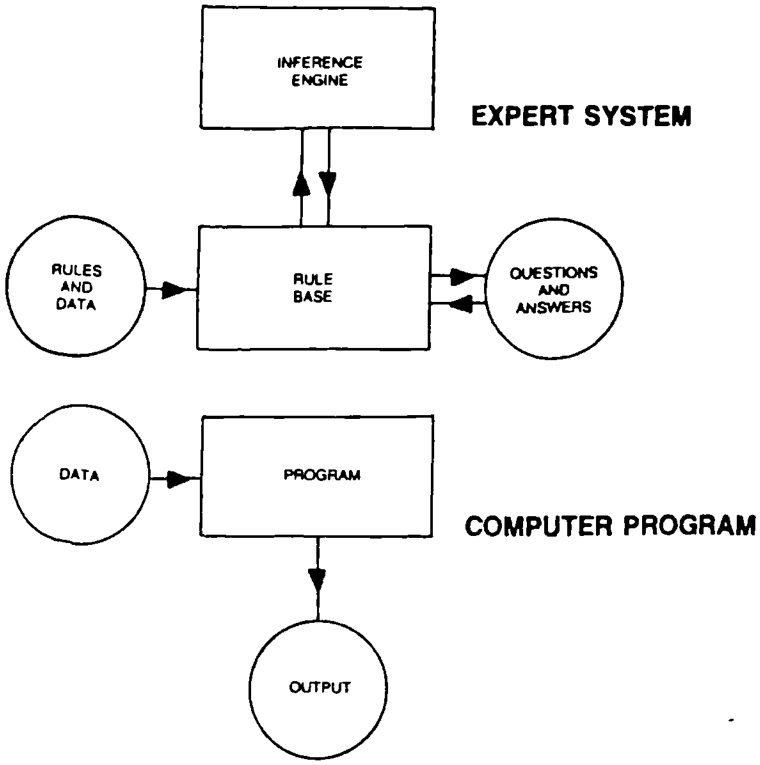


Fig 7.1 Expert System vs Conventional Computer Program

<u>What is AI</u>

Expert systems can be classified by function.

Interpretive programs infer situations based on descriptions from data.
Predictive programs infer the likely consequences of given situations.
Diagnostic programs infer system malfunction from observables entered into it.
Design programs configure objects under restraints.
Planning programs recommend actions.
Monitoring programs compare observations to the vulnerabilities.
Debugging programs recommend remedies for malfunctions.
Repair programs execute a plan to administer a prescribed remedy.
Instructive programs diagnose and recommend methods to get trainees/students to learn.
Control programs interpret, predict, monitor, and repair system behaviour.

Typical architecture of an expert system is shown in Fig

7.2 [FORSYTH,1984], comprising of :-

1. **Inference engine** The frame based problem solving system which considers the hierarchies of objects. Each of these objects has attributes which are assigned to it, inherited or computed for it and there is an inference which gives an automatic inheritance. These are logical processes of various types which are followed by the system. To work through the available information forward tracking and backward tracking are the most common.

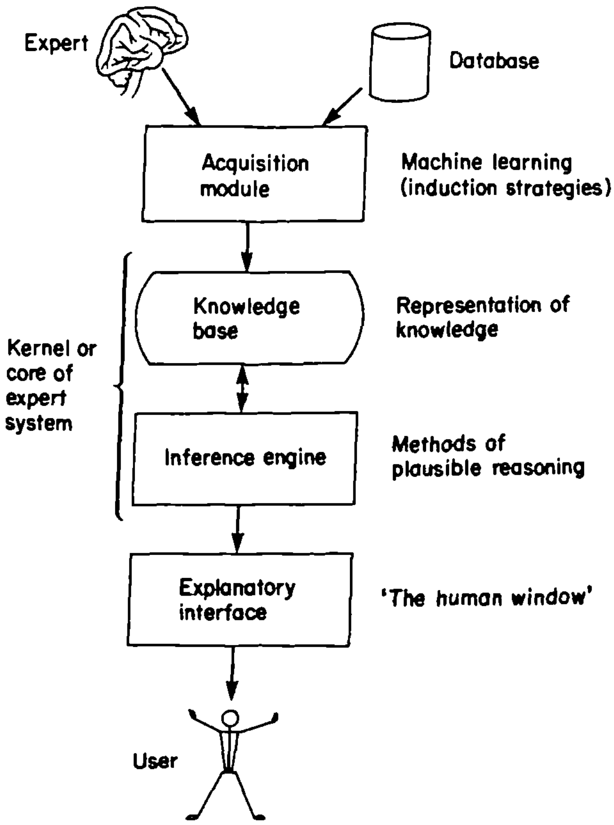


Fig 7.2 An Expert System Frame Work

2. **Knowledge Base** The rule based system where every feature of the system is expressed as a rule. The rule takes the form that if certain condition(s) is(are) true then a fact is established. Satisfaction of this rule means that the conclusion is added to the data base.

3. **Data Base** This describes the world to which this program is applied in a form which can be understood by both the operator and by the computer. Thus for the condition of the engine, certain parameters will have to be supplied which describe that condition.

These parameters need not necessarily be numeric. They could be based on observations eg. nick marks on the fan blade (FOD) or feathers stuck to blade (BIRD STRIKE).

AI and The Diagnostics

An expert system in condition monitoring could incorporate maintenance records, design data, new technical knowledge whilst learning from monitored information. The expert system is a branch of artificial intelligence that aims at emulating human reasoning in computing. The objective of these systems is to capture the knowledge of an expert in a specified domain, represent it in a modular expandable structure and transfer it to other users in a similar domain.

The expert system thus has a **knowledge base** (also called a rule base) which is separate from the system logic program (inference engine). Rules are descriptions that are matched to actions. They generally take the form of "If...then.." If a condition is met then take some action. The knowledge base is a series of such rules eg. IF the HP spool rpm goes down and ECT goes up THEN LP compressor is fouled. The rules can be variable and more rules can be added with experience. Rules can also have a certainty value associated with them.

The Knowledge base holds information (set of rules) that can be used by the inference engine to interpret the current contexual data in the data base. The **inference engine** is independent of specific subject and hence can be used as a multi-application tool. The knowledge base carries specialist knowledge and hence is devoted to the application. The more comprehensive a knowledge base is, the less is the inferential logic, and hence quicker is the diagnosis. For a real time diagnosis the modern concept of parallel processing is very essential and effective.

For the purpose of diagnostics the first step is to provide measured data to the inference engine. This is done by the **data base.** The inference engine then decides if anything is wrong with the engine. Thus comparing with a base line and with-in certain tolerances, the inference engine would decide whether or not to call elaborate diagnostics.

Logical Goal Search Techniques of AI

There are two main search techniques that are used called forward and backward chaining. **Forward chaining** also known as bottom-up processing begins with the condition clauses of a rule and works through the chain (of rules) attempting to prove the correctness of the implied action clause. Starting from fault signals (facts) it will search all the rules that say something about what each fault signal might mean and will give the faults that may have occurred.

Thus starting with the data measured on the engine the fault is diagnosed according to the list of rules. This processing works from known "ifs" to new "thens". It is particularly useful in "what-if" questions. Fig 7.3 [FORSYTH,1984], shows an example of forward tracking procedure logic.

FORWARD TRACKING

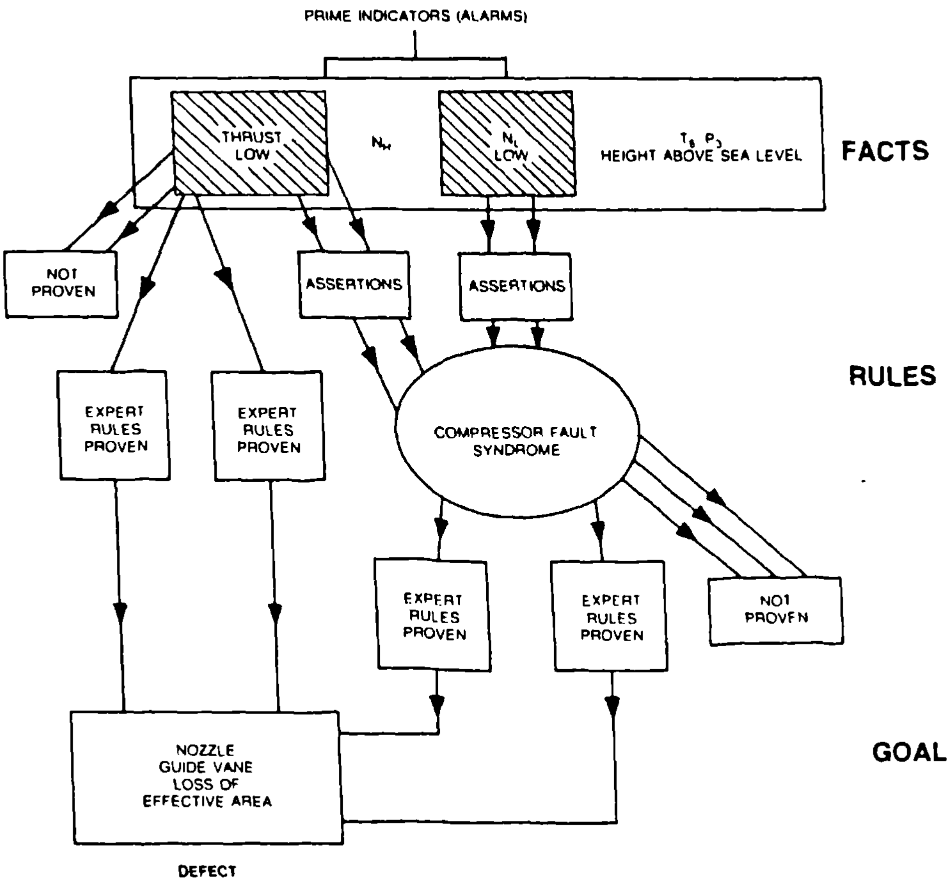


Fig 7.3 Forward Tracking Logic

Backward chaining or top-down processing begins by asserting the implied action clause and then implying from the conditional clauses what would have had to be true for that clause to have been initiated. It then works progressively backward through the rules until a point is reached when the implied conditions correspond to the information in database. Satisfaction of all the comparisons proves the implied clause asserted initially. It takes the "thens" and works backwards to find the "ifs" that would support the "thens". Thus an hypothesis such as LP compressor fouled can be proved to be true only if the measured data shows that HP spool rpm has decreased with increase in ECT at given LP spool rpm.

Searching methods consist of depth-first, breadth-first, best-first and others. Knowledge and connections to other bits of knowledge can be thought of as a tree, the paths of knowledge supplying the solution being branches of such a tree. A **"depth-first"** search plunges deep into the tree from a given state, a sequence of successes to a state being considered until the path is exhausted, after which the next alternative path down the tree is explored in depth. In **breadth-first**, all the initial points of the branch are searched before moving down a branch thus first generating all possible alternatives at a given level and then all alternatives at the next level. The search is thus conducted in breadth across the tree. This is illustrated in Fig 7.4 [FORSYTH,1984]. In **best-first** search heuristics are used to find the one most likely branch that will lead to a solution.

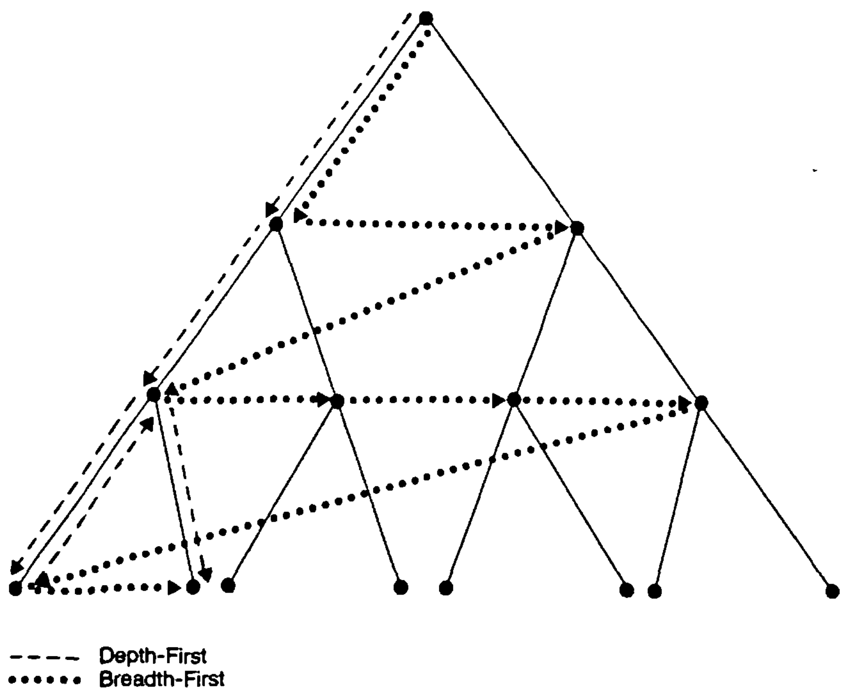


Fig 7.4 Depth- and Breadth-First Search

Once the measured data causes the inference engine to infer that the gas turbine has deteriorated beyond a certain limit then using the knowledge base "what is wrong" is determined. If deterioration is with in statistically significant limits then inference engine may not call an alerting system or preventive action.

For diagnostics and maintenance two types of expert systems are in use to-day. In the first the user reads values off various test instruments and manually keys them in to the knowledge base (program). When the system needs more information, it requests the user to measure the required parameter and enter its value. The other system uses advanced technology (and at a higher cost) thus the necessity of reading the data and entering it into the computer is eliminated by automated data collection. In either system the foundation is a knowledge based system properly interfaced with a test and measurement instrument allowing users to write their own rule bases.

Application Of AI to Gas Turbine Diagnostics

Consider the system in which the pilot reports a snag of fluctuating EGT to the maintenance crew. When asked by the ground crew if fuel flow was also fluctuating or what was N1, the pilot may not have noted these. So in next flight the pilot is asked to keep a check on EGT and if fluctuating note fuel flow and RPM. Here the pilot is the user and inputs the data manually into the expert system viz the maintenance staff. In system 2 it could have been an experienced pilot who detecting fluctuating EGT would have noted if fuel flow was also fluctuating and at what RPM. In some cases the pilot through his/her earlier experience and/or inference could have diagnosed the engine fault.

The data measured on the engine forms part of the data base. These measurements are noisy, susceptible to sensor failure or malfunction and possibly misread. Various techniques to minimise these errors have been discussed else where in the thesis. These techniques allow different "weights" to be allocated to the certainty of the measured data. There is also the qualitative data keyed in from observations eg. FOD to the blades. This qualitative data may not be precise in time and in assessment thus making correlation a difficult task.

For example, an expert system based on rules, can be conceived as a list. Each rule could be self-contained and tested against the knowledge existing at the time of implementation of the rule. The rule may not be absolutely conclusive. The conclusion may be that something is 60% true, or some other conditional type of result. The interpretation of these conditional results is included in the knowledge base. The rules are accessed one by one and assessed independent of the order of listing. This allows additional rules to be added even if they are contradictory to the existing ones. Apparently contradictory conclusions are used by the expert program in the same way that inconsistencies in data are treated by the humans provided of course the inference engine has been taught this by the humans.

Building Knowledge Bases

Methods to construct knowledge bases for diagnostic expert systems which can be applied by engineers/scientists who are experts on the system (and not necessarily experts on AI) have been developed. These are based on Fault Tree Analysis (FTA) and/or flow charts [APOSTOLAKIS,1978]. One such fault tree for a 2 spool engine [ROLLSROYCE,1983] is shown in fig 7.5.

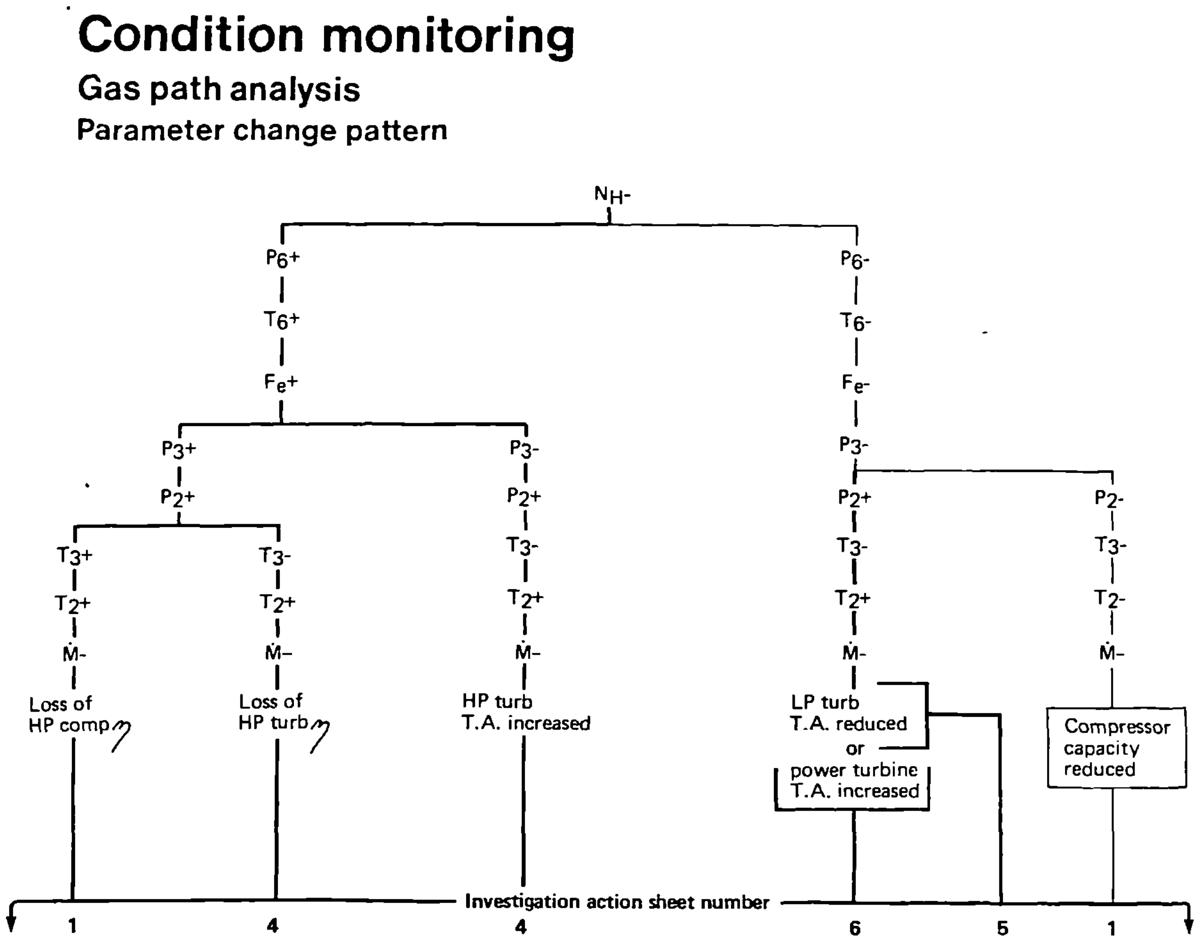


Fig 7.5 Fault Tree of a Two-Spool Gas Turbine Engine

The main concept of FTA is the transformation of knowledge about a particular system into a logic diagram or fault tree in which a number of basic causes are combined to lead to a certain unwanted or critical state of the system or both.

Various vibration faults for gas turbine engine are given in table II [AGGARWAL,1986]. These can be translated to a flow chart as shown in Fig 7.6 [AGGARWAL,1986]. This is quite akin to a way an expert would proceed to evaluate data to diagnose a fault. Multiplexity and parallel presence of faults however do complicate the problem.

FAULTS	SYMPTOMS	INFORMATION	ACTION
Unbalance	Large synchronous amplitude. Low 2, 3/rev. Balance correction within weight capacity	One/rev amplitude per peak	Identify condition Determine if balanci ng feasible. if yes balance rotor, if no reject rotor.
Misalignment	Large 2/rev amplit. Low 3/rev amplitude Large 1/rev amplit.	2/rev ampli. at Crit speed. 3/rev at crit speed. 1/rev at crit	Identify. Reject the rotor for reassembly
Incr/Decreased	Large 1/rev amplit. at crit speed. Out-of tol. location.	1/rev amplitude at critical speed.Freq at critical speed	Identify, reject the rotor for cracks or loose support check
Rubs	Large 1/rev,2/rev & 3/rev amplitude.	Existence of multipl peaks.Broad band.	Bearing/seal inspec to be carried out
Accessory Vibration	Large amplitude at an accessory freq.	Ampitude at Access -ory frequency	Identify which access ory and correct.

TABLE II Gas Turbine Rotor Diagnostics

The fault tree is in itself helpful since it provides a visual representation of the way in which modes of failure are propagated in a system. This could be regarded as a conceptual knowledge base of the system under analysis.

The fault tree is translated into **IF-THEN-ELSE** rules and incorporated to a general purpose expert system package of programs.The logic combinations **"AND"** and "OR" establish the relation between primary events described by the fault tree. An "AND" and "OR" gate representation in an **IF-THEN-ELSE** type rule is shown in Fig 7.7. This together with the experience and judgmental capabilities (**heuristics**) of an expert often represented by rules of thumb, accumulated through years of experience is the knowledge base of the expert system. The knowledge base thus is the repository of the human expert knowledge.

Fig 7.6 Flow Chart of Gas Turbine Rotor Diagonstics (Faults given in Table II)

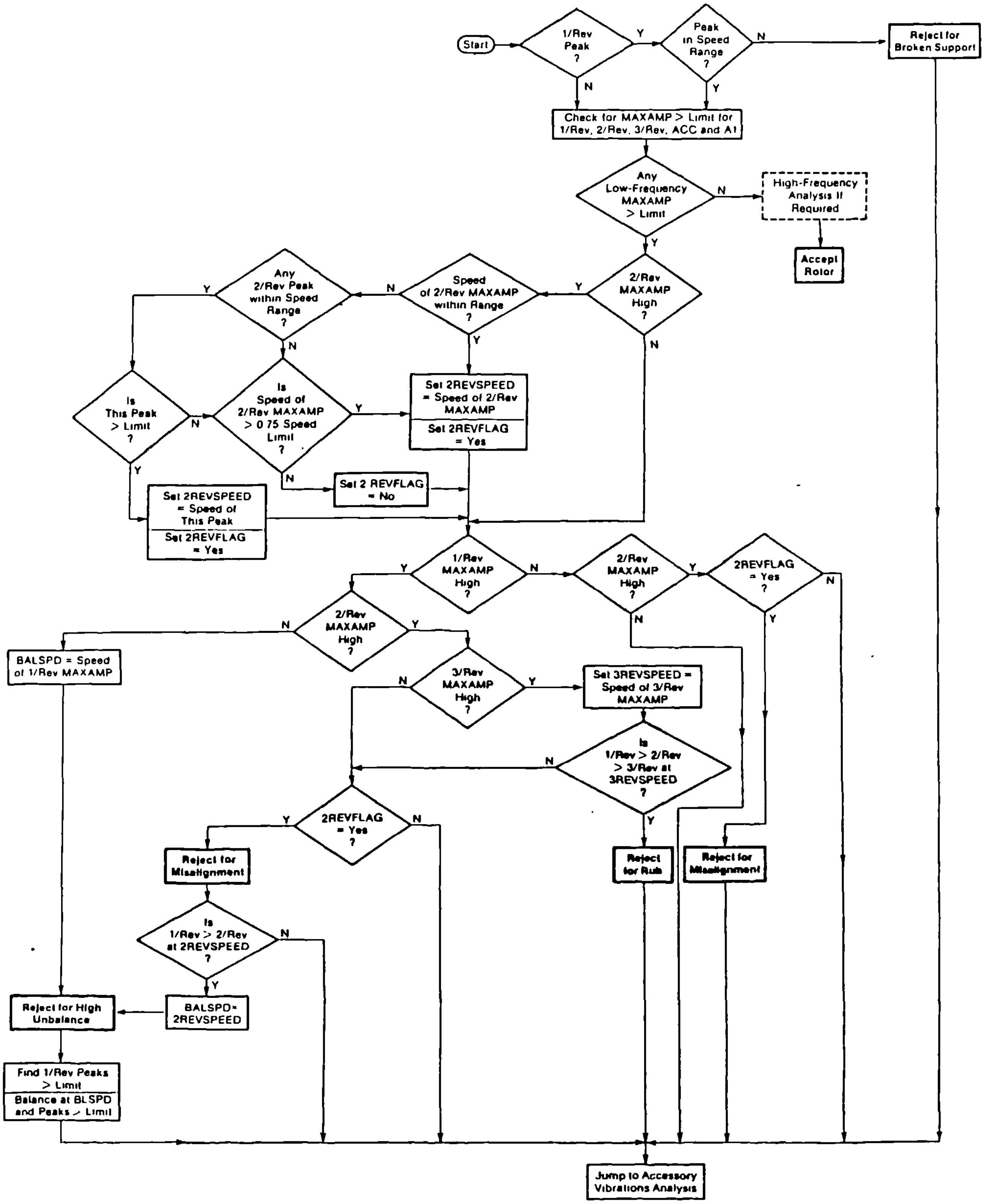
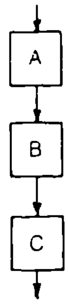
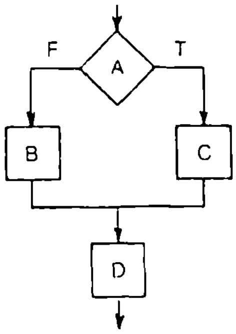


FIG 7.7 IF-THEN-ELSE and .AND. .OR. Rules



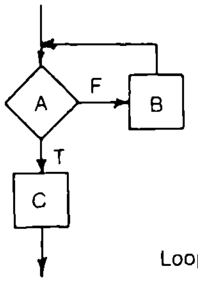
If A and B and C

Sequence



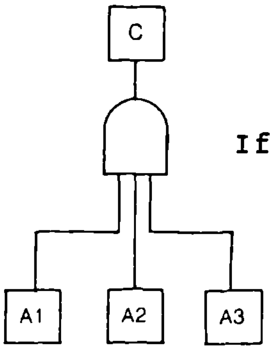
If A and C then D
If not A and B then D

Decision



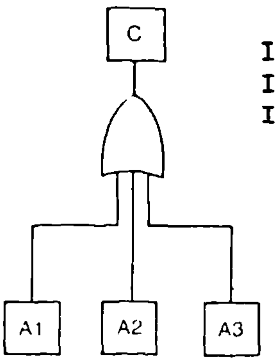
If A Then C
If B Then A
If C Then B

Loop



If A1 and A2 and C Then C

.AND.



IF A1 Then C
IF A2 Then C
IF A3 Then C

.OR.

The knowledge base methodology of building an expert system has following advantages :-

(a)It is especially suited for people with little or no background in Artificial Intelligence.

(b)It is a way of relating the knowledge expressed as a description of a system to a knowledge base of IF-THEN rules.

(c)The intermediate product viz. the fault trees and/or flow charts are conceptual knowledge base of the expert system. This conceptual base is easier to review and modify since they are visual representation of IF-THEN rules.

(d)It facilitates the modular growth of the knowledge base since it is based on descriptions of real systems that usually are modular.

(e)It is simple to use because the number of building blocks is small : AND/OR type decisions.

Heuristics

There is another shell which to an expert may not have any logical answer but means a lot. This is knowledge based on examples in the past. These systems operate from a set of case studies inducing their own rules from examples. Confidence in diagnostic system is not something that is attained quickly but grows with experience. It is this experience that is used to develop the rules of diagnostics. This requires a large number of examples and in a condition when a direct rule cannot be given by an expert the problem can be solved through an example based shell. A spread sheet type of input format is normally used for this purpose.

Although the rule based systems are adequate for many kinds of trouble-shooting, they also have limitations. For one, they do not incorporate comprehensive knowledge of how a system works, a major flaw that may prevent them from coping with unexpected failure modes or with multiple faults. In addition, if the system to be diagnosed is changed even slightly, the new behaviour must be incorporated into new rules by a knowledge engineer working with the domain expert, in much the same way the trouble-shooting was originally built.

A major road block for building an expert system has been the fact that the tools and techniques have so far remained largely in the field of knowledge engineers, who in general lack knowledge of applications in other fields. Even though it is an application oriented system engineering and development activity, so far it has been treated as a research activity only.

One of the best things of a classic expert system is the user-interface. In an ideal situation the enquirer should be able to ask the system why it made a certain deduction/decision or a particular question. Rule based systems generally reply by retracing the reasoning steps that led to the conclusion/question.

One of the common tasks which computers are used for in diagnostics is the trend analysis. Thus it is desired to know not only when a particular parameter exceeded the limit, but also when it will exceed such a limit at present rate. The trend direction, rate, change of rate, and change in trend due to say a maintenance action are of great importance. In many cases the use of a spread-sheet and graphics are adequate to detect a trend, whilst in others an elaborate processing and reasoning may be necessary.

Another common task is the correlation of measurements with trends to understand how symptoms are related to faults. The learning work in AI has produced techniques, such as learning by induction, that can be very effective. However these techniques being highly computational intensive, are effective only in few very simple problems so far.

Fuzzy Set Approach Of Expert System

Because of the action of some external and internal influences the gas turbine engines degrade gradually. The degradation manifests itself as measurable parameters and as discussed previously could be in any of the component of the gas turbine engine/system. These measurements are dubious because of gradual drift out of calibration of the instrument systems as discussed in chapter 5. Hence the state of system failure cannot be uniquely defined. To assure reliable operation of the system, the functional faults and difficulties should be eliminated, or brought down to a manageable level (subjective).

The probabilities of failure of the system components cannot be determined because of the intrinsic vagueness or when determinable they are irrelevant. This is because common laws of logic cannot be applied to complex systems as gas turbine engine, in the same way as they are applied to simple logical elements. Approximations and trial - and - error methods have hence given way to **FUZZY** sets [GAZDIK,1985]. Thus it is possible to quantify the qualitative statements, vagueness, uncertainty, lack of data or opinion subjectivity and perform mathematical operations on them [BALDWIN,1985].

In fuzzy set theory a model has to be formulated to handle fault diagnosis and prevention of the system.

In diagnosis of turbo-machinery Meher-homji [1985] has pointed out that the degradations are normally not mutually exclusive thus diagnostic methods based on Bayes's rules are not always valid. Also the "experts" think in a diffuse manner and not step-by-step. The problems in machinery may be classified in a hierarchial structure in which certain class of problems may be a subset of a larger problem category.

In abductive logic method of building a knowledge base, the problem manifestations (observations) are used to evoke a set of hypothesis [MEHER-HOMJI,1985]. Since certain manifestations could evoke several hypotheses a weighting procedure is used. For example in a single spool turbine engine shown in fig 7.8. Power loss could be because of

- -Compressor fouling
- -Labyrinth seal leak
- -External leakage
- -Drop in turbine efficiency
- -Drop in combustor efficiency etc.

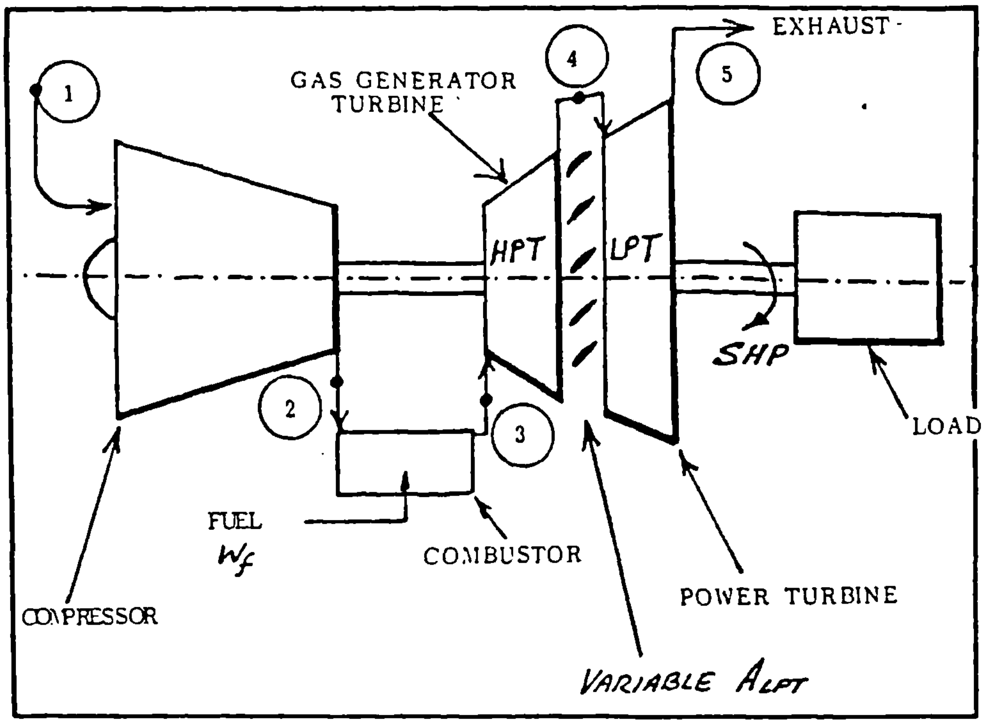


Fig 7.8 Single Shaft Gas Turbine Engine With Load.

Each of these hypotheses would then generate a set of consequences and these hypotheses would have to be grouped into mutually exclusive subsets corresponding to specific problem areas. Three relations defined can be :-

1. E(M,P) This relates to the Evocative association that Manifestation M has for a Problem P.
2. M(P,M) This is a reverse association between Problem P and Manifestation M.
3. FORM_OF (P1,P1.1) which implies that problem of category P1.1 is a form of Problem Category P1.

Languages for Knowledge Base

Whatever method of building the knowledge base is used the computer has to be taught these rules in a computer language. Language for integration of the expert system to the industries has been a problem. While LISP has been the lingua franca of the logic programming , PROLOG appears to be well suited for specialised applications like the diagnostics of gas turbines. PROLOG is specially suitable in applications that require creating knowledge bases of regulatory requirements but lacks real time processing capabilities. This gave birth to language for real time processing such as FORTH, POPLOG etc [GIBSON,1986].

The languages available at CIT for AI are PROLOG-2 , LISP and POP-11 (POPLOG). POP-11 has POPLOG as the core language with capabilities of interfacing with high level languages, such as ADA, C, FORTRAN etc on VAX. POP-11 is a general purpose programming language for increasing range of purposes including design, graphics, text processing, compiler design, image processing, expert system design and design of tools for interactive program development. The software has a screen editor (VED) and can be utilised effectively for teaching purposes , program development, accessing teaching and documentation files and for text processing. The editor VED permits upto two files to be simultaneously edited and individual construct such as a procedure, a range of lines in a file or the whole file itself can be passed directly from an edit buffer to the compiler. This allows the compiler error messages and output of run to be included in the original file itself or in another file. The data stored on VMS files can be directly utilised by the system.

For purpose of teaching and others, certain libraries are available from whole package to single procedures. These libraries can be auto-loaded when a program attempts to use a procedure which is otherwise undefined thus making it possible to have procedures and other facilities to be loaded on demand.

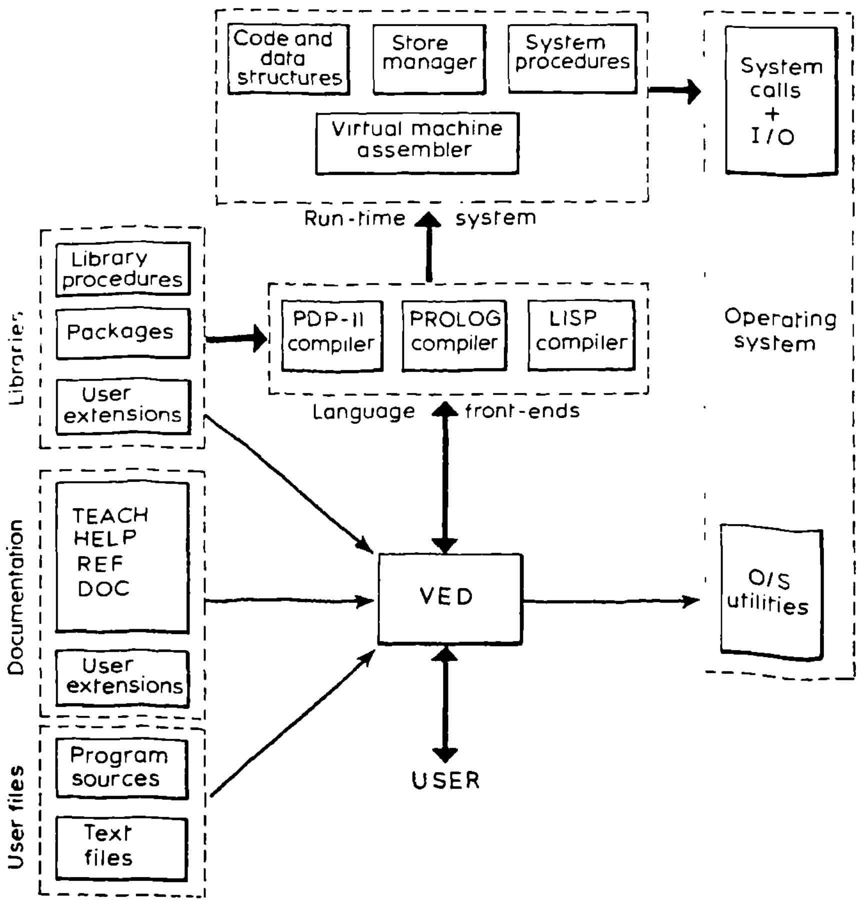
A description of the POPLOG architecture is given in Fig 7.9 [GIBSON,1986]. The language PROLOG though widely used has very little error-protection against minor misspellings etc. It is not a true logic language [FORSYTH,1984] and the user must understand the implementation details of the back tracking mechanism to write a code. Prolog provides a rational data base , where every thing is global without local facts or modules. In prolog the order is crucial to their meaning and many built in predicates have side-effects which make it unsuitable for efficient parallel execution.

APPLICATION OF AI TO GAS TURBINE DIAGNOSTICS

Even though application of AI has been wide and in use, publication of successes achieved in such applications is not enough. The reason is that being too successful they can either be exploited commercially or because of security (eg in Military applications and maintenance or control of nuclear installations).

Gas turbine diagnostics are carried out in field where the engine is installed. It may not be possible to have a main frame computer (eg onboard an aircraft or at a platform) to carry out expert system diagnostics. So far it was not possible to have a language like POP 11 on micro computers for use in the field. However it should be transferable to the new generation of computers with 32-Bit address spaces. Alternatively the program could be written in PROLOG 2.

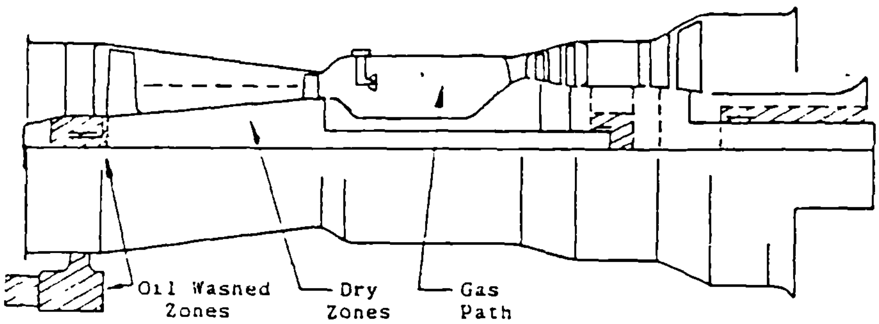
Thus there are many languages available for expert system and different tasks can be best served by different languages. Many library routines exist in various languages.



It will be a waste to convert the existing library programs every time. It is here that POPLOG or POP 11 has an advantage. POPLOG could be employed for any application where program development costs are significant or where the restrictions built in to more conventional languages introduce design difficulties. The integral 'help', editor 'VED' and teaching facilities can help an experienced programmer to learn AI techniques and can also be used to teach novices the programming.

Advantages of AI in Diagnostics

Computerized tools for testing, trouble-shooting and diagnostics are being developed incorporating AI. This increases the effectiveness and flexibility of maintenance. Today's performance monitoring methods are more sensitive due to improved modelling techniques. Even though this can provide an early warning on mechanical failures, to increase the confidence level and for the requirement of safety, various techniques used for gas turbine engine monitoring discussed in previous chapters are shown in fig 7.10 [STEWART,1986].



MONITORING SYSTEM	PERFORM	DEBRIS OIL/GAS	VIBRATION	VISUAL	USAGE
GAS PATH					
OIL WASHED.					
DRY ZONES					
SUPPORT					

Fig 7.10 Gas Turbine Engine Diagnostic Effectiveness

It is evident from the Figure that no one technique has anything like 100% performance.

To achieve a satisfactory diagnostic level all the available indicators must be looked at by the user eg Performance, Vibration, Debris in exhaust, S O A P, etc. Thus identifying a problem through more than one methods increases the confidence level. An expert system is ideal to confirm and link interpretations between various systems. One of the most sophisticated parts of an AI software are not the rules for diagnostics of the engine but those for ascertaining that the sensors are in good working order. If not then the program should either ignore them or recalibrate. Expert rule structures for gas path diagnostics are thought to be approaching several hundred for the basic diagnostics and perhaps 50 odd for the sensors.

While rule based software can be written in any computer language, development is far easier with so called expert system shells. These programs contain tools for creating and editing rules and for carrying out forward - and - backward chaining inferences. This development of shells has 3 major goals :-

(1) Eases the knowledge encoding task, so domain experts can enter much of their expertise without the help of a knowledge engineer.

(2) Improves the design of the user interface so technicians on the shop floor can use the system with a minimum of trouble

(3) Should be able to run adequately on the shop floor in a relatively small rugged package with limiting computing resources.

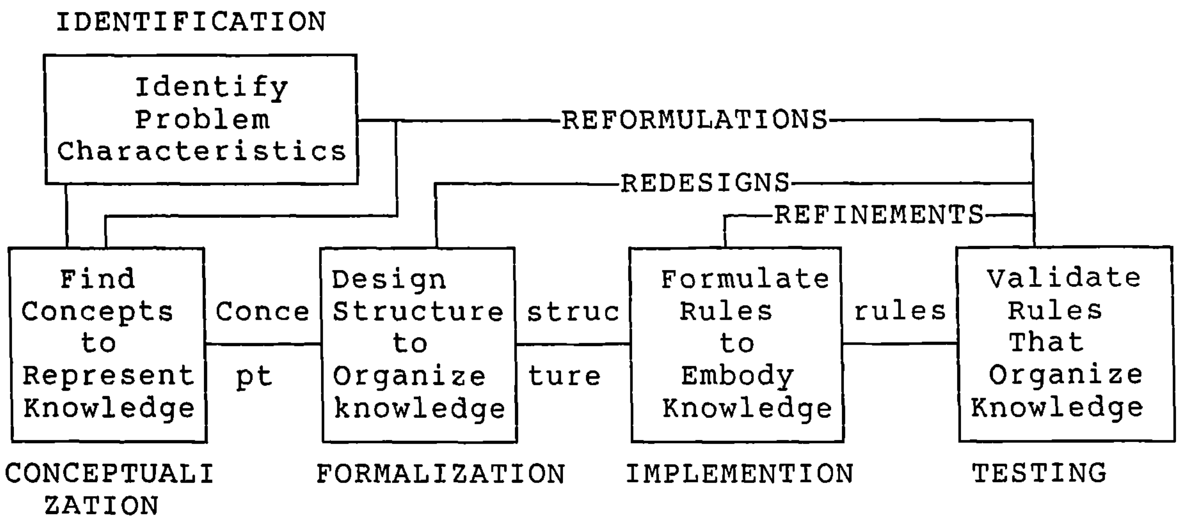


Fig 7.11 Development and Testing of Knowledge Base

Once the language and basic rules have been decided, the knowledge system is developed as shown in Fig 7.11. The fig shows the iterative, evolutionary process of knowledge system development highlighting the ways of testing a knowledge system feed back to earlier stages of construction.

Gas Turbine Diagnostic AI Shells

Qualitative simulation of turbo-jet engines using AI has been demonstrated [RAJAGOPALAN,1985]. Application of AI in turbine engine diagnostics and maintenance has also been implemented by General Electric, [JELLISON,1986], in the form of a shell called GEN-X for diagnostics of F-404 and TF34 engines.

General electric have used FORTH and developed GEN-X language for aircraft engine diagnostics (F 404, TF 34). The GEN-X shell has been built through refined tools used to build its CAT [APOSTOLAKIS,1978]. Gen-x has used three separate forms of knowledge representations :-

Rule tables
Decision trees
AND/OR trees

All map to the same underlying structure, but one or the other may make more sense for representing a particular portion of a problem. For example, a decision tree is well suited to represent a set of sequential actions - such as performing diagnostic tests to home in on the cause of a failure - while a rule table could be more effective to represent a larger set of rules to be applied to a single body of facts.

The shell also has provisions for attaching procedures to facts and inclusions in the knowledge base. Thus, if the application of a rule requires the value of a parameter like temperature or pressure, GEN-X could issue instructions to read the data from a sensor instead of just requesting its value from the user. Similarly a conclusion that a particular part has failed could trigger a video-disk sequence showing the part's location and a method to counter-act the effects of the failure.

On-Board Diagnosis and The AI

Real time on-board fault monitoring and diagnosis can be important where quick response to failure is very critical. Quite often the pilot must compensate for the failure while diagnosing it. The behaviour of the aircraft may change rapidly as the failure effects propagate through the system. Crew or operator's information about state of the engine is often incomplete and the evasive action taken following a failure is by inference or experience. Most of the transport aircraft presently have an alerting system which triggers crew to an out of tolerance condition, but do not monitor and diagnose the faults in automated mode. Crew is required to monitor the instruments and alert system and determine the engine state, diagnose the fault and take evasive action (accommodate the fault). An onboard automated expert system through inference engine, can analyse and inform the pilot of the failure (faults) and the evasive action to be taken. The action to be taken to compensate for and/or correct a fault and hence the functionality of the aircraft is essential. Based upon such recommendations the flight crew will take the action [SCHUTTE,1986].

From a survey it was revealed that most of the pilots tend to think qualitatively rather than quantitatively, diagnose using comparison and experience and must take action through reason or knowledge. Thus the fault monitoring and diagnosis system must transfer quantitative values to qualitative. The component frame work are shown in Fig 7.12 as well input/output for each component.

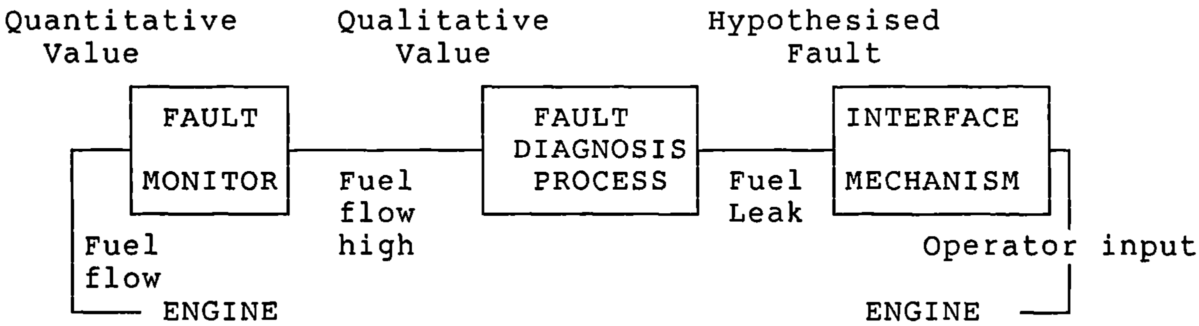


Fig 7.12 On-board Diagnostic Function

The quantitative values are derived from the engine sensors. To detect abnormal sensor readings, the fault monitor should compare the sensor data (actual engine state) to those of the simulated model (expected state) and if the difference exceeds a certain limit, it should signal a fault/warning. The number of false alarms can be reduced by use of heuristics to recognize normal conditions which the model cannot accurately describe.

The fault diagnosis could be described in three stages, each using different representation and reasoning. In the first stage the symptoms are compared to fault-symptoms known a-priori. These associations are a compilation of knowledge about known faults and their behaviour. The most commonly occurring faults hence can be quickly identified.

The second stage is reached if symptoms do not correspond to a known fault. The reasoning now is to localize the failure and to generate as much information about the fault as possible. The physical working of the system rather than the failure is the focus now. For this method of reasoning is desirable to have functional and physical models.

For this localization of the fault further information may be necessary especially if all the parameters entering the reasoning are not available. This is the third stage of diagnostics. The performing tests may be carried out passively or actively, depending on the type of data collection. Whether the data is automatically being recorded (active diagnosis) or manually supplied (passive diagnosis), the third stage of diagnosis is responsible for proposing the tests to obtain the additional information.

Fault Monitoring System

Modelling an engine is not as difficult as modelling the actual engine. For example, to model an engine one can require that the bleed valves open anywhere within a certain range and that is acceptable. To model the actual engine one must be able to predict exactly when a bleed valve is going to open so that the monitor can distinguish between the normal opening and an abnormal one. These problems of modelling are aggravated by the variation and hysteresis in measurements and by the fact that difference in tolerances vary from one engine to another. It is not yet practical to produce a detailed model for each and every engine produced. This requires to have a different approach to the problem of diagnosis on engines.

The alternative technique is to combine the flexibility and common sense of the user's monitoring process with the completeness and quantitative accuracy of the engine model. Thus the monitor assumes certain measured data to be true and the simulation model is fed this data to generate the expected outputs. Thus in the above example if the model was informed of the bleed valves position (assumed true) then all temperatures and pressures could be compared. Flight crew normally do not predict a normal state change of the engine but know it after it has occurred. Occurrence of these known or expected state changes can be distinguished from faults.

Once the monitor has determined that a fault exists or is likely to occur soon, it must then classify it in qualitative terms. For this purpose not only instantaneous information is important but also time-based information. Eg EGT is high is instantaneous but EGT is increasing is time based. To generate the time-based information, the fault monitor must keep track of what the values were over time.

The use of time-based information allows the monitor to have prediction capability. It may be able to predict if it is likely that a parameter value will exceed its normal operating range and if so then issue a warning. Since modelling a faulted system is extremely impractical, an exact estimate of the time of failure may not be possible to be predicted.

Fault Diagnosis system

Once the quantitative sensor values have been converted to qualitative form the fault monitor communicates them to the fault diagnosis system. The diagnosis system uses a qualitative model of its domain rather a quantitative model (fault monitor).

The first stage of the diagnosis process is diagnosis by fault-symptom association. This stage corresponds to the experience of the user. Since the users use static (instantaneous) values as well as time-based information, it is useful to incorporate the temporal reasoning about sequences of symptoms and their associated faults. Reasoning about sequences over time is possible through extension of the rule-based system to permit temporal reasoning functions within the rules in a knowledge base. Let us assume that we can have EGT fluctuations followed by decrease in EGT as a consequent of say FOD. Thus we can say "If EGT was fluctuating and then decreasing then foreign object ingestion is a possibility".

This could be represented as:-

```
((foreign-object)
    (and
            (during epr   fluctuating)
                    egt     fluctuating)
            (during epr     fluctuating)
                    fuel flow fluctuating)
            (during epr     fluctuating)
                    epr     fluctuating)
            (meets egt      fluctuating)
                    egt     decreasing)))
```

When the current symptoms fail to correspond to known faults, or when several hypotheses cannot be distinguished, the fault diagnosis system enters the second stage. The purpose of reasoning here is to localize the problem and to construct a fault hypothesis. At this stage since the physical cause cannot be identified the fault hypothesis identifies the responsible component(s), the fault type, affected component(s), and the propagation history.

Three types of faults are identified :-

(a) **Non intermittent** When a non intermittent failure occurs. Component(s) faulted by this failure stay faulted and do not return to normal operation without corrective action.

(b) **Intermittent or temporary failures.** These are the failures which originate from one initial failure. and the affected components do not remain faulted but return to normal operation after some period of time without corrective action.

(c) **Multiple independent failures.** The failures where any two or more faults from those described above are affecting simultaneously.

The diagnosis process faces two situations. In the first situation no prior symptoms have appeared and the system must generate hypotheses to explain the current symptoms. In the second situation some symptoms had appeared earlier and some hypothesis were generated then. Here the previously generated symptoms are either corroborated to explain new symptoms as well as the old symptoms, or the old hypotheses are discarded and new hypotheses are generated. When there is uncertainty of truth of an event eg. of a measurement or an hypothesis, abductive logic can be used.

<u>Abductive Logic</u>

Figure 7.13 shows how this abductive logic can be applied in a trouble-shooting or diagnostic work. The above mentioned procedure can be outlined as :-

1. Obtain information (via keyboard or actively). This would be an interactive query type session.

2. For each information, the EVOKE operator would evoke a problem set Pi.

3. For each problem Pi, lists A,B,C & D would be created. These lists essentially indicate how close the manifestation "match" the problem under consideration. If particular problem has been previously provoked then the list is updated.

4. Hypotheses regarding the problem are then screened and a top few selected. Dominance of two Hypotheses H1 and H2 is established by checking if the list "A" for H1, less items explained by previous diagnoses, is a subset of a similar construct of H2. If it is a subset, then H1 is dominant.

5. Once hypotheses have been narrowed down, by specific tests or questions, an action recommendation can be developed by the user.

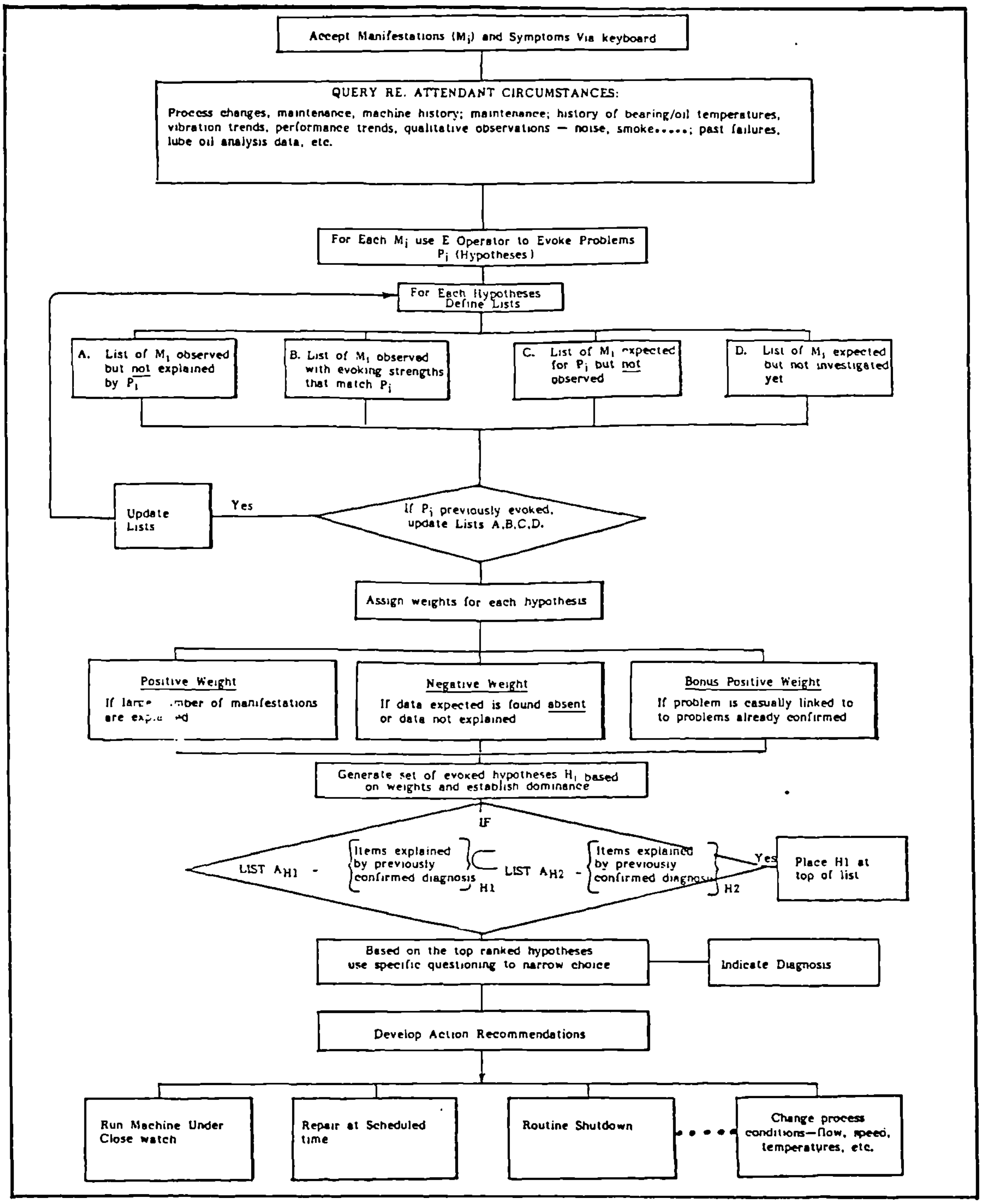


FIG 7.13 Diagnostic Logic Model [MEHER-HOMJI,1985]

For example in the above case of the turbine engine, under constant power, the symptoms shown in Fig 7.14(a) will lead to the conclusion of fouled compressor. The case under constant speed is more difficult as the manifestations are qualitatively the same. The manifestations evoke hypotheses of "fouled compressor" and "increase in LP turbine nozzle area ". In such a case the Expert system would request a quantitative description which would allow discrimination between compressor fouling and a drop in low pressure turbine nozzle area. The constant speed operation is shown in Fig 7.14(b)

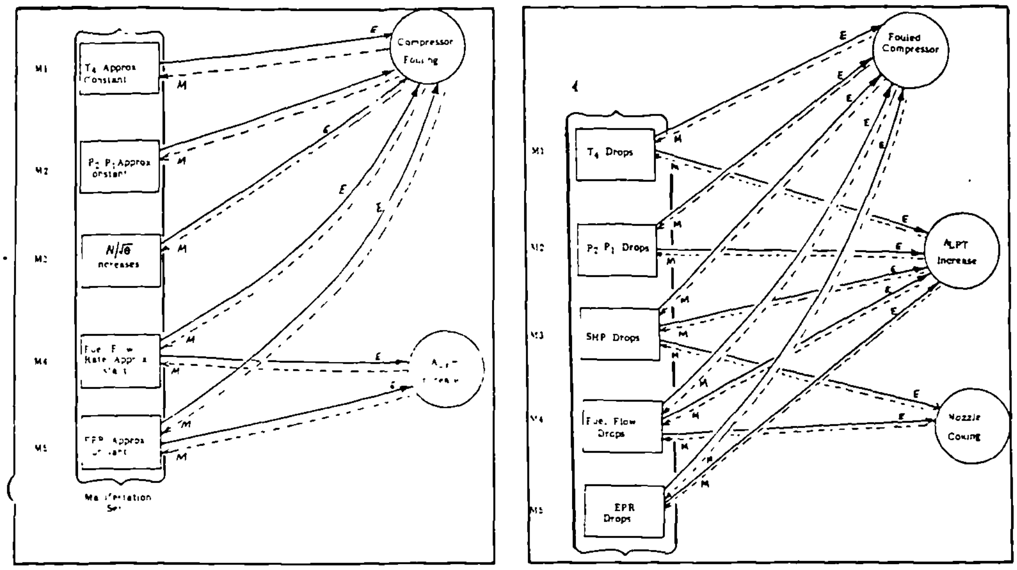


Fig 7.14(a) and (b) Split- Shaft Gas turbine Diagnostics

Effectiveness of AI in Gas Turbine Diagnostic

The success and efficiency of the diagnostic process depends to a great extent on the models of functional and physical structure of the system, and how these models are applied using diagnostic heuristics. There are many ways of modelling an engine, but from diagnosis point it is important to use model of functional and physical structure to identify the faults. The level upto which the rules of the expert system are written is also a compromise between the cost, efficiency and elimination of fault hypothesis. For example diagnosis by an active test is preferred but costs inhibit its use until and unless extremely necessary, eg. space shuttle engine or control monitoring.

Optimization techniques play an important role in knowledge systems. They are required to be fast in performing their task, have an interactive with the user and capable of adding rules learnt to the data base. The queries the knowledge system generates (the dialog) should be expert in nature and in order of appearance. A wide variety of users are interested in knowledge systems because of its ability to explain and justify the conclusions. End-user in many applications (gas turbine is no exception) need to trust the recommendations of a knowledge system thus ascertaining the reasonability of the system and building confidence.

Knowledge base maintainers, who may include experts and technicians, continually revalidate knowledge system by assessing performance on test cases. This validation is of the system reaching the right decision and of doing so for the right reasons.

The communication with the user is the capstone of the capabilities of the knowledge system. They communicate with knowledge engineers, experts, end-users, data bases and other computer systems. The knowledge system, just like a human, needs to speak to each of these in its own appropriate language. Knowledge systems communicate with knowledge engineers through structure editors that allow them to access and modify components of the knowledge base easily. knowledge systems communicate with experts through sample dialogues with explanations that elucidate their lines of reasoning and highlight for the expert where to make knowledge-base changes. For end-users, knowledge systems may exploit natural processes to generate questions and answers or to interpret user responses. Some knowledge systems today use video-disks to retrieve pictures and replay instructional sequences for end-users.

For gas turbine diagnosis the knowledge systems have to access and retrieve information from on-line data system automatically or from the user when on-line data is not available. Frequently a knowledge system may serve the primary goal of knitting together diverse sources of knowledge that reside in different data bases, reflect different formats and coding practices, and require heuristic means to produce a meaningful, integrated interpretation. This type of need exists for on-board real time engine diagnostics when complexity of gas turbines, controls, environment, condition of operation etc make knowledge systems a necessity.

"XMAN" The Ground Based TF34 Engine Diagnostic "EXPERT"

Expert systems have been successfully applied in ground based diagnostics of aircraft gas turbine engines. One such system is the System Control Technology (SCT USA) "XMAN" for the USAF TF34 engine. XMAN applies the expert system technology to maintenance aids increasing its flexibility and effectiveness. USAF has a stand-alone Engine Diagnostics / Comprehensive Engine Management System Increment IV ED/CEMS that integrates several information processing programs into a single, unified, engine management system to support jet engines. This includes data retrieved from on-board automatic monitoring systems or manually collected condition monitoring programs. In addition oil analysis and maintenance information are organised with the data base providing flexibility and real time maintenance decision support [JELLISON,1986].

XMAN accesses ED/CEMS data-base direct via RS-232 link, extracts facts which it uses in the trouble-shooting/fault isolation process. These facts are stored in an XMAN fact file and used along with other inputs to trouble shoot engine faults. There is an input required from the maintenance technician when enquired by XMAN. The diagnostic procedures associated with interpreting ED/CEMS data products, trouble shooting engine alarms generated by TEMS and ED/CEMS, and isolating engine discrepancies are automated by XMAN using expert system technology. The initial knowledge was developed by the engine manufacturer. Engine discrepancies which have not been analysed previously by the maintenance technician are transferred to XMAN on a daily basis. The XMAN control system links the engine discrepancies present in the XMAN fact file to the appropriate trouble shooting rules. When the trouble-shooting is completed, XMAN prompts the technician with corrective maintenance procedures.

The language of XMAN is LISP and the rules are deterministic. These will be changed to include propagation of uncertainty [JELLISON,1986]. Fig 7.15 shows a typical XMAN fault and the decision trees while Fig 7.16 shows the fact generation and transfer to XMAN.

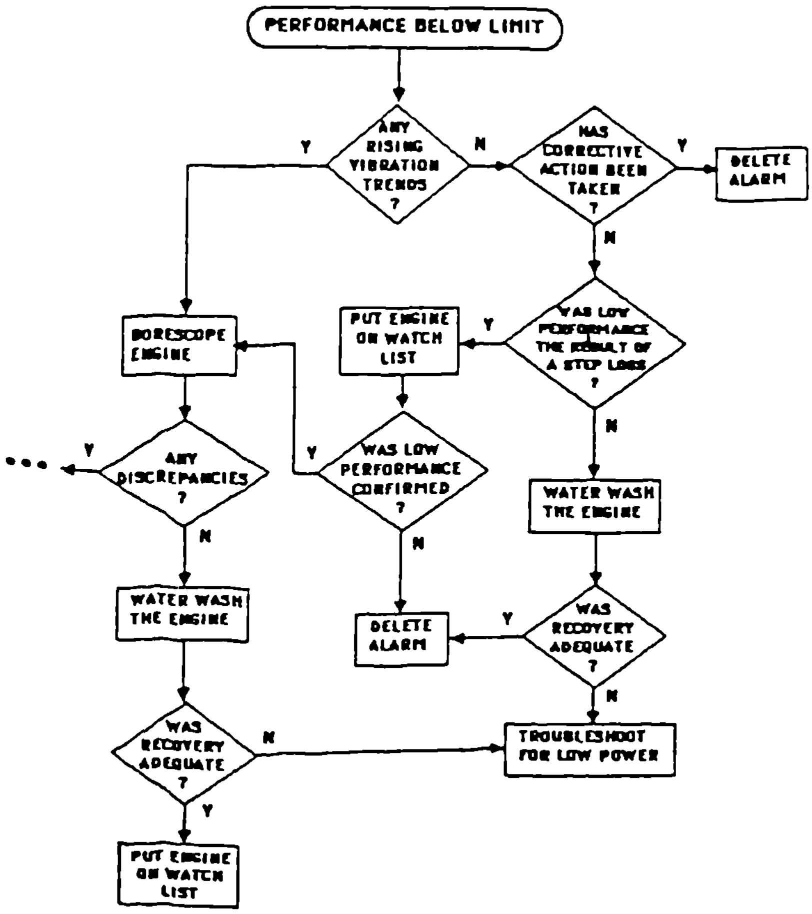


Fig 7.15 The XMAN Fault and Decision Trees

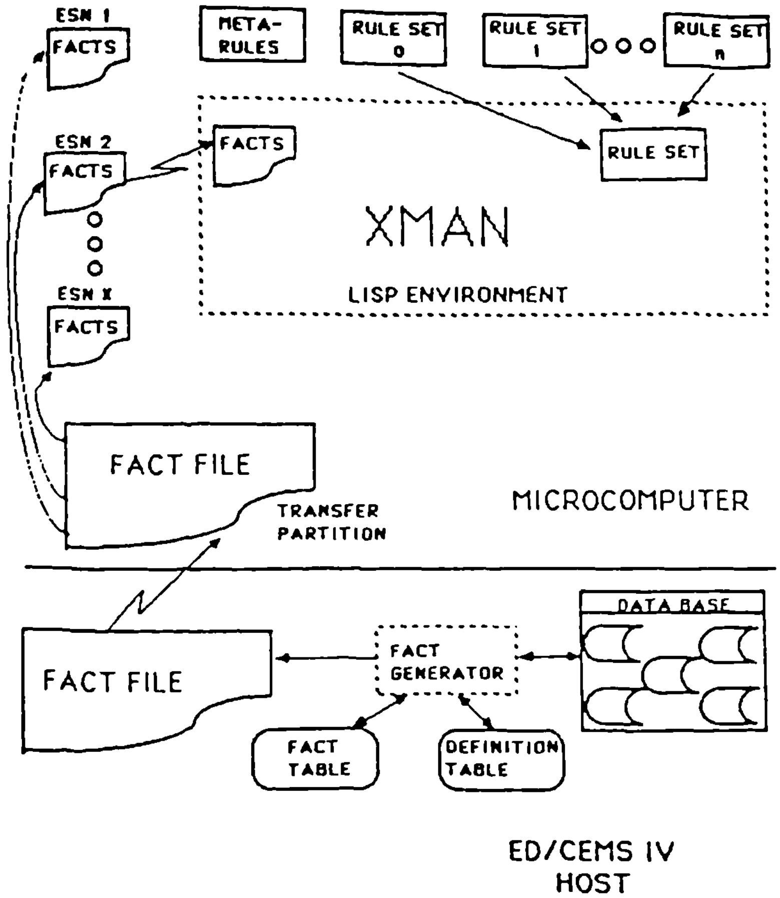


Fig 7.16 XMAN Fact Generation and The Fact File

Future of AI in Gas Turbine Diagnostics

Knowledge based rules and inferential algorithms will be an integral part of the next generation maintenance tool and an important element of integrated maintenance diagnostics. This technology is both timely and critical to achievement of increased equipment maintainability at reduced cost. Expert systems represent a significant step forward in the evolution of ground based diagnostics. As integrated maintenance diagnostics takes on an increasingly important role in weapon system procurement, development and maturation, the benefits of automated trouble-shooting, fault isolation and maintenance procedure prompting surge to the forefront of weapon system supportability.

CHAPTER 8

MODELLING THE DETERIORATED ENGINE

Introduction

In the preceding chapters various degradations of the gas turbine engines have been identified, at the module level, in terms of the changes in the component flow capacity, pressure ratio or the efficiency. The techniques to detect these degradations and determine the level of the engine deterioration were also evolved. The Gas Path Analysis Technique, described in chapter 3, is accomplished through the detection of the changes in the measurable parameters, caused by the engine deterioration. To detect the change, hence, there must exist a base for comparison. This base for the GPA, is the undeteriorated state of the gas turbine. The procedure to model the base line and the deteriorated engine are explained in this chapter. This chapter describes the technique utilised to change the steady state characteristics as effected by the degradations. To be able to simulate a real engine, the engine data output must have the noise of measurement superimposed on the calculated values. This chapter also explains the details of the sensor model built in the program to provide the instrument noise.

Model Necessity

Performance analysis is a well established technique successfully employed during the development of the gas turbines. For this purpose, the engine is simulated on a computer, using the component matching technique [COHEN, 1986] and certain steady state component characteristics. Once the engine enters service, the environmental and the operational conditions cause a deterioration of the engine performance. To determine the new performance level, some measurements must be made at the engine level during its operation. The analysis of the measured data can give an estimate of the present performance level of the engine, but to determine the level of the engine degradation, this measured data must be compared with the data stored "when new" or the base_line model.

Hence, two sets of data, viz the measured values and the expected values, must be available to accomplish the analysis. The expected data can be generated by any of the modelling techniques, described in chapter 3. The importance of accurate determination of the base_line was emphasised in chapter 3. For an effective Gas Path Analysis, accuracy of both, the measured data and the base_line, are essential. Whereas the measured data is available wherever the engine is, to generate the base_line data, a knowledge of the steady state component characteristics is essential. Such a data may not be available neither from the manufacturer nor from the users, especially if the engines are very old. For reasons of security, there is a reluctance to give away the component characteristics and the relevant engine data, for the current engines.

In the past, the deteriorated engine performance data has been generated by implanting mechanically damaged components in otherwise good gas turbines. One such attempt was on T_{53} turbo-shaft engine [URBAN,1972]. First a base_line signature was established through calibration runs, and then the bad parts inserted in the engines, either singly or in combinations. Engines were then flight tested to gather the in-flight data of the deteriorated engine, for diagnostics. This is an extremely expensive method, and it is not possible to implant severely damaged components because of the likelihood of causing further more serious damage. In addition, the stripping and the rebuilding of an engine even with the same parts, can cause changes in its performance, hence, the signature base_line is no longer valid. The measured data may be obtained either from the user or the engine manufacturer. Even if a set of accurately measured data for a particular engine was available, in the absence of an accurate base_line, effective analysis of gas path may not be possible. The error in determination of the base_line generally shows up as the engine faults (chapter 3).

Modelling

Computer simulations provide the means for analysing the behaviour and the interaction of the constituent components during the development of the gas turbines. Simulations can also serve as aids in understanding and solving problems that arise after the propulsion system has been developed. Generalised computer simulations allow paper studies of many different kinds of engine configurations. Many generalised digital engine simulations exist today and most of them are limited to steady state performance calculations. Since they are general their applicability is high and the user needs only specify an accurate data for the desired configuration.

Since detailed computer models of gas turbine engines have demonstrated a record of success in predicting the engine behaviour for the design purpose, they are considered appropriate for modelling various engine faults. An alternative solution therefore, and the only feasible one in the present case, is to assume certain component characteristics and generate, both, the base line as well as the measured data, with a mathematical model. In such a case the base_line data is very accurate whereas the validity of the measured data, to simulate engine deterioration, depends on the component degradation modelling.

To simulate a deteriorated engine, the knowledge of the changes in the component characteristics brought about by the deteriorations, is very important. Various causes of the gas turbine performance degradation were described in chapter 2. The gas path analysis is concerned with detecting these degradations either at the microscopic level or macroscopic level. The two approaches of GPA viz, the **top-down** and the **bottom-up**, were discussed in chapter 3. To apply the bottom-up technique, once the algorithm for changes in the microscopic level degradation with the usage are established, determination of the module level deterioration is a straight forward addition of these effects. The cumulative effects of the component degradations, viz clearance increases, changes in aerofoil contour, change in aerofoil roughness, nozzle bowing, vane twisting, burner nozzle plugging etc. can be manifested as changes in the flow capacity, efficiency, area etc. The effects of each of the microscopic degradations on the module flow capacity and efficiency can hence be determined. The overall degradation at the module level will be the addition of the effects of all the module components.

The top-down approach would analyse the degradation level of the modules from the overall measurements of the engine. The first step, hence, in both the approaches of analysis, is the determination of the present performance of each module. This is accomplished through the measurement of the dependent parameters such as pressures, temperatures, speed, fuel flow and control positions etc.

A major advantage of using a mathematical model for analysis, is, that it permits the implementation of faults to be controlled, thus systematically investigating the engine deterioration. The performance predictions of a model can then be compared with the engine test results. The requirements of such a model are :-

1. It must be general in nature so that all gas turbine engines could be modelled.

2. It must be representative of the engine, i.e. modular in concept, with or without controls.

3. It should account for non-standard engine operations, e.g. types of fuel, air bleeds, environmental conditions, power off-take etc.

4. Must be capable of generating temperatures, pressures, speeds and fuel flow at various stations.

5. The engine output should be realistic. This would require use of sensor models in addition to the mathematical model of the engine.

6. Must be capable of simulating engine degradations individually as well as in combination at the module level.

7. Should be capable of generating accurate deltas and influence coefficients that truly reflect how the measurements respond to the potential module problems.

As described in chapter 2, the effects of the module degradation can be qualitatively described but have not been published quantitatively. This has been primarily because of the complexity of erosion prediction in the multistage turbomachines and different seal rubs. The flight and the thermal loads are typical to each engine type and installation. Thus while the thermodynamic models, described above, may be used in conjunction with field data to identify engine health, they cannot be used to predict the effect of component model without the knowledge of the deterioration of the components. These may be calculated from algorithms developed based on statistical data or from testing the module. In view of this a general deterioration model in terms of the independent parameters is attempted wherein the changes in the independent parameters at the module level are the input.

An interactive program **DETEM** (**DE**teriorated **T**urbine **E**ngine **M**odel) has been developed to generate such data. Temperatures and pressures at various stations are generated for undeteriorated and deteriorated engine, simultaneously, at the design conditions of the engine operation. Any type of gas turbine engine can be modelled. The data output can be superimposed with "white noise" to simulate real data, and this could be continuous or at fixed time intervals (predetermined by the user).

Since it is a general model and the fact that absolute accuracy of the engine model is of no great consequence; as long as the major performance effects are represented accurately, the model can be used as a useful validation tool over the entire operation range, for all kinds of gas turbine engines. The model hence, is a believable representation of engines but not of a specific engine. Specific engine modelling could however be obtained from the general model by modifying the estimated component data until a good match with the known engine operating parameters are obtained.

Compressor deterioration modelling

The compressor characteristics are primarily affected by changes in the aerofoil contour, the surface roughness and increased clearances. Opinions have varied as to whether compressor deterioration affects the early stages, which are directly exposed to the incoming air hence face the impact of solid particles, or the later stages, where the impact of particles is pronounced after rebounds and at the same time higher temperatures bake the deposits making them difficult to be removed [SARAVANAMUTTOO,1985].

The compressor performance is normally depicted by characteristics as shown in Fig 3.3. These characteristics may be formed by making use of the individual stage performance characteristics by method of the stage stacking. From the knowledge of the inlet conditions and the mass flow, the inlet coefficient may be determined while the total pressure rise and polytropic efficiency can be found from the stage performance map. Assuming that the drop in the polytropic efficiency is closely approximated by the loss in the stage efficiency, the stage exit temperature can be calculated. The stage exit total pressure, mass flow and area give a mean exit velocity knowledge of which determines static pressure. The exit velocity is used as the inlet velocity to the succeeding stage. The stage stacking thus permits the incorporation of controlled degradation effects in a detailed model of the compressor, providing a capability for an in-depth physical understanding of the behaviour of the compressor. For convenience similar stage characteristics can be assumed, especially when detailed performance characteristics of each stage are not available. In the latter case individual stage performance characteristics can be derived from overall compressor characteristics [BATCHO,1987].

The overall effects of erosion and tip clearance increase using the stage stacking technique are to decrease (1) mass flow, (2) total pressure rise and (3) compressor efficiency [BATCHO, 1987]. The tip clearance effects do not change the slope of the characteristics but produce an overall shift of the pressure coefficient and the efficiency versus flow coefficient curves. Then using previous total pressure loss formulations with the knowledge of the stage characteristics, efficiency and performance of the stage are determined. Normally change of performance is modelled at design point and these results are used to produce an entire deteriorated performance. Modelling results may be accurate at the design point but are not very accurate at off-design operating points. A shift in the constant speed lines on the compressor characteristics is observed. The effect of the shift is a decrease in corrected mass flow and total pressure rise at a constant speed [BATCHO,1987]. The effect of fouling on the compressor performance is almost similar i.e. loss in compressor delivery pressure and mass flow at a given speed.

These two changes, viz the decreases in the flow capacity and the pressure ratio, are of-course accompanied by a loss of the overall efficiency of the compressor, which results from increased viscous forces and the changed flow patterns. There is a change in the surge margin as well. For constant properties, the inlet axial velocity is given by the compressor mass flow and for a given mass-flow the inlet flow coefficient remains unchanged. Hence at high speed the mass flow at surge, under deterioration is same as that corresponding to the mass flow at undeteriorated surge. In the case of a low-speed surge, the front stages are at high incidence, due to lower flow coefficient, and the back stages are approaching a choking condition. With increasing stage deterioration, the back stages experience a lower density, at the same speed. This causes higher exit velocity and at same flow coefficient, the deteriorated compressor moves closer to choking the rear stages. But the flatter low speed characteristics delay the surge which occurs at the same mass flow as the undeteriorated.

Thus the compressor module deterioration can be modelled by a judicious changes of the mass flow, pressure ratio and the efficiency. Even though the stage stacking technique generates accurate model of the compressor deterioration, the programs are often quite large, requiring high computational effort. Since the stage stacking technique is used to develop the compressor characteristics, and the overall characteristics are employed for the engine performance determination, it is reasonable to effect the changes on the compressor characteristics themselves. Even when the deterioration effects are implied at the stage level, ultimately the effect will be on the overall compressor characteristics, since these are developed from the knowledge of the stage degradations. In this thesis the compressor deterioration has been modelled based on the overall compressor performance characteristics and not by stage stacking method. Hence the changes because of deterioration are effected on the compressor maps.

Two techniques of modelling the changes in compressor characteristics have been traditionally in use. The first called "flow scaling", results in shifting the entire component performance map horizontally to the left. The second method renames the corrected speed lines to new values and is called "speed scaling". It is possible to modify the compressor characteristics, which are generally represented in four variables, viz. mass flow, pressure ratio, speed of rotation and the efficiency, in any of the three. The fourth parameter is taken as the reference.

Neither of the two techniques described above provides the deteriorated characteristics of fig 3.5. A third technique wherein the pressure ratio, mass flow and the efficiency are independently scaled, has been used in the present analysis. Table III [DUPUIS,1986] shows typical values of the scaling factors for a typical gas turbine engine. The results of experiment [SALLEE,1980b] show that the entire component map shifts down and to the left, along a typical operating line slope. The changes in the compressor characteristics can be brought about by changing the respective scaling factor viz. speed, pressure ratio, mass flow and efficiency. Such a model would impose the restriction of linear scaling throughout the entire range of pressure ratio and mass flow. But as discussed above, the effects of deterioration are non-linear and hence a changing scale was assumed for pressure ratio, mass flow and efficiency. The speed is often used as the control parameter, and hence was taken as the reference.

Based on the values of the compressor pressure ratio mass flow, and the efficiency, the compressor characteristics are modified such that almost all the conditions above could be satisfied.

Similarly for analysis, the compressor degradations can be said to have been detected if accurate values of changes in pressure ratios, mass flow and efficiency at any operating point are established. This would increase the number of measurements which are already scanty. To utilise the restricted number of the measurements to their maximum extent without a loss of the accuracy, the variables at the compressor level can be brought down to two if we can express one of them in terms of other. The experimental results for the compressors, described above, provide the relationship between the pressure ratio and the mass flow. Two techniques were used to model the degradations of compressor performance. The first one assumes that, as seen from a wide number of cases, the decrease of pressure ratio and fall of mass flow are almost of the same magnitude i.e. the slope of the operating line is 1. Thus if one was expressed as equal to the other, only two parameters could define the deteriorated compressor module. Pressure ratio can be measured directly whereas mass flow measurement is not carried out in operational engines. Hence equating the mass flow decrease to the fall in pressure ratio was adopted.

Even though the above technique may hold at lower speeds and high pressure ratios at a given speed, it is not the solution at high speeds and lower pressure ratios. Thus an empirical relation, which was varied with operating speed, mass flow and pressure ratio, was used. This empirical relation was seen to satisfy the observations of [DUPUIS,1986] and [BATCHO,1987].

Three different models are incorporated in the program. They are switchable by a selection of a variable called **model** equal to 1 for the case when mass flow is equal to the pressure ratio, equal to 2 when all the three variables are independent and the default value of negative quantity when the empirical relations are used such that no shift in the operating line of the engine is implied. When the model has a value 2, the user supplied degradations are effected at the design point and proportionately at the other points on the map.

When the variable model has a negative value (which is default as well) the knowledge of the mass flow and the efficiency is required, as when model = 1 , but the assumption of the slope of working line being 1 is waived off. Here the fact that at design speed and below, the surge mass flow is same for deteriorated and undeteriorated cases is utilised. The relation between pressure ratio is determined and different empirical relations are used along the constant speed line, and constant pressure ration (increasing speed). Fig 8.1 shows the LP compressor characteristics and the working line for model = 2 when the pressure ratio was degraded by 3%, mass flow by 3% and efficiency by 2% and in the second case (lower maps) the pressure ratio was degraded by 5% instead of 3%, other degradations remaining constant. Fig 8.2 shows the LP compressor characteristics (Compressor pressure ratio vs mass flow and pressure ratio vs efficiency) and the working line for model = 1 with pressure ratio degraded by 3%, mass flow by 3% and efficiency by 3%. Typical turbine maps for different Turbine Flow Function (TF) are shown in Fig 8.3

Turbine deterioration modelling

The component degradations responsible for the turbine performance change are the vane bowing and twist, and the increase in tip clearances. The Vane twist manifests itself primarily in turbine area changes while effects of clearance increase and vane bowing are to reduce the turbine efficiency. In-service changes of these two characteristics of turbine deterioration, viz. nozzle area change and efficiency change, were discussed in chapter 2. The flow rate is primarily determined by the nozzle areas and the effect of mechanical damage to the rotor can be simulated by reduction in the turbine efficiency with no change in the non-dimensional mass flow [SARAVANAMUTTOO,1983]. Whereas the nozzle area may decrease or increase depending on erosion or deposit, the efficiency always decreases.

The turbine characteristics have been rescaled to allow changes in the nozzle area (hence the flow) and the turbine efficiency. The turbine swallowing capacity increase and decrease has been simulated by rescaling the flow function TF by a value directly related to the change in the area in the appropriate sense of change. This technique of simulation of gas turbine engines is the bottom-up technique at macroscopic level, described in chapter 2.

Combustor

There is a negligible change in pressure drop and the combustion efficiency due to degradation of the combustor, as discussed in chap 2. The direct effects of combustor faults on the engine performance, hence, are insignificant. But the indirect effects of the combustor faults are quite significant. These include overheating of the turbine blades, increase in clearances of HP turbine, vane twist and vane bowing etc. Primarily these indirect effects arise from the combustor exit temperature distribution profile, radial and circumferential. However from the performance point of view, the deterioration of the combustor was not considered significant and hence not modelled.

Modelling the deterioration

The compressor and turbine characteristics are changed as described above, depending on the magnitude of the module deterioration, in a subroutine FOUL. The subroutine has the access to the built-in steady state maps of the program through a common data statement. Similar access is available for the user supplied maps as well. In order to change the maps again and again, for different levels of degradations, and often have clean maps for the base_line values, the program was provided two sets of maps, the first set are the stored values, either the built-in maps or user supplied, and the second set is the working maps. This does increase the storage memory size, but provide a set of reference maps to implement the degradations. When the subroutine is called with the switch IFOUL as zero, it implies that, there is no deterioration of any of the modules, and the subroutine returns the working maps with the stored map values.

When the subroutine is called with switch IFOUL "ON", the working maps are changed as described in this chapter. This facilitates the deterioration to be effected at any stage of the program run as the call to the subroutine could be from other subroutines as well. Thus when the engine run is to determine the base_line data, the characteristics have the undeteriorated values through a call to FOUL with the map degrading switch off. When the degraded engine run is made, for engine_run, transients, analysis or for simulation, the deteriorated module maps are calculated by call to the subroutine foul with the ifoul switch ON. In all cases, the subroutine is called, to establish the appropriate working characteristics, just before the call to the subroutine engine.

Computer Model

The design and off-design performance of a gas turbine can be predicted using well established techniques of component matching which are well documented [COHEN,1986]. These methods dwell around the compatibility of the flow and the power between the various components of an engine. To generate data for an engine subject to in-service deterioration, it is necessary to modify the component characteristics, changing the flow rates and the efficiency, or modify the internal bleed flows to simulate problem as excessive seal leakage or regenerative leakage. The changes in the compressors and the turbines characteristics are represented in terms of the pressure ratios, mass flows and the efficiency. Degradation of the inlet is simulated through fall in pressure recovery only. For turbine the changes in areas and efficiency could be introduced in a controlled manner to permit in-depth study of the expected behaviour of a deteriorated engine. It is implied that depending on the type of deterioration expected or to be studied, the user would input the numerical values of the degradations.

In addition to the engine faults, sensor faults could also be introduced,in the bias and the random "noise errors, thus permitting simulation of a real engine. Basic errors of measurements and the measurement system output was discussed in Chapter 5. Computer programs in general are consistent in that, same numbers are generated every time a parameter is computed. The output from a simulated engine will hence be same for same engine data points, whenever the program is run. In order to generate a realistic data, similar to that from a real engine, the engine output must be modified, superimposing the instrument model for each measurement.

A sensor model was used to simulate a wide variety of sensor measurement errors. The model used could be represented by the equation [BEATTIE, 1978] ;

$$Z_{SN} = K_{SF}Z + K_{BI} + A * v$$

where Z_{SN} - Sensor output

K_{SF} - Scale factor (assumed = 1.0)

Z - Measured variable

K_{BI} - Bias of measurement

A - Noise amplification factor

v - Noise with zero mean and normal distr.

Nag routine G05DDF was used to generate the noisy data for various instruments depending on their repeatability (the standard deviation of noise). The engine output for a simulated run of a two-shaft gas generator free turbine engine is shown in Fig 8.4 together with the typical values of the engine parameter repeatabilities shown in table II [URBAN,1975]. The mean values in the figure are the values determined by the computer program, while the scatter depends on the repeatability of the particular measurement. The values of repeatabilities given in table II were used and the standard deviation are shown in the figure. Different noise for different instruments is ensured not only in magnitude (depending on repeatability) but also in pattern. This was achieved by a call to the Nag routine G05CCF before call to G05DDF thus not allowing the computer to reset its random number generator. This allows to simulate any bias (including drift) and level of repeatability.

Conclusions

A description of the program and the method of modelling the gas turbine engine faults on computer are discussed in the chapter. The ability to model any type of gas turbine, in any of the operating modes, eg. changing design point off design, degraded state simulation, generate realistic data in the steady state and the transient conditions, and many more, make the program DETEM very versatile. The applications of DETEM can be as follow :-

1. Modelling deteriorated engine for purpose of data generation and also to study effects of various component degradations during design stage. This could be for steady state as well as under transients.

2. Single or multiple faults in any of the components can be simulated.

3. Graphical representation of the above

4. Generate realistic data continuously or at fixed time intervals.

The method of implementation of the module faults on the compressor and turbine steady state maps has been described. Various models of compressor deterioration considered in the study are described and general working of the program DETEM has been described. A detailed description of the program structure and its operation is given in the next chapter.

CHAPTER 9

DETEM THE PROGRAM

Introduction

The necessity of a computer program, that could simulate deteriorated gas turbine engines, was established in the previous chapter. Computer simulations provide the means for analysing the behaviour and the interaction of the constituent components during development of the gas turbines. Simulations can also serve as aids in understanding and solving problems that arise after the propulsion system has been developed. Generalised computer simulations allow paper studies of many different kinds of engine configurations. Many generalised digital engine simulations exist today and most of them are limited to steady state performance calculations. Since they are general their applicability is high, the user needs only specify an accurate data of the desired engine configuration.

A similar program to model all types of Gas Turbine engines, called TURBOMATCH [PALMER,1983], is available at the Cranfield Institute of Technology. Aero and thermodynamic balancing of the gas turbines, using the technique of the component matching in which the compatibility of flow between the various compressors and the turbines are established, determines the station parameters of temperatures, pressures, velocity and the component operating characteristics. The only diagnostic simulation possible on this program is that of rescaling the module efficiencies. The mass flow or the pressure tend to increase in such a model. This is not in agreement with the data observed on the degraded engines, and hence, it cannot be said to represent an accurate model of the degraded engine. The program written in FORTRAN IV is modular and calls subroutines that represent the engine modules. The program has input/output from a file and also can be interactively run when the screen is scrolling type.

The versatility of the program (and availability) influenced the thinking to develop and modify the same to model degraded gas turbine performance. The current program **DETEM** (DEteriorated Turbine Engine Model) thus originated in the Turbomatch. In its current version the program has a subroutine **engine** which is similar to the parent program only in respect of calling the module subroutines and the balancing technique.

Some of the existing modules have been modified, as well as, new subroutines have been added. The program is completely a modular with new routine written in **VAX/11 extended FORTRAN 77**. The data input and output are controlled by the subroutines input and output respectively. The changes to the component characteristics are made in a subroutine, called FOUL, that can be called from any of the subroutines or the main program. This subroutine has two functions, when the degradation switch is set **"OFF"**, the subroutine returns clean maps for all the components. But when the deterioration has to be simulated, the degradation switch is **"ON"** and depending on the level of degradation of the component its characteristic maps are changed as explained in the previous chapter.

The main program **DETEM** calls module selector which depending on the selection made, calls the subroutine **ENGINE.** The call to the subroutine Engine (which represents the gas turbine) is by the module design, off_design, transient, diagnostic, engine_run, coeff_loop ,analyser or the graf_loop. With a function associated as the name implies, these modules call the engine as and when required.

The advantages of having the part of the program, that carries out the component balancing, as a subroutine are many. In the present program the component balancing is carried out by the subroutine engine. This subroutine can be called by any of the subroutines, or the main program itself. When ever the subroutine engine is called, a new operating point of the model is determined by the balancing technique. Thus the parameters around which the new balanced condition is required, are dictated by the calling subroutine. It is thus possible for a subroutine to call "engine" with only one parameter changed slightly. The engine subroutine will return back to the calling subroutine with a new balanced condition. In the mean time, the subroutine output would have recorded the results of such operating conditions, in a file.

The new balanced point of the engine depends on the parameters changed in a particular calling subroutine. It is possible to loop a parameters to determine certain characteristics, when the subroutine is called again and again. Graphic routine, calculation of the coefficient matrix, simulation of an engine run are a few. As described in the previous chapter, the engine degradation is simulated by changing the characteristic maps. This modification of the component characteristics is carried out in the subroutine FOUL. Thus other conditions of operation remaining constant a call to the subroutine ENGINE without a call to the subroutine FOUL implies clean engine run, or determination of the base_line values, while a call after changing the characteristics is the simulation of the deteriorated engine performance.

The existence of the component matching program as a subroutine has a physical equivalence too. In case an engine has to be tested for a variety tasks, by a number of different departments, each with a different interest. Every time a particular department wants to test_run the engine in a particular mode eg. may be after an adjustment or a module swap, the run in that configuration is made, and after completion of the test, the engine is returned to its pre-test state. Similarly each of the calling subroutines could change the parameters of interest, call the subroutine ENGINE, generate the new data, return the engine to its previous state and return to the main program. Whereas the physical engine is ready to be tested by any other (or the same) department, the subroutine ENGINE can be called by any other (or the same) subroutine. The call to the subroutine that in turn calls the engine is determined by the program DETEM. The function of these subroutines is described as and when required. The hierarchy of the main program and the subroutines is given in Table D1.

The program has integrated graphics incorporated which have been developed to be called through the input routine. The user has a choice of 8 non-dimensional graphs available, to be plotted automatically, for the specified range of operation. The range is specified by the user, in terms of the limits of the speeds (rotational and forward speed i.e. Limiting Mach Number). Since the upper RPM limit is generally around 105% and the lower Mach Number limit is 0.0, only the lower RPM and the upper Mach Number are required to be input. For stationary engines, the value of Mach number is not required to be input, and if input, is ignored by the program. For aero-engines upto 10 curves are drawn in the range of the sea level Mach number specified in the range. The subroutine Graf_loop loops the engine (as described above), in small increments, to generate and plot the data automatically. The looping parameter is Mach number for aero-engines and RPM (non-dimensional) for all the engines. Thus aero-engines are involved in double loop, inner one being the RPM and outer the Mach number. The layout, size and the orientation of the paper can be decided by the user by a fairly simple selection technique. It is possible to direct the graphical output to a graphic terminal rather than a hard copy. This is through the use of character "@". Similarly the output could be prepared for the laser plotter when symbol "$" is used and "*" prepares the plot across.

The graphs depend on the type of the engine being simulated and the mode in which the engine is run. Table D2 lists various non - dimensional graphs available for power generating as well as for thrust generating engines. In the off design case, the graphs are in a single run, while in the diagnostic case the clean engine and the degraded engine performance are plotted on the same sheet thus allowing a direct comparison of the effects of the degradations to be made. In either case, if the plots are drawn singly, each on a separate sheet of paper, the design point performance is written on the sheet for reference. In addition to the 8 plots given in Table D2, for each type of engine, it is possible to plot the component characteristics being used for the compressor and the turbines. The working line is shown on the LP compressor map. It is not necessary that all the 10 graphs be plotted. The user has the control over the graph(s) required to be plotted, even though data is generated to plot all the graphs, only those graphs that are specified by the user, through the input file, are plotted. It is also possible to plot 4 graphs on 1 page for direct comparison, better representation and economy. Fig D12 shows the changes in the performance characteristics of a turbo-shaft engine as a result of the deterioration, the graphs plotted on two sheets (4 on 1) have been further reduced in the fig to be accommodated on one sheet.

When the actual characteristic of the components for the simulation are plotted, the engine running line generated, as a result of the looping for generation of the graphical data, is also plotted for off design and diagnostic runs. Fig 8.2 shows the compressor characteristics and the running line for a three spool turbo-shaft engine with an undeteriorated (full line) and a deteriorated compressor (broken line).

The main data input to the program is through a file. The layout of the input file is similar to that acceptable to the turbo-match with few changes. Since the current program caters for a higher number of options, fuel composition for example, the number of inputs in general are more. But a value of "-11" in any of the data informs the program to stop looking for any additional information for the module and equate all the remaining data to zero. This ensures that the user does not have to input data for the items of the module not intended to be used. To convert the present Turbomatch programs to DETEM only one data with a value -11 can be appended to all the data qualifying calls.

Since the primary use of the program is intended to be that of the diagnostics and simulating a degraded engine, the concept of measuring the engine output is considered essential. The program calculates engine vectors of mass flow, fuel air ratio, temperatures, pressures, velocity, area and humidity at every station. In addition component performance parameters such as efficiencies, rpms, surge margin etc. are calculated. But as discussed in chapter 5 many of these are not measurable physically and a few other are not possible to be measured with the present technology. Since the program is general and capable of simulating all types of gas turbines, the user requirements of the measurement could be different. Even for the same type of engine, each user could have a different set of instrumentation. Hence the choice of what data to be monitored and recorded separately, is with the user. The user can, through the input file, specify the parameters that are being monitored (or measured). This specification comes after the variables call and is preceded by any of the alphabets M, N, X, Y or Z. The specifications of input at each module are the same as the variables.

Another useful facility provided to the input file is the possibility of "comments" in the input file which follow the character "!". These are considered very helpful to the user, and can describe what a parameter relates to, or why a particular value and wherefrom. The program ignores the character itself and all the text that follows it. With all the parameters of measure and the comments etc, the input for each event can exceed the total screen width of 80 characters. Thus to facilitate additional line for continuation of the data, the character "&" has been utilised. Appearance of this character at the beginning of a line informs the program to treat the present set of information as a continuation of the previous statement.

The program is a user_friendly especially from the view of Input/ Output. This friendliness comes through the use of the "window" concept. The Screen Management System (SMG) on VAX/11 allows the user screen to be composed of small displays where the data are displayed. The size of each of the displays could be specified by the programmer (not the user) and the display called a window can be "pasted" to the screen at the desired location. The incoming data are directed to its window at the appropriate part of the screen, and only the required part of the display is updated. This prevent the screen from scrolling and losing other data.

The input requires the user to make a selection by moving the cursor to the field of choice, using the key pad arrow keys. The up_arrow key ^ moves the cursor to the field above, while <- -> and | move the cursor in those directions. Each field is marked with a self explanatory text. All that the user is required to do is, bring the cursor to the field of the choice. The field selected is identified by inversing the field's video when the cursor is present in the field. This helps the user to know exactly what is being selected. Acceptance of the field is on pressing the keyboard <RETURN> key.

Use of the SMG has been made in three different fields.

1. **Creation of the program input file.**
2. **Interactive input during the program run.**
3. **Interactive output during the program run.**

Creation of Input File

The program allows an input file to be prepared in an interactive manner. There are two levels of programs embedded, the first is for novices to the computer techniques and to running of the program. Basic knowledge of the gas turbines and its components is implied. For such users the engine layout, that is, the module sequence and the stations are first worked out through a series of questions/answers requiring the user input. Options at various stages are given to change the layout which is drawn on the screen of the VT100 and later terminals. The SMG concept is not compatible with the old VT52 terminals. Example of a layout for four different configurations is shown in Table D3.

Having decided the configuration of the engine for a particular use, a choice of certain selectors for the engine simulation can be made in a similar way. These parameters are the information required either to identify, at a later time, the title of the simulation or certain selector switches of the program. To facilitate easy input these are displayed in such a way that only one selection at a time from the screen is required to be made. The input is selected by moving the cursor to the sub window and accepting in the usual way of the RETURN key. Each window appears with the cursor in the default sub window. The default selection of SI units, commonly used off design run, use of AVTUR fuel, Full Print output and use of the built in maps, can be made by pressing the return key as soon as the window appears. The five windows appearing for selection of type of run, maps, units, print, etc., are shown in Table D4 in the sequence from top to bottom.

The experienced users of the program, or the users fully conversant with gas turbine layout and details, are the second type of users. They can opt right at the start and skip to this part directly. However it is assumed that all the activity above has been accomplished by them.

The data for each of the module is then required to be input. This is accomplished by selecting the module for writing the data or automatically when on the completion of the engine layout the program displays the next module. The automatic selection is not available to the experienced users, since the program has, so far, no knowledge about the configuration of their engine. The sequence is entirely derived from the knowledge of the layout the user had accepted. In each of the display, the component performance parameters are required to be input adjacent to its description. Once the data for a particular item is typed, the RETURN key indicates to the computer to move to the next data item. Characters, except decimal and R (for result) are not accepted. Help is available for each module input which describes what each module requires as INPUT. The Help can be activated by typing H or h (HELP is also acceptable).

It is possible to change the data input and the stations. Module variables and results are also indicated and every time a new selection is to be made, a prompt for the event appears on a window at the bottom of the screen. For the modules utilising results of previous modules, a separate window appears, with all the results calculated so far. Table D5 shows the layout of the turbine module input together with the help form displayed. The results calculated are displayed in a window pasted on right hand corner, an area often used to display small hints. A prompt just below the turbine module form also suggests the action or a recommended value of the input. Yet another small window on the right hand top corner informs the user of the availability of the help module. An option to change the values of the sub windows of the module is given after all the data in the sub window has been input.

The module data is followed by station vector input of the massflow, temperature, pressure, velocity, area at any desired stations. The off design data can then be input, when two windows are created, one displaying in a scrollable zone, the module data. Input is made in the other window.

The data is stored in the file OUTPUT.DAT along with comments marked by "!" as shown in Appendix D11. These comments and the text appearing after them are ignored by the program.

It may be remarked here that to create an input file for the program, it is not necessary for the user (novice or an experienced) to go through this part of the program. The input file could be created separate to the main program, with the editor. This part of the program is considered only as a helping tool. For novices, the program is useful when they can benefit the prompting and follow instructions to achieve the desired goal of building the input file. For experienced users on the other hand, this is considered to be a quick way of creating the data file with a minimum of errors. However the program for building the input, described above, is separate to the main program.

Interactive Input/Output During Program Run

The second part of the input through SMG concept is during the interactive run of the program DETEM. Initially, a choice is given where the user can select the type of program run i.e.:-

(a) Read data from the input file and write results in the file. - Non interactive. This is the default value and pressing <RETURN> assumes that the run data has to be input from the file only.

(b) To display output on the screen and accept the input interactively. The input data is either the engine data, e.g. Altitude, rpm, load etc, or the vector values of temperature, massflow, velocity.

(c) To control the engine through the engine control parameter. This allows the variation of the engine control parameter only, hence, accepts and expects only one input.

The selection is made by moving the cursor to the field of choice and accepting through the <RETURN> key. If the selection (b) or (c) is made then the input of the control parameters is through the window(s) displayed whenever the input is required. For selections (b) and (c) above, it is possible to change from one mode to the other at any time during the program run. Thus whereas the choice (b) allows any of the engine parameters to be changed (module data or the engine vectors), the choice (c) is for changing the control parameter only.

In either case the engine design point is first established. As soon as the initial design point calculations, based on the data from the input file, have been carried out, the results of the calculations are displayed on the screen.

During the interactive runs, for the choices (b) or (c), selective displays are made. The VDU screen is partitioned into small displays or the windows. Each window is capable of displaying certain data and is a VDU screen itself. The size of the window could be from 1 x 1 character to the complete screen size of (23 x 80) characters. The screen is first divided into two vertical halves for reasons explained later. Each half is further divided into smaller windows. These windows contain the display data for the appropriate run. Every time a new data is to be displayed, it is routed to the appropriate window, though the screen address system. This ensures that the data in the other displays is not corrupted or lost. Further the stationary windows ensure the screen does not scroll. The values of temperatures and pressures at the entry and the exit to each of the module are displayed in the window marked for the module.The rpms for rotating components, mass flow for intake, fuel flow for combustor, turbine power and thrust are displayed. In addition the surge margins for compressors, at the operating point, are displayed with the prompt s m .

The complete screen is divided into two halves vertically. The displays in each half is decided by the type of run. Various types are:-

Type of run	Left half	Right half	Table No
Design_pt	Design Point	New Design Pt	D7
Off-design	Design Point	Off design	D8
Diagnostic	Base line	Degraded	D9
Analyser	Observed values	Simulated	D10

Thus after the initial design point calculations only the left half of the screen displays a window as shown in the Table D7. A choice to change any of the design parameters is given at this time. The user has a window to select the option to change the design point performance or continue further calculations with the present design. If design changes are opted, the user is required to input the data to be changed and the new values. The new design point is then determined based on the previous calculations as modified by the user. The engine performance parameters and the module temperatures, pressures etc based on the values of the new design point are displayed in the window on the right side as shown in Table D7. This can carry on till the user is satisfied that the engine design point is fully established. Option for further calculations can now be made and the design point will not be altered any further.

For further calculations the user can decide the new engine mode. The choice of selection exists between various modes of engine run, viz. off-design, diagnostic, analyser, coefficient calculation, engine run and transients. Since a choice is made through a window as shown in Table D6(a). This window is displayed as and when required till stop selection is made. Change over to continue the calculations reading the data from the input file can also be made through this window, but there is so far no possibility of coming back to the screen mode from the file, neither in output nor input. The output to a hard file is always written whether the run is interactive or not.

The window layout as described in the paragraphs above, allows the user to compare the calculation result which are displayed side by side. In the off_design case for example, the design point calculations are on the left half, the right displaying off design calculations. The input to change the engine state, either through engine data control, choice (b) or the engine control parameter, choice (c), is required to be input in the windows displayed as and when required. A prompt appears in the same window describing input required. Another prompt appears at the bottom of the screen describing the format of input and other input related information.

Once off_design parameters have been input, the program establishes the new engine balanced condition satisfying the desired parameters and the results are displayed on the right hand of the screen. The screen displays design and off design performance at the same time thus allowing the user to decide what additional changes are required in the input data to achieve the condition of engine that is most appropriate. The design and off_design values as displayed on the screen are shown in Table D8. The off design calculations can continue till a selection is made to change the engine mode.

When the run mode is selected to be a diagnostic, the engine module degradations are required to be input. This is through a superimposed window as shown in Table D6(b). Arrows are used to move to the module that is to be simulated degraded. Upon acceptance of the field through the return key, the cursor moves into the display where input is to be made. The display for input depends on the the model of fouling selected. The EXIT window is the only exit. In case no module is selected to have undergone degradations, the exit takes back to the choice of run window.

When the selection of diagnostic run is made, the windows change. Left window is now the base_line values which could be design point conditions or off_design, depending on the previous calculations. In either case the display is the base_line and the degraded results are displayed in the right window. The screen output for such a configuration is shown in Table D9.

The parameters specified to be monitored, are recorded separately in a file thus saving the user the time to look around for the data of interest. This saved data can also serve as the input for analysis. The measurements from the engine serve a special purpose in the interactive mode when the display containing these parameters is high_lighted through inversing the field video. This is explained in the latter paragraphs. It is also possible to specify a limit on the parameters being measured. In case such a limit is exceeded during the engine simulation, the display becomes a blinking display drawing the intention of the user.

The display of the base_line and degraded engine performance allows the user to identify immediately the effect(s) of a particular degradation or of a combination of the engine degradations. This feature of input/output of the program makes it very useful as a teaching aid and for study of the effects of degradations.

In the analyser mode the concept of the program is to degrade the engine in all its module to a level such that the engine output in respect of the parameters monitored, matches the measured values. The left window now displays the measured parameters whereas the right window displays the results of the engine simulation. The data in the left window could be the data measured in the field (from a real engine) or that generated by another program run. The level of degradations is not displayed till the program run has fully converged. This facilitates monitoring the convergence of the program iterations. A comparison of final results of simulation and the data observed for a three shaft turbo-shaft engine, with a new HPT installed in a otherwise degraded engine, is shown in Table D10. A comparison of the actual faults is also made in the table which however is not displayed in the windows during the interactive runs.

CHAPTER 10

ANALYSIS OF THE DEGRADATIONS

Trending

In its simplest form Engine monitoring can be accomplished by directly trending the measured data. This could be carried out at any level of gas turbine operation, viz. the operator level or the base level. The basic problem with simple trending is that if a different power settings are used from day to day, there will be a large scatter in the data, even for a perfectly healthy engine. This is because of the changes in the environmental conditions (temperature and the pressure of air) and the engine power level at which a particular set of readings are made. A base_line data for comparison is hence necessary and often used. Normally the deviations from the base_line are plotted as a function of the time. The difference between the base_line data and the measurements, so plotted, is "jagged", and is not easy to be trended automatically without considerable smoothing.

Even though trending the manually recorded data is possible, various factors, such as manpower, motivation, lack of planning of log sheets, poor instrument read-outs etc, make automatic trending of the recorded data desirable. With the new generation of micro-processors, automatic trending can be carried out even at the field level, thus making it possible for the user to identify the problem and take the corrective action in almost real time. Trend analysis has a potential of extracting a large amount of engine performance information, which would otherwise be discarded. Since deterioration of the engine performance is a slow process, it is also possible to carry out prognosis of the problem, through accurate performance shift calculations.

Outlier Detection

All measurement systems may yield wild data points. These points may be caused by temporary or intermittent malfunctions of the measured system, or they may represent actual variations in the measurement. This type of error cannot be estimated as part of the uncertainty of the measurement. These points are out-of-control points and are meaningless as steady state test data [ABERNETHY,1973]. These are known as outliers and should be disregarded. To determine the outliers all data has to inspected as a continuous quality control. The identification criteria is based on the engineering analysis of instrumentation, thermodynamics, flow profiles and past history with similar data.

A program was written to analyse any type of data for the purpose of trending. The first step to trend the data is smoothing of the "jags". This smoothing effect was attained through a transfer function control in ARIMA (Autoregressive Integrating Moving Average) models. The Figs 10.1 and 10.2 show the model output trended for a few parameters in time. The amount of smoothing carried out can be varied as per the user requirements. When the smoothing or damping is low, the response is fast and large variations in the trend can be noticed Fig 10.1. For sluggish response, fairly smooth curves can be obtained Fig 10.2. It is possible to use the program to trend the data input from an outside source, for example, data milked from an engine, or trend the data generated by the engine itself. The ARIMA model used was that generated by the NAG routine G13BAF with transfer function parameters supplied from outside the program. The plotting routines are drawn using the GINO library.

The capability of the program, to ignore the outliers is quite evident from the Figs referred above. The resulting trends in measureands and/or engine condition parameters can be employed to diagnose malfunctions affecting the gas path performance or to prognosticate on when the performance will fall below an acceptable level. The utility of the overall procedure however is determined by the uncertainty intervals of the trend information.

Analysis mode

In the analysis mode the program can estimate the level of module degradation from the monitored data. As mentioned in chapter 5 there is a restriction on the number of the measurements that can be performed on the gas turbines. Thus the data available from a real engine is limited to a few parameters. Starting with these measurements the program can simulate the present condition of deterioration of the engine. Thus comparing the measured values of all the parameters for the engine the present state of the engine degradation can be determined.

For gas path analysis the measured data must be compared with an established base_line value. Establishing the base_line is equally important as obtaining the error free measurements themselves. If there is an error in establishing the base_line, it will always show itself in the degradations. Fig 3.5 shows how an error of base_line can be transferred to the implied change (fall) in a compressor. The engine base_line is developed from the thermodynamic model or from a set of measurements for the candidate engine or, more generally by a judicious combination of both. Development of the base_line was discussed in chapter 3 and chapter 8. For the present work, the base_line is the aero-thermodynamic balanced state of the gas turbine components derived through the component matching technique.

In addition to the normal errors of base_line determination, the computer simulation, because of the matching technique, has error of round-off. The off design performance is calculated based on establishing a relation between the engine variables and the errors. The errors are minimised to a level of tolerance. Thus whenever off_design performance for a particular operating set of conditions is computed the final balanced engine state is achieved when the errors are with-in a given tolerance. This would mean that two balanced states of the engine, for same operating point could be with-in a range of (2 x tolerance) of each other. The new balanced condition depends on the prior engine state. If the conditions of the engine are the base_line conditions, then the difference in the balanced states is the difference of the two base_lines. This difference is likely to be accounted in the next diagnostic run as the engine fault. Hence to ensure that the off_design base_line is always the same, a common procedure was adopted to perform the base_line run. Every time the base_line operating point was required to be estimated, the engine was run at its design point and then shifted to the off_design conditions. This increased the computational time, but ensured the same base_line values and the accuracy of the analysis.

Having established the base_line for a given engine configuration, the first step was to generate the data output of a deteriorated engine. The program DETEM was run in the diagnostic mode and with the desired level of engine degradations. The model output, in respect of the monitored parameters, was written to a file. This formed the data available from a deteriorated engine. The program could now be run in the analysis mode. The aim of the analysis run is to establish the level of the deterioration (or the faults) from the measured data available (recorded in the previous run with imposed faults). The program, at this time, has the following information :

(1)The Engine Base_line
(2)The Measured Data from the run with imposed faults

The technique applied to identify the faults was to degrade the present model (undeteriorated so far) to such a level, that it generated monitored output identical to the measured values (2) above. Thus at each level of degradation of the present model, we have 3 different set of values, i.e.

(a)The Engine Base_line Values
(b)The Degraded model output
(c)The Measured Data from the run with imposed faults

The difference between (a) and (b) is the level of the model deterioration. The difference between (b) and (c) is the error of the model, signifying the deviation of the present model from the engine being simulated. The difference between (a) and (c) is the engine deterioration that we want to identify at the module level.

The analysis is accomplished by establishing errors between the observed values of monitored parameters (c) and those estimated by the computer model (b) under similar conditions of operation. These errors are then used to alter the degradation level for each module. The errors E and the degradations X are related by the expression

$$[E] = [H][X] \qquad \ldots\ldots \qquad \ldots \quad (10.1)$$

where [X] and [E] are (n x 1) and (m x 1) column matrices. The matrix [H] is hence a (n x m) matrix. The solution of the equation is given by:

$$[X] = [H]^{-1}[E] \qquad . \ . \ . \ . \ . \quad (10.2)$$

Since matrix [H] is in general not always a square matrix pseudo-inverse may be used. Determination of the matrix [H] is discussed in detail in paragraphs under the coefficient method. For analysis matrix [H] was obtained by causing each of the degradations to be perturbed by 0.1%. The degradations were perturbed one at a time while other degradations were held constant. This empirical method of determining the coefficients was for a general application when a subroutine is called to carry out the iterations. For each compressor the degradations of efficiency and mass flow are simulated by a reduction of 0.1%. For each turbine the degradations are in the efficiency (a decrease) and the nozzle area (increase).

Since the engine has its own variables, errors and tolerance, the matched engine condition for reference as the base_line depends on the previous engine state and the tolerance. As discussed earlier, the difference between the two base_line values, as a result of matching at a different point would normally influence the error, hence resulting in a different level of degradation. To avoid this error the engine is matched at the operating conditions in exactly the same way for each perturbation. The errors thus correspond to a single point which is unique. This requires to start every time at the design point, proceed to the off design point of the undeteriorated engine and then cause perturbations. The repetitive determination of the base_line and the double looping of the iteration requires considerable computational effort, this has been further discussed in the next chapter. The results of the iteration converged for a tolerance of 0.2% are discussed in the next chapter.

Influence Coefficient Method

Thermodynamic model, described in the previous chapter, could be used to identify engine health, and also be used to predict the effects of component models on the complete engine. However the analysis by the thermodynamic methods, described above, are iterative in nature, hence the computational requirement is often high. Once the engine model is complete it can be used to generate (1) base_line data (simulating engine without deteriorations), (2) raw_data (simulating real engine data), and (3) the fault coefficient matrix. This fault coefficient can then be utilised to identify the faults. To diagnose the raw data (measured values), following steps are required :-

1. The raw data has to be corrected to reduce to standard conditions of operation including those of power off-takes, bleed etc.

2. Installation correction factors are to be applied which will account for pre-body and aft-body effects or mis-alignment etc.

3. Gross deltas from base line are calculated for all parameters of measure.

4. The apparent error in each sensor is calculated as a function of the set of gross deltas.

5. Gross deltas are adjusted for these errors to yield the net deltas (error free deltas).

6. The module performance deviations and other performance parameters of interest are calculated.

7. Overall engine diagnosis, sensor fault isolation and module health diagnosis is carried out.

Method of Determining Fault Coeff Matrix

Even though the interest of the GPA is in determining the physical faults such as component efficiencies and flow capacities, the engine diagnostic system has to rely on discernible changes in the observable parameters in order to detect the physical faults. The relation between the changes in the physical faults X and the changes in the measurable parameters Z can be written as (chapter 3 and 6):

$$[Z] = [H][X] \quad \ldots\ldots\ldots \qquad (10.3)$$

The influence coefficients matrix [H] must therefore be known before an attempt is made to solve the equation. A general coefficient matrix can be derived for any particular gas turbine cycle using two different methods, the **theoretical** method and the **empirical** method. Both the methods to determined this matrix viz Analytical and Empirical, were adopted in the program.

The analytic technique is based on the relationships between the physical faults and the measurable quantities. Equations relating the dependent variables (measurable quantities) and the generally non-measurable independent component performance variables, can be established for each type of engine. once these differential thermodynamic equations are formed for the engine, then their differential forms are manipulated to determine certain coefficients. This manipulation takes into account factors such as component efficiency variations, specific shapes of component performance maps, engine power balance, conservation of mass, energy and momentum, variable specific heat effects, nozzle unchoking effects etc.

A matrix, formed by these coefficients, represents a set of linearised equations in a form that interrelates various dependent and independent engine performance parameters. Such equations for a turbo-shaft engine with a 2 spool gas generator are given in Appendix E. Use is made of these generic equations and the coefficients are determined. A simplified tabulation of the coefficients can be used, Table E1 [Urban, 1971], shows a generalised chart of inter-relationship between engine components. These coefficients are normally valid for a given condition and hence have to be recomputed for all different points of operation.

Linear interpolation of the coefficients between a few selected conditions of operation can give a good approximation, provided the points are close to each other. The hand calculation of the coefficients is a tedious process. Further to avoid the loss of accuracy due to interpolation, the coefficients can be determined at each operating point by the computer. A computer program was written to evaluate the influence coefficients for a 2 spool high by-pass non-mixing turbo-fan engine. Table E2 shows the computed values of the coefficients for the design point operation of the above described turbo-shaft engine. Similar coefficients were derived for a two spool split shaft, industrial gas turbine engine. The results of the calculation are given in table E3. The coefficients, when calculated with the help of Table E1 are given in Table E4.

The analytic technique requires a lot of data which is normally derived from the component characteristics. Also, the equations of modelling the components and the engine are typical to each type of engine. Hence the program to generate such coefficient matrix has to be re-written for each type of engine. This calculation of the theoretical coefficients is quite tedious and requires computational effort. In general it is time consuming and difficult to determine the coefficients theoretically over the complete operating domain. Hence these are computed in the low, medium and high power conditions at sea level static conditions [KOS, 1974] and a linear least square line is fitted to this data. Coefficients at other operating conditions are then interpolated. Further the evaluation and utilisation of the matrices is dependent on the instruments utilised to monitor. Hence a change of instrumentation will warrant re-evaluation of the matrices.

An alternate approach, is to use the simulated engine model for calculating the fault influence coefficients. Use is made of nominal base_line engine data as well as steady state engine data with known, deliberate small perturbations. Suppose all independent variables, (the factors of degradation viz mass flow, efficiency, area etc), except one are held constant, their variations (deltas) will hence be zero. Thus the deviations the measurements show from the base line are due to the non zero parameter only. Now if this parameter was to have varies by say, 1%, then the % differences of the measurements from the base_line values is same as the corresponding influence coefficient. The value of the influence coefficient thus can be directly derived from the % of the measurements deviation under the test. Appendix F shows the determination of one set of coefficients by empirical method. The resulting influence coefficients of the independent variable as a result of the known perturbation will thus form the respective column of the matrix.

Similarly the other columns can be generated. For this purpose the engine is run alternatively in clean and degraded condition. The clean engine run establishes the base line operating point and is always after a run at the design point to eliminate errors in the base line determination. Only one degradation for one module at a time is introduced, while other values are held constant. Component efficiencies are reduced by 1% and areas are increased by 1%. For the degradation introduced, the differences in the monitored parameters determine the respective column of the fault coefficient matrix.

The matrix so developed is the Influence Coefficient Matrix. This matrix is dependent on the engine layout and the number of measurements taken. In general thus, for n measurements (other than the control parameter) the fault coefficient matrix for an engine with m parameters would be a (n X m) matrix. The first column (n X 1) will be developed when all the engine faults are null except the first. Similarly in the next loop of calculations the second column of the matrix will be calculated when only second degradation parameter is non-zero. Such a matrix for a 3 Spool turbo-shaft engine where, 10 parameters would define the engine's degraded state, the matrix calculated by the program, corresponding to 10 measurements is shown in table V. Table VI shows such a matrix generated for a two spool turbo-fan engine with 9 measurements. The faults are 10 (six for the three compressors and four for the two turbines).

Once the numerical values of the fault coefficients are determined, applying them to the engine diagnostics is relatively straightforward. In general for m faults, at least (m+1) measurements must be made. One measurement, usually N1 or the EPR serves as the base_line abscissa parameter against which deviations of the other parameter from the base line are computed.

In the first case the instrument non-repeatabilities and the engine generated scatter was set to be zero. The engine run was made and certain faults imposed. The measured parameters were recorded separately. The matrix of table V was then utilised to analyse the faults imposed on the engine. The results of the analysis are presented in Tables VII-XV. The faults were imposed singly and in combination. Influence of the number of measurements and the parameters measured was studied. The results are presented and discussed in the next chapter.

This simple technique of Influence Coefficient Matrix, does identify, fairly accurately, the faults that appear singly and in the region of the value of fault used for determining the FCM. It was brought out in chapter 6 that the detectability of the faults is shadowed by the noise in the measurements, and the engine performance noise. This introduces additional faults @ 1 per measure. Thus the engine faults are increased by a number equivalent to the number of measurements.

Since the engine operation cannot always be under standard atmospheric conditions, the raw data must be standardised. P_{in} and T_{in} are normally used to standardise the measured data. In addition the engine performance requires a control parameter, which allows the engine to perform at a particular performance. These three parameters must also be measured, and their measurement introduces errors because of their sensors. The number of unknowns is yet again increased by 3.

A method which can adapt to the requirement, whilst still using a small number of sensors is based on a state estimation technique and uses statistical analysis to enable fault discrimination to the module level. One important advantage of this technique is that the correlation of the data is possible not because the specific relationship is known but purely that it is a fact that the parameters are related to each other. The theory of the best-estimate solution for the present problem of too few known and too many unknowns was built in chapter 6. The engine deviations have been modelled in vector notation, and can be represented as :

$$\mathbf{Z} = \mathbf{H}_e \mathbf{X}_e \quad \text{and} \quad \ldots\ldots \quad (10.4)$$

$$\mathbf{Y} = \mathbf{G}_e \mathbf{X}_e \quad \ldots \ldots\ldots \quad \ldots\ldots \quad (10.5)$$

As described earlier, even with highly accurate sensors some kind of errors or "noise" can be expected. This introduces a vector of "apparent" sensor errors $\mathbf{X}_s$ which accounts for the main gas path parameters, inlet parameters (used for reducing data to standard conditions) and the base parameters. Thus our basic model (eqn 10.4) then becomes :

$$Z = H_e X_e + H_s X_s + v \quad \ldots \quad \ldots \quad (10.6)$$

$$Y = G_e X_e \quad \ldots \quad \ldots \quad (10.7)$$

The matrix Hs is a (m x (m+n+3)) matrix of "sensor fault" coefficients and other symbols have been defined. This can be simplified to give a simultaneous solution for $\mathbf{X}_e$ and $\mathbf{X}_s$ by concatenation as :

$$\mathbf{Z} = H\,X + v \quad \ldots\ldots \quad (10.8)$$

$$Y = G_e X_e \quad \ldots \quad \ldots\ldots \quad (10.9)$$

where

$$x = \begin{bmatrix} X_e \\ \hline X_s \end{bmatrix} \qquad , \qquad H = [\ H_e \mid H_s\ ]$$

these are composed as shown below. The abscissa parameter Π has an influence on all the parameters as also the basic sensors of non-dimensionalising values.

$$\begin{bmatrix} Xs \end{bmatrix} = \begin{bmatrix} \text{N1sens} \\ \text{N2sens} \\ \text{P3sens} \\ \vdots \\ \text{Tnsens} \\ \text{T2sens} \\ \text{P2sens} \\ \Pi\text{sens} \end{bmatrix} \qquad \begin{bmatrix} Xe \end{bmatrix} = \begin{bmatrix} \Gamma\ \text{LPC} \\ \eta\ \text{LPC} \\ \Gamma\ \text{HPC} \\ \eta\ \text{LPC} \\ \cdots \\ \text{ALPT} \\ \eta\ \text{HPT} \\ \text{ALPT} \\ \eta\ \text{LPT} \end{bmatrix}$$

The column headings of H_s refer to the deviation of the individual "raw" measurements while the row values refer to the aero-corrected component of Z. The sub-matrix (m X m) starting with (n+1)th column is an identity matrix. The identity submatrix indicate that a deviation in main gas path parameter produces a deviation only in the corresponding 'corrected' parameter, whereas a change in the inlet or the abscissa parameter affects all components of Z according to the aero-correction relation or the base line generation relation.

The matrix He and Hs are determined in the subroutine Coeff_loop, where steady state characteristics at the engine operating condition are obtained with known perturbations introduced one at a time. This method has been explained earlier in the chapter. The sensor coefficients matrix is also determined at the same time and in a similar way. Here the control parameter, the inlet pressure and the inlet temperature are varied by 1% and one at a time. The sensor coefficients depend on the parameters monitored and first m by m elements are an identity matrix, and columns m+1 to m+3 are determined by the above perturbations. The empirical matrix derived by perturbing the balanced engine condition through the degradation of each component (one fault at a time) for a 3 shaft Turbo-shaft engine are given in Table XVII.

The fault influence coefficient matrix [He] and the sensor coefficient matrix [Hs], determined above, form the

[H] matrix.

$$\underset{(m \times (n+m+3))}{[\ H\ ]} = [\ \underset{m \times n}{He} \mid \underset{m \times (m+3)}{Hs}\ ]$$

Thus in order to obtain a unique estimate of the n unknowns, we must have at least n (= m) measurements and precisely all the n measurements must be linearly independent. if we have exactly n independent measurements, then H is a (n x n) non-singular matrix and we can carry the solution a step further with the knowledge that the inverse of a product of two or more non-singular matrices is equal to the product of their inverses in reverse order and obtain :

$$X = H^{-1}W^{-1}(H^T)^{-1}H^TWZ = H^{-1}Z \quad \ldots\ldots \quad \ldots(10.10)$$

for a system of measure the weighting matrix can be taken as the inverse of the covariance of the random errors $W = R^{-1}$ and this gives the solution as eqn. (10.10)

Two possible solutions can be considered the weighted least square solution, and the best-estimate solution. Thus

$$X = (H^TR^{-1}H)^{-1}H^TR^{-1}Z = DZ \quad \ldots\ldots \quad \ldots (10.11)$$

where $D = (H^TR^{-1}H)^{-1}H^TR^{-1}$ is called the **Diagnostic Matrix.** gives the weighted least square solution while the other solution, for the value of x (denoted x) which maximises the conditional probability distribution function p(xz) (probability of **x** given that Z has occurred, is given as

$$X = X_o + D\ (Z - HX_o) \quad \ldots\ldots \quad \ldots. \quad (10.12)$$

Here $\qquad D = P_o\ H^T\ (\ H\ P_o\ H^T + R\ )^{-1} \quad \ldots\ \ldots\ (10.13)$

This requires **a-priori** (known previous to analysis) some statistical information regarding **X** and **v** viz. their mean value and the level of scatter (i.e. P_o and **R** respectively). The matrix **D** relates the independent fault variables to the measurements and thus represents a pseudo inverted set of engine/sensor fault coefficients.

Where X_o denotes the expected value (mean) of X

i.e. $\qquad X_o = E(X_o) \quad \ldots\ldots. \quad (10.14)$

then the estimation error e is defined as

$$e = X - X_o \quad \ldots\ldots\ldots \quad \ldots \quad (10.15)$$

and the symmetric positive semi-definite covariance matrix of the estimation error is given by

$$P_o = E([X-X_O][X-X_O]_T) \quad \ldots. \;\; .. \;\; \ldots \quad (10.16)$$

An alternate expression for P_o is in terms of the diagnostic matrix as

$$P_o = DRD^T \quad \ldots.. \quad \ldots.. \quad (10.17)$$

The elements along the main diagonal of the matrix P_o are the variances of the estimation error. We have assumed that the mean and covariance of v are known and given by

$$\text{mean} = E(v) = 0 \quad \ldots\ldots\ldots \;\; \ldots (10.18)$$

$$\text{Covariance} = \text{cov}(v,v) = E(v,v_T) = R \quad .. \quad (10.19)$$

where R is a symmetric (m x m) positive definite matrix.

The number of problems is now more than the number of equations, we have m measurements and (n+m+3) unknowns. The solution is however possible by best estimate technique explained earlier. In order to use equation 10.12, X_o, R and P_o must be known. The vector X_o is an a-priori estimate of the percent deviations in the engine/sensor independent faults for a particular engine in question. This matrix is developed with the help of the knowledge of the deterioration in service as a function of time or number of cycles etc. In the absence of any information nominal values can be assumed, when X_o can be taken as zero matrix. In that case the system will isolate the deviant modules and measurement errors but may tend to either under-assess or over-assess the actual magnitudes. The matrix R is obtained from instrumentation repeatability statistics and the relations contained in Hs.

The matrix R is formed from the knowledge of the sensor repeatabilities data. In its simplest form it is the variance - covariance matrix of the instrument noise discussed in chapter 6. Assuming the noise to be uncorrelated all elements except the principal can be taken as zero. The principal diagonal is the value corresponding to σ^2 where σ is the repeatability of the sensor. Thus the matrix is a diagonal matrix of dimension (m x m) with each element i,i of the diagonal given by the relation :

$$R(i,i) = \sigma_i^2 \quad .. \quad . \quad . \quad (10.20)$$

We have seen that for gas turbine diagnostics we have the engine module deviations and sensor deltas as variables and of course a set of measurements. The matrix D relates the independent fault variables to the measurements and thus represents a pseudo inverted set of engine/sensor fault coefficients. The main task of the diagnostic program is to estimate the changes in the module performance from some reference point, the "**base line**", that represents the expected performance of a nominal engine operating in a noise free environment with nominal exhaust nozzles and some assumed level of engine air bleed and power off take. These conditions of operation are unlikely to be maintained in real life when in addition to module deterioration, non-nominal fan and/or core nozzle areas, overboard and cooling bleeds, Reynold's number, engine intake and bed configuration, the instrument non repeatability etc. contribute to the magnitude of the observed gas path parameter. The measured parameters require to be corrected for these effects before they can be used for estimating the module deviations.

Determination of the state vector covariance matrix $\mathbf{P}_o$, is not easy, [VOLPONY,1983]. Either a lot of data on engines is gathered and analysed statistically for the most probabilistic occurrence of a fault. The second approach allows equal detectability of each of the engine/sensor faults. This is an ideal, fictitious statistics approach which assumes that all the faults can occur with equal probability.

The covariance matrix of the measurement deltas, based on the sensor non-repeatability errors is determined next. For a perfect abscissa sensor the dependent parameter delta would be independent of each other and the covariance matrix of the measurement deltas would be an identity diagonal matrix. But for the real cases (non-ideal), whereas, for n measurements, the first (n X n) matrix is an identity diagonal matrix, that is the measurement affects only itself, the columns corresponding to the abscissa and inlet parameters are not necessarily zero.

The matrices involved in the estimation of the true level of degradations from a limited number of corrupted measurements have to be worked out before an attempt to solve the equation. So far we have only the values of [Z] the (m X 1) vector of the measured values. The estimation of other matrices is worked out in the succeeding paragraphs.

For the compressor modules, since it is possible to have either two independent parameters viz mass flow (related to area) and efficiency, or an additional parameter of pressure ratio, the type of deterioration model determines the characteristics changed. The monitored parameters are the users choice and can be changed through input data. In general independent characteristics for compressor are the mass flow and efficiency, and turbine flow function and efficiency for turbines. This means that the columns of the influence matrix are twice the number of compressor and turbine modules. It may not always be possible to have same number of measurements available, thereby forming a (m X n) matrix with m rows (= number of measured parameters) and n faults.

The state vector covariance matrix is typical to each type of engine, and its determination is not straightforward. At the manufacturer level a large amount of data is collected for the engine type to derive a probability density function for the module degradations and the sensors. This pdf distribution basically determines the mean level of degradation at for each module of the engine with usage. This data and its processing makes the state vector covariance matrix and its evaluation, a propriety item [BARWELL,1987, URBAN,1972]. In the absence of such data, hypothetical pdf distributions for a representative twin spool turbo-fan engine was assumed. Fig 10.3 and Fig 10.4 show the distributions of the pdf, with respect to count (cycles, starts,time or hours) for various modules. Based on these distributions, for each module, the deterioration was determined. The engine was then run with these values of the degradations and the overall performance of the engine determined.

The computer program has capability of modelling sensors and hence generate realistic data. The monitored parameters for the above mentioned representative engine were hence generated through the engine run. At the same time the sensors faults were also imposed. The sensors followed the failure probability rate according to their own pdf's (hypothetical). This data was then utilised to develop the covariance matrix for the representative engine which is given in Table XVIII. The determination of the covariance matrix in the present case, was based on 500 run points only.

The matrix of the estimated values [X_o], composed of two sub matrices, viz the expected level of degradations and the expected dependent values (monitored). The level of degradations for the module faults and the sensor failures were determined from the pdf's with small variations from the mean.

The measurement matrix [Z] was also generated by the program separately with *a different level of degradations*. This generated data (m elements of measurement) was then used to analyse the degradation level and errors of measurement system.

Once all the element matrices of the equation are determined the solution of the equation is straight forward. For this purpose Nag routines F01CKF and F01AAF were used to determine inverse and for multiplication of matrices.

Starting with the degradation probability distribution function shown in Figs 10.3 - 10.4 the data of degradations at various life times was calculated. For each of this data point and the level of degradations accrued, the parameters, which would be monitoring the engine and provide data for analysis, were used to record similar data. In addition the values of the control parameter, taken as abscissa, the inlet temperature and pressure were also recorded. The run data was then analysed to compute the variance-covariance matrix. The elements of the diagonal of the matrix are the variances S_{ii} whereas the elements i,j is the covariance of X_i with X_j. The matrix is symmetrical about the diagonal. Since this is a variance- covariance of deltas, the measurement errors do not effect each other. Hence the non-diagonal covariance of measurements were assumed to be 0. Such a matrix is given in table XVIII .

The solution determined for the engine is in the form of the fault coefficient matrix defined as the "INVERTED" Fault Coefficient Matrix of the engine and the sensor faults. The calculated inverted engine/sensor fault coefficient matrix is given in Table XIX.

Review

Apart from trending the engine parameters, three techniques of the gas turbine engine fault identification have been utilised. The iteration technique using the thermodynamic computer model, does not require prior knowledge of the engine degradation history, but an accurate data and the base_line. Accurate results are possible with this method, though the computational efforts appear to be a bit high. Identification of new modules in a deteriorated engine and vice versa is possible with this technique. The technique of Influence coefficient Matrix has been used, with matrices developed analytically as well as empirically. Single faults could be accurately identified, but when the faults were in combination, the identification showed smearing.

A statistical best estimate technique with hypothetical failures distributions for a representative engine was evaluated. The covariance matrices have been evaluated and the inverted fault coefficient matrix evaluated for a case where the number of measurements is less than half the number of faults present.

CHAPTER 11

RESULTS AND DISCUSSIONS

The primary task defined was of developing, either a new program or modifying an existing program to simulate deteriorated gas turbine engines. The program should be general in nature and a user friendly. This task has been accomplished and the existing, general program, Turbomatch has been suitably changed so that it can accommodate model of deteriorated gas turbine. The program developed is called DETEM (DEteriorated Turbine Engine Model). The parent program has been retained in the program as a subroutine (with a few alterations).

The primary advantage of making the program Turbomatch a subroutine was to have a complete modular concept of the program. For the identification of the faults in a gas turbine engine, through performance analysis, two sets of data, the base_line and the degraded engine values must be available for analysis. This could be possible with-in a program, when first pass is made with a switch (corresponding to deterioration) OFF and thus simulate the base line. The second pass could then be made with the switch ON (i.e. Degraded condition). Alternatively this could be accomplished by incorporating the component matching in a subroutine. The advantage in this case would be, apart from a modular set-up, that the subroutine could then be called from with-in the other subroutines.

Right from the start the problem of the deterioration of various modules was identified as change in characteristics of the flow capacity, pressure ratio and the module efficiency (chapter 2). Hence to simulate a deteriorated engine, the program should be able to change these parameters independently. From the results of various studies available (chapter 2) it was realised that degradation of characteristics may not be possible to be achieved through the use of a linear scaling factor alone. The changes in the components are not of the same magnitude across the entire range of the variable, and the variations of the parameters may not necessarily be in a fixed ratio to the value, but a varying ratio with the magnitude of the parent parameter. For example in Fig 2.31, the mass flow at surge is almost same till 100% RPM and decreases for higher speeds. Hence appropriate empirical relationships between parameters were established that would simulate a deteriorated engine.

Turbomatch, like similar general programs, uses steady state maps that determine the module characteristics, and the technique of component matching to arrive at an aero-thermo dynamic balanced solution. Thus for a normal (undeteriorated) and for the degraded engine, the same technique of component matching could be used. This implied simulating the degradation by matching the degraded engine modules, which in turn are changed in their characteristics by the changes in the maps.

The main module characteristics that are effected by the degradations are the flow capacities, pressure ratio and the module efficiency. For each module all the three could be specified and the module characteristics changed. It was seen in chapter 2 that the degradations across turbine can be expressed in terms of flow capacity and efficiency. Thus whereas turbine deterioration could be modelled by two parameters, mass flow and the efficiency, in general the compressor requires an additional parameter of pressure ratio. These three parameters for compressor allow the degradation model of the compressor to be controlled by the user. Fig 11.1 shows the compressor chracteristics that have been modified by different values of degradation. The original characteristics are drawn in full line. The characteristics in the upper map are deteriorated by 3% in pressure ratio, 3%in mass flow and 2% in efficiency. Lower maps are achieved through 5% decrease in pressure ratio, 3% in mass flow and 2% fall of efficiency. The user can thus specify different values of the three variables till to achieve the desired characteristics.

Unfortunately, this means that, when the program is used to identify the faults in a compression module, and the faults are represented by three parameters, we would require an higher number of measurements than the case where the characteristics could be represented by two variables. The limit on the number of measurements in the gas turbine is quite serious. Hence the modification to the compressor characteristics was brought about in such a way, that only the changes in the flow capacity and the efficiency could define the compressor module deterioration. It is not possible to arrive at the deteriorated compressor characteristics by mass flow and efficiency alone (i.e. without altering the compressor pressure ratio). Fig 11.2 represents the deteriorated compressor maps when the pressure ratio change was 0%, mass flow change was 3% and the efficiency change was 2%. Similarly the mass flow also must be changed (reduced) for simulating the observed effects.

From the tests on the compressors, it was established (chapter 8) that the working line does not shift as a result of the deterioration. Hence, the pressure ratio changes could be represented as a function of the mass flow change. A similar technique has been used [DUPUIS,1986] for modelling J57 engine. The concept of changing the pressure ratio and the mass flow as a function of each other, could be transferred to the characteristics, either through the slope of the working line or certain restrictions such as mass flows at the surge point.

The development and implementation of these empirical relations were discussed in chapter 8. The characteristics of the turbine and the compressor modules could hence be represented by changes in the mass flow (or area) and efficiency. The turbine characteristics are varied by linearly changing the value of the Turbine Flow Function. For compressor three models of deterioration are available in the program. When the variable MODEL, specifying the model is equal to 2, the user can modify the characteristics through all the three parameters, viz. the pressure ratio, the mass flow and the efficiency. For model = 1 the slope of working line is taken as unity and pressure ratio is deduced from mass flow. Fig 11.3 shows the compressor characteristics for a three spool gas turbine with model = 1 and mass flow reduction of 3% and efficiency decrease of 2%. The lower half of the Fig shows the compressor characteristics when model follows the observed restriction of mass flow at surge, as discussed in chapter 8, and model is less than zero. The changes in this case were also 3% of mass flow and 2% in efficiency. The changes in the efficiency maps are shown in Fig 11.2, and are the same for all the models of deterioration.

The combustor normally does not undergo significant changes in performance parameters, pressure drop across the combustor and change in combustion efficiency. The combustor deterioration thus has insignificant direct effects on the engine performance, but the indirect effects are significant. The primary faults in the combustor can usually be detected by monitoring the turbine exit temperature spread.

Having established the switch between the clean and deteriorated components, Turbomatch subroutine could be called for matching the components in clean configuration, or the deteriorated configuration. The change of component characteristics is always before the call to the component matching subroutine ENGINE. The component changes were carried out by the subroutine FOUL, thus allowing the main program to call for the degradations or call clean characteristics. When the ENGINE was called by the program DETEM with clean characteristics it was to establish the base line parameters, while with modified component characteristics the run was considered deteriorated.

This modular concept of the subroutines had its advantage in that, the subroutines could be called by any of the subroutines. This facility was utilised to generate the data for graphs, when the subroutine graf_loop could call the engine at various speeds (rotational and forward) as applicable to the model and the user requirement. Figs 11.4 and 11.5 show some of the graphs that could be plotted for a thrust generating and a power generating engine. The integrated graphics for non-dimensional parameter plotting are selected by the user, but plotted automatically by looping in a specified range of the engine speed and the platform speed. Similarly the program could generate coefficients for analysis by matrix method by causing small perturbations in the degradations and calling the subroutine ENGINE in a loop till all the coefficients of the matrix are determined.

This concept of being able to simulate the engine in clean and in deteriorated condition was further utilised to run the model for simulating the engine transients in clean and in deteriorated state enabling the effects of deterioration on transients to be studied. Fig 11.6 shows the effects of degradation on the transients. The results are discussed later in the chapter.

The Gas path analysis must have the two sets of data, base_line and deteriorated engine, and be able to compare the two data. The basis of the gas path analysis is the implied changes brought about by the degradations. Comparison between the data generated for base_line and for deteriorated model was accomplished through the screen management technique. VAX allows the output the VDU screen to be controlled by simple address system. Using such a system does not involve any library. The engine data from the runs could be represented simultaneously on either of the vertical halves of the VDU screen. Not only is the data displayed simultaneously, but the incoming data can also be routed to the appropriate part of the screen, so that only the affected area is updated. This avoids the scrolling of the screen. This technique of the output representation is quite similar to the concept of modern instrumentation, where only one display can cater for all the data. However, in that case the user selects the data to be displayed whereas in the present case all the data to be displayed was decided in the program. For all the modules the inlet temperature and pressures, outlet temperatures and pressures , rpms, fuel flow, essential engine outputs and the surge-margins are displayed. A detailed description has been included in chapter 8.

The Deteriorated Engine Model

The necessity of modelling the gas turbine deterioration as discussed in chapter 8. The program DETEM can model any gas turbine engine and its degradation. The effects of the engine degradation can be seen during the program run through the screen management of the data on the screen. This has an advantage, in that the user has immediately, the knowledge of the deteriorated engine performance and the effects of certain degradations. Since the faults are controlled, a study of the degraded performance can be made at any stage of development, for a real engine or a paper engine.

The program output could be used to demonstrate or study the effects of any desired faults either singly or in combination. The program is considered to have a potential for teaching.

The results can be output graphically which allows the user to better interpret the effects of the faults. A total of 8 non-dimensional graphs for the engine and in addition the component maps could be plotted with a variety of choice. Fig 11.4 (a) and (b) shows a few of the plots for a two spool turbo-jet engine. Degradations of 1.5% in massflow and 1.2 % in efficiency were imposed on the LP compressor and 1% and 0.75% on the HP compressor. Only four out of the eight plots ar shown in the figure and the plots have been reduced to half size. The effect on Net Thrust of the engine at all Mach numbers and rpm can be seen. Similarly the effect on s.f.c is clear. The loss of net thrust, and increase in s.f.c would justify maintenance action to restore the engine performance. It is seen from the figure 11.4(a) that whereas the operational thrust could be obtained at very high engine speeds, this is neither advisable from stress point of view, nor economical, as seen from the s.f.c plot, which shows very high increase in the s.f.c at high rpm.

Similar results for a three spool turbo-shaft engine are shown in Fig 11.5. The engine degradations for these figures is given in table 22. The decrease in mass flow and changes in the shaft power are quite significant. But the increase in the engine s.f.c is very predominant. The figure also exhibits the advantages of having all the plots on one sheet, for a better comparison.

Using the model, it is possible to build a diagnostic set which can be the basis of a fault tree. Tables 20 and 21 show such a diagnostic tool built up as a result of the program run. Each of the faults was imposed in turn to the value as described in the tables, and the diagnostic matrix built. This type of diagnostic matrices can then be converted to fault tree, from which rules for a data base can be derived. This rule generation aspect, makes the program a potential for application of the expert systems in gas turbines. The applicability of such a system was discussed in chapter 7.

Input Output File Generation

Using the technique of the screen management, a program was developed that could generate input file to the main program DETEM. This program starts at two levels,(1) a novice, with basic knowledge of gas turbine engines and (2) an experienced user of the program. The program, depending on the level of the user, goes step by step, prompting and helping at each step by displaying additional screens (windows) on the VDU that contain required information of help or for input by the user. The program creates a file that can be used as input to the program DETEM.

Analysis Program Results

The Third part of the program carries out analysis of the data, to identify the engine module deterioration. The fault can thus be imposed on the simulated engine, which will cause the operating point to shift. Various engine parameters can be monitored from such a simulated model and represent the measured values. The program DETEM incorporates provision of the user selected output to be recorded separately in a file. These parameters are nominated by the user in the input data, and are identified by the preceding alphabet M,N, X, Y or Z. Thus not only is it possible to monitor the measurable quantities, but even unmeasureable ones could be recorded. For example, it is not possible, in general, to measure the TIT, but the calculated values of TIT can always be output from the program. This output data represents the data of a deteriorated engine.

To analyse this data for identification of the faults, any or all of the following techniques could be used.

1 Trending the data by the program
2 Iterative Analysis
3 Analysis by Influence Coefficient Matrix
4 Statistical best estimate

Four types of gas turbine engines were studied for analysis viz two and three spool turbo-shaft engines, two spool turbo-jet engine and two-spool turbo-fan engine. The data for the degraded engine was first generated by the program DETEM when known deterioration was imposed through characteristics. Only the user defined monitored data was then utilised for the analysis. The analysis program hence did not have any information of the expected values of the faults to be identified. Apart from this data, the only information the analyser program (DETEM in the analysis mode) had was about the engine configuration and the design data.

For the iterative analysis the faults in respect of a three spool turbo-shaft engine and a two shaft turbo-shaft engine are shown in TABLE 22 to 26. The tolerance set for iteration to be considered completed, was 0.2%. An accurate identification of the faults can be seen from the table. The program output of the degraded engine simulation and the converged values, for the three spool iterations of Table 22 are shown in Table 24. Tables 22 and 23 show the iterative performance of the program as a thermodynamic model for a three spool turbo-shaft engine. In Table 23, the HP turbine module was simulated to have been changed to a new. The fault detectability of the program proves itself in the results from the two tables.

Table 25 and 26 show the capability of the program to identify faults and the presence of the new modules in two shaft engine.

For the iterative analysis, the program follows a double loop. The first or the outer loop is when the level of degradations is altered and the errors against the measured data are checked to be within the tolerance. For each of the new degradation levels imposed, the subroutine ENGINE is called that re-matches itself to the new operating conditions and thus performs the inner loop. This double loop is considered to be time consuming and does require high computational effort. However the program does not depend on any data, other than the measured values and the information about the type of engine being modelled.

Matrix Method

The second technique of analysis adopted was that of generating the Influence coefficient Matrix through perturbations, and then utilising this coefficient matrix to identify the engine degradations. This technique was applied to a three spool turbo-shaft engine and the results of the analysis are shown in Tables VII to XVI.

The coefficient matrix is determined by the program, if the coeff_find switch is ON. Causing a variation of the degradation, from 100% level, in each of the variable singly, the changes observed in the measured parameters are the coefficients. The influence coefficient matrix is given in Table IV to VI. Table VII (a) to (e) show the results of analysis when the faults were imposed singly and each to a value of 1% (the same value as the magnitude of the perturbation caused to generate the matrix of table V. Table VIII shows combination of faults of LP compressor and LP turbine. Table IX shows LP compressor fault of mass flow of 0.4%, and the analysis when all the faults of all the modules were imposed, each to a value of 1% in the appropriate sense.

The detectability with the use of the matrix is with in 0.5% error when the faults are single and in the vicinity of the value of the variation imparted to generate the matrix (1% in this case). The effects of a combination of the faults, in small and large values (all together and each at 1%) were calculated and are presented in Table IX. Large errors arise because of the deviation of the engine from the operating point at which the initial calculations were made. Recalculation of the coefficient matrix, would basically align to the technique of the computer iteration discussed in the last chapter.

The effect of accurate determination of the engine base_line was studied by implanting faults one after another. The engine was returned to the base_line balanced state after every fault. In total four faults were imposed each to a value 1% (for comparison with previous results). Table X, XI and XII show the results.

The effects of the number of instrumentation can be studied with the help of the coefficient matrix. The number of measurements was reduced from 10 to 9 and the faults re-evaluated. The coefficient matrix in this case need not be recalculated since removing a measurement has the same effect as eliminating a row of the coefficient matrix. This reduced matrix, was then used to detect similar faults as in the previous case. Not presenting all the results, a few representative ones are shown in table XIII, for comparison of the effects. The error is far increased with increased "smearing". The solution to the equation with less number of measurements than the sought faults is based on the method of Least Squares using the NAG routine F01JDF.

The effect of different instrumentation can be studied with this simple matrix before approach to an elaborate system, as developed in the next chapter, is made. Table XIV shows the effects when one of the instruments was changed. The pressure probe between the HPT and the LPT was replaced by a probe to measure the power turbine exhaust temperature. The effects on the detectability for a few representative cases are shown in Table XV. The error when all the possible degradations are of a value of 1%, is approximately 300% vis a vie 180% in the first case.

The results show the identification of almost all the faults imposed to a value 1% singly except the fault of the turbine efficiency Table VII(e). This undetectibility of the fault by this method is attributable to the measurements chosen. The parameters down stream of the power turbine were not monitored. Whereas the swallowing capacity of the turbine does affect flow on the components upstream, causing its detectability by upstream measurements, the degradation of efficiency does not cause any parameters to change except the load on the turbine.Probably a measurement of the temperature down stream of the turbine could have analysed the deterioration of the turbine efficiency.

Combination of faults was also tried when

1. The LP compressor flow and efficiency were reduced by 0.5 %. Reasonably accurate detectability was observed Table VIII.

2. LP Compressor mass flow reduced by 1%
   HP Compressor efficiency reduced by 1%
   HP turbine area increased by 1%.
   The analysis showed a 3% error for the LP compressor but 22.5% error for the HP compressor and 15% on HP turbine area. The smearing increased and almost all the faults were observed to have been identified to a certain level.

3. All the faults were imposed together, and each to a value of 1%. The errors of detection were upto a range of 90% on the imposed faults. This implied a shift in the characteristics and the inability of the method to identify a combination of faults.

The number of measurements was reduced from 10 to 9 when the pressure probe between the two compressor turbines was removed. This does not affect identification of faults on the cold side, but induced significant errors for faults of the detectibility of the LP and HP turbines.

An error of 152% was now detected when all the faults were imposed together and each of 1% value. This shows the importance of the number of measurements for equal detectibility.

In the third part of this analysis the pressure probe between the LP turbine and the HP turbine was now placed after the power turbine to measure power turbine exit pressure. The detectibility in respect of LP spool faults was not observed to have changed significantly, but an error of 95% was noticed on the HP spool faults. When all the faults were imposed together, as before, the error noticed was 237% and primarily concentrated on the HP spool components.

This could be explained, since the power turbine exit pressure is almost atmospheric, hence does not change appreciably with changes in the operating point of the engine. Thus the detectibility with the help of this measurement is hardly changed. Once again the importance of the implicit change in the parameters for detectibility by the gas path analysis is identified. Thus the engine degradations do not cause any change in the measurement of pressure down stream of the power turbine and hence this measurement is unable to identify the faults.

Transients of a two spool turbo-jet engine are compared in clean and deteriorated conditions. The program run in transient mode was automatically followed by a deteriorated engine run in transient mode. Degradations of HP turbine by 1.5% in efficiency and 2% increase in area was imposed. The results of comparison are presented in Fig 11.6. The nature of the curves does not exhibit any appreciable deviation. This is because the fuel flow is not restricted to a maximum value. The deteriorated TIT thus shoots much higher than that for the clean engine, and the transients appear to have similar characteristics. Further study of the engine transients with the maximum fuel flow limited to the design value or the clean engine maximum (fixed PLA/fuel flow relation) is recommended.

A representative turbo-fan engine diagnostics were studied using the best estimate approach. The engine module failure rate probability functions were assumed to be as shown in Fig 10.4. Based on these probability of failures (degradation) the engine data was obtained. The 500 points so obtained were then utilised to evaluate the covariance matrix. The variance covariance matrix generated is given in table XVIII. The engine fault matrix and the sensor fault matrix was determined by the perturbation and looping technique described above. The influence matrix and the sensor matrix are given in Table XVII. The inverted engine/sensor coefficient matrix was then calculated utilising the matrix algebra. This is given in table XIX.

CHAPTER 12

CONCLUSIONS

From the results and other discussions of the preceding chapters, the following conclusions can be made :

1. From the fault analysis it is seen that the behaviour of a twin spool gas generator is the same whether it is a turbo-jet or a turbo-shaft engine. The analysis of their deterioration and performance has been given in Figures 11.4 and 11.5

2. It is important, that for accuracy in the identification of the faults, the parameters measured are judiciously chosen in such a way that all the sought problems are depicted in the measurements.

3. Such depiction of the measurements must be identifiable. This requires an analysis of the errors and the detectability of the symptoms by the sensors.

4. Gas path analysis, a technique of performance monitoring is based on the measurable changes caused by the engine faults. Inability to detect a change in the measured parameter results in the ineffectiveness of the GPA. It is thus the measurement technology that has mired the progress of the GPA.

   The hostile environment make the sensors unreliable and generate corrupted signal. There is currently a limit on the parameters that can be effectively measured. Thus whereas diagnostic engineer may want to measure some engine parameter, but as a result of many factors, no suitable sensor or technique of measurement may be available. For example TIT measurement.

   Further since the quantities measured are not usually the best, parameters for fault detection or the isolation determine how these measurements are utilised. Real time analysis is costly and must prove to be very effective to justify its implementation. The other alternative is to record the data and analyse later. Recording thus becomes essential part of the GPA and induces some more errors.

5. A computer simulation of deteriorated gas turbines has been developed. This is a generalised model capable of simulating any gas turbine.

6. The program has capability of diagnosing the engine data for fault identification and utilises three different techniques for this purpose.

7. The program has capability to trend parameters either generated within the program or outside data.

8. The program incorporates integrated graphics that can graph automatically any/all of the plots at user's request

9. The program is user friendly and considered to have a potential as a teaching aid.

10 The program can generate fault trees which can form the basis of knowledge base for gas turbine diagnosis. Sample fault tree for a two spool gas generator are shown in Tables 20 and 21.

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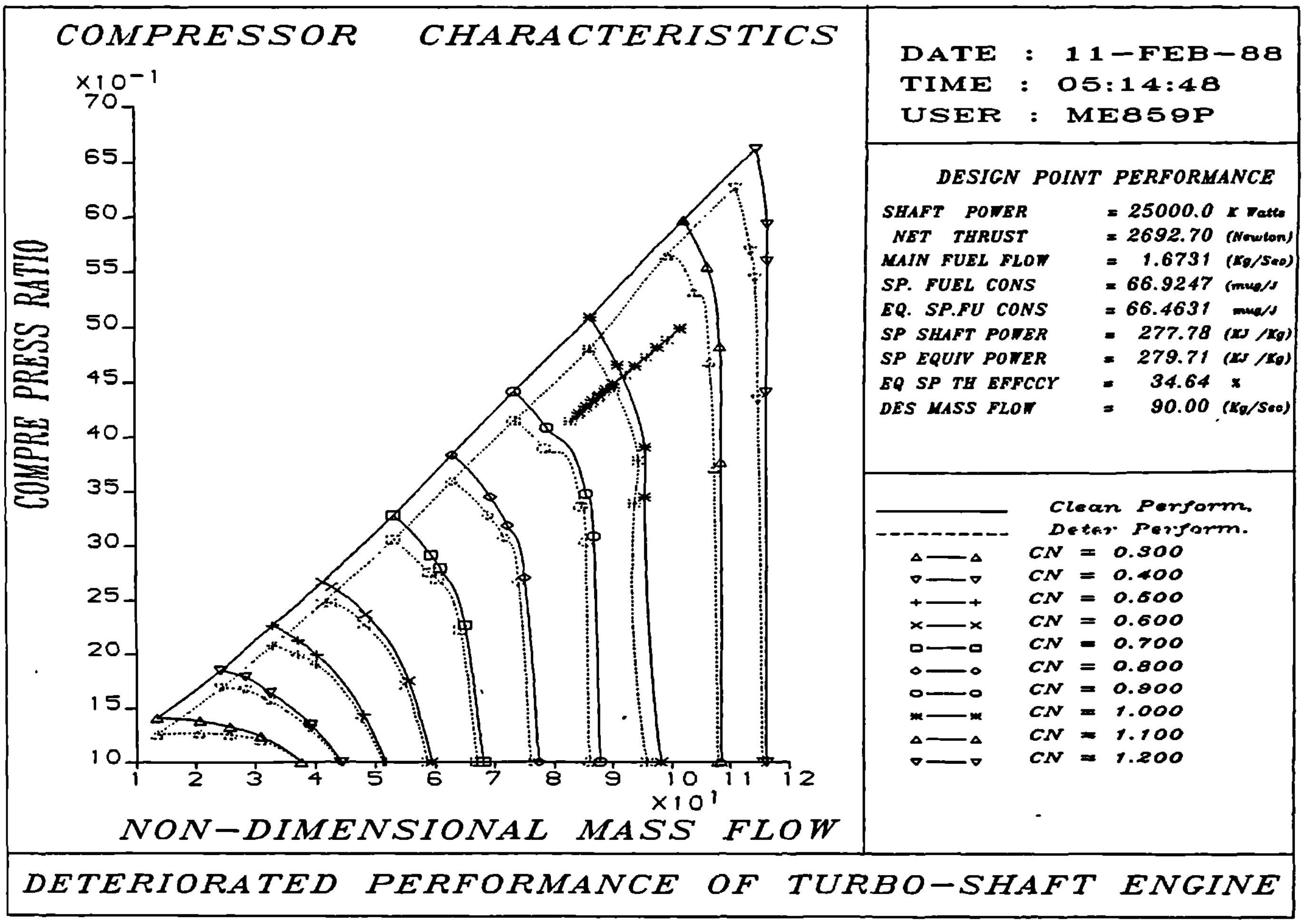
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SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
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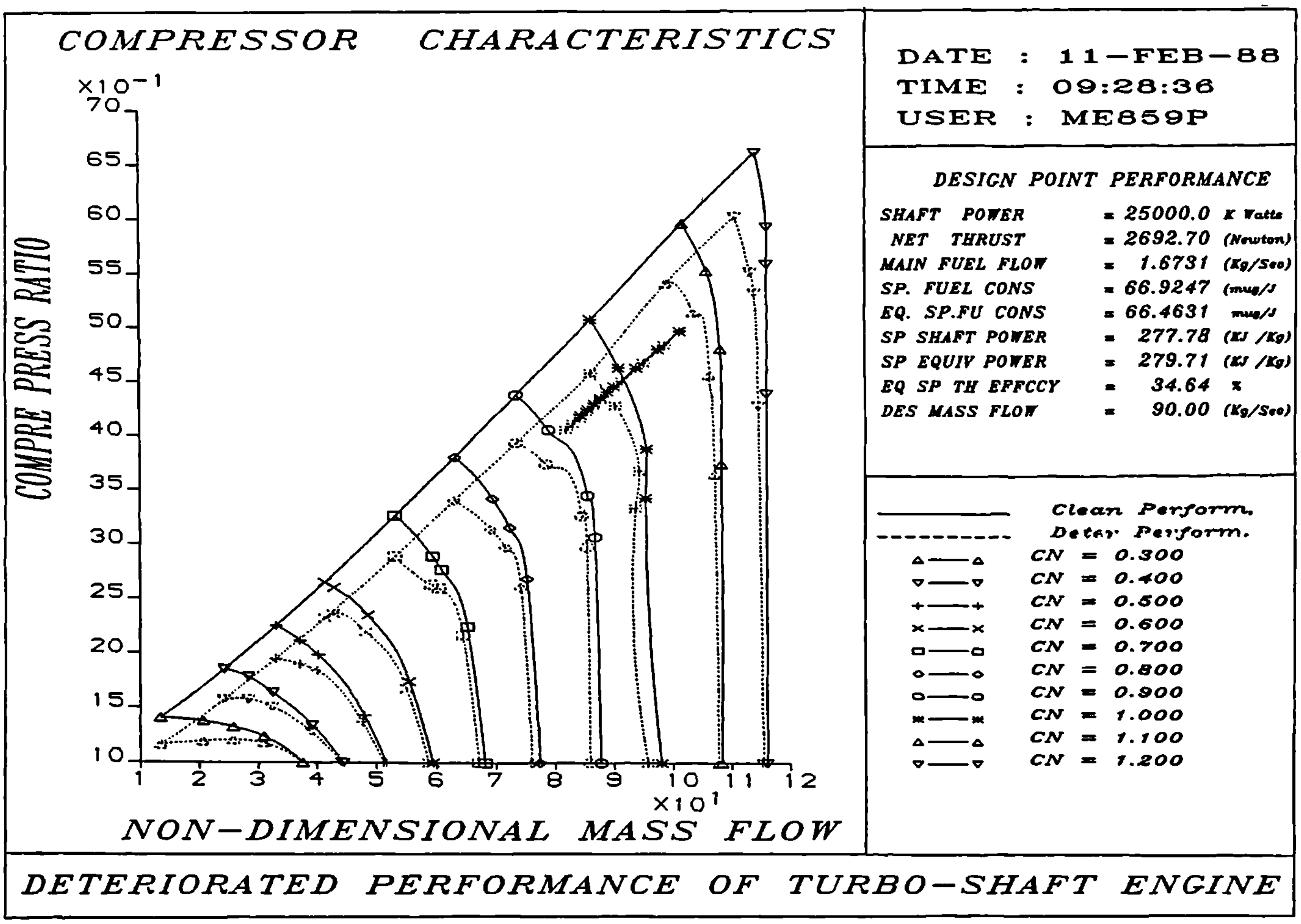
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE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EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
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EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
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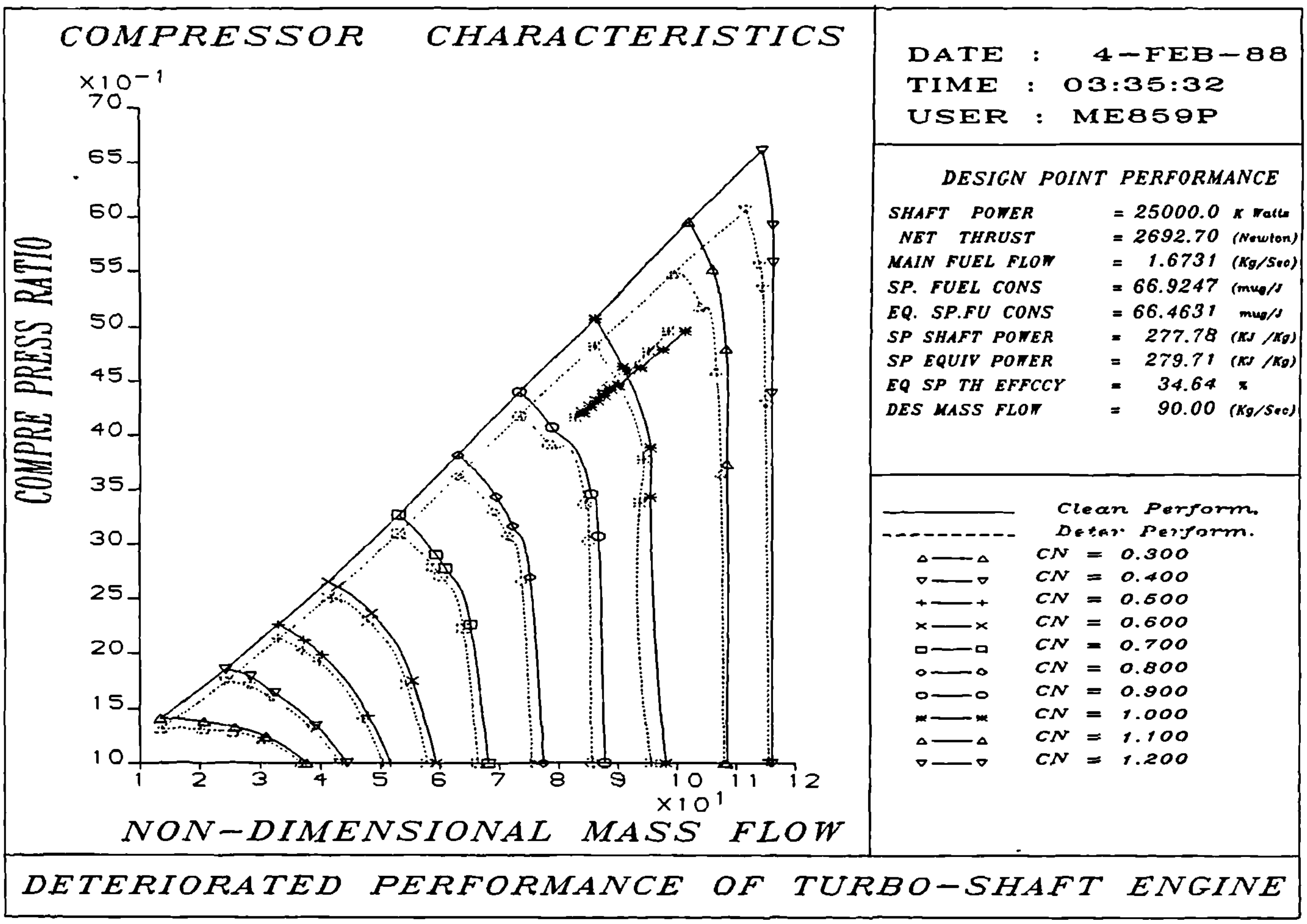
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 8.1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X10^-1
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X10^1
NON-DIMENSIONAL MASS FLOW
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NET THRUST = 2692.70 (Newton)
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SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
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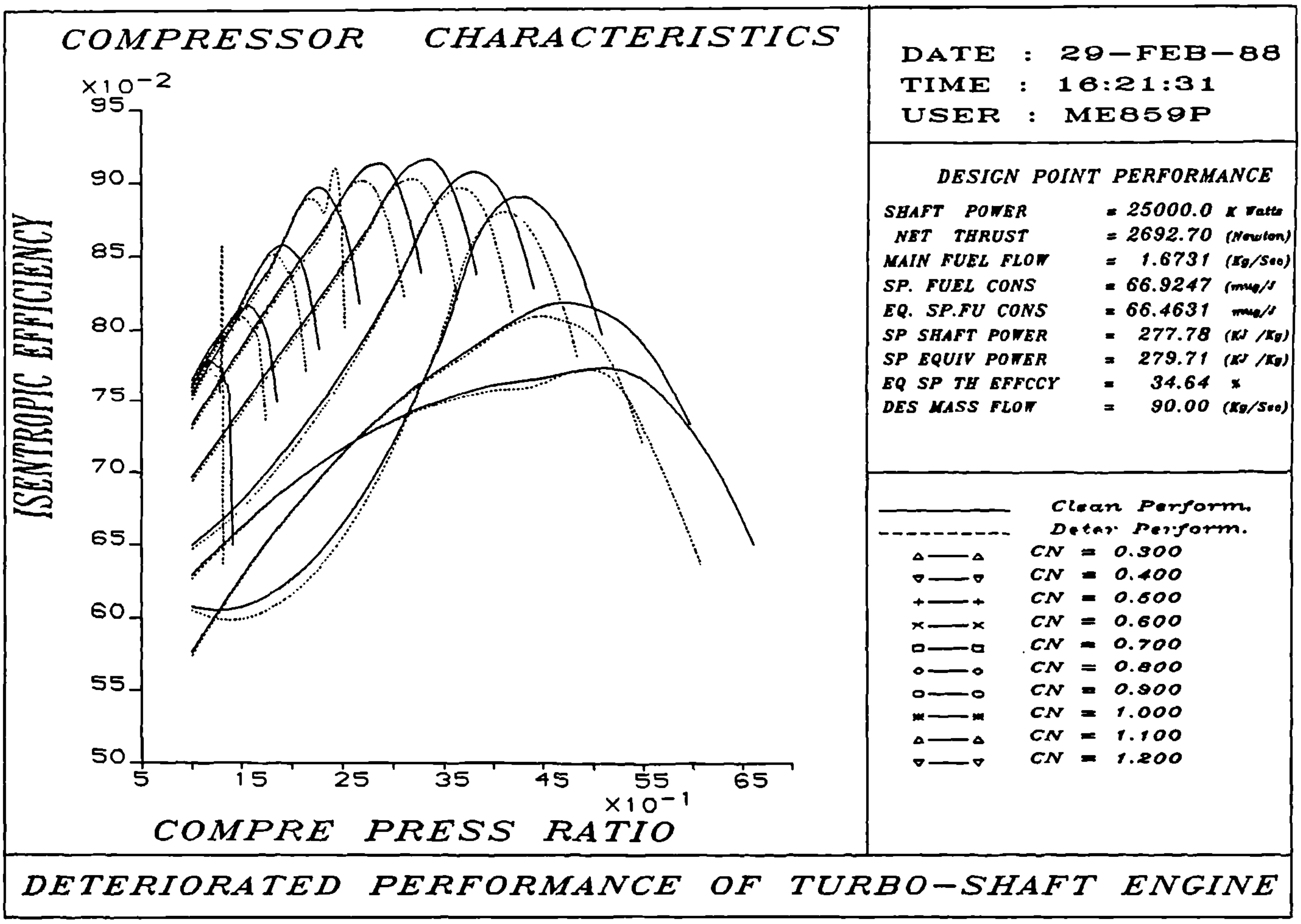
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE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SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
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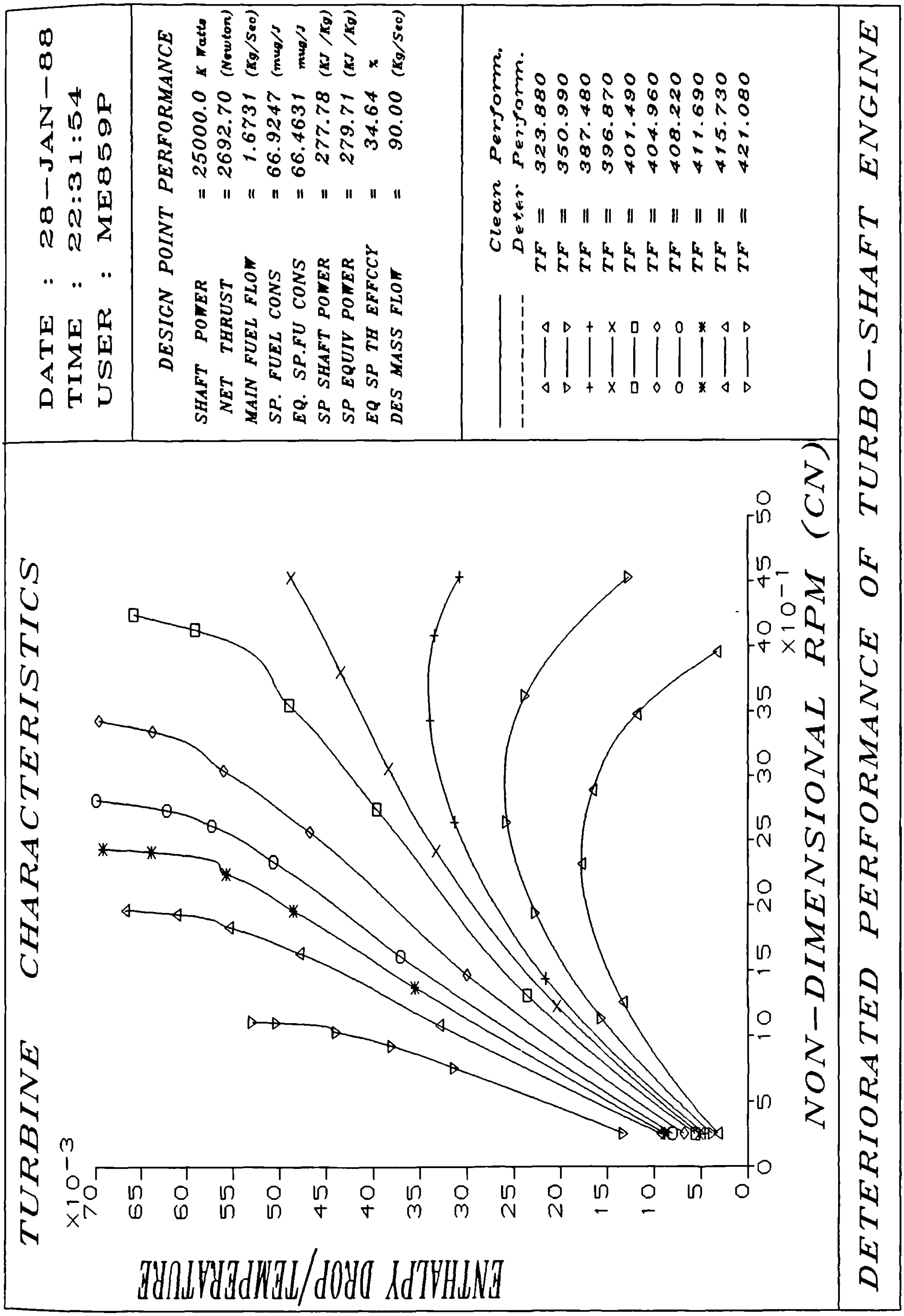
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 8.2



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EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
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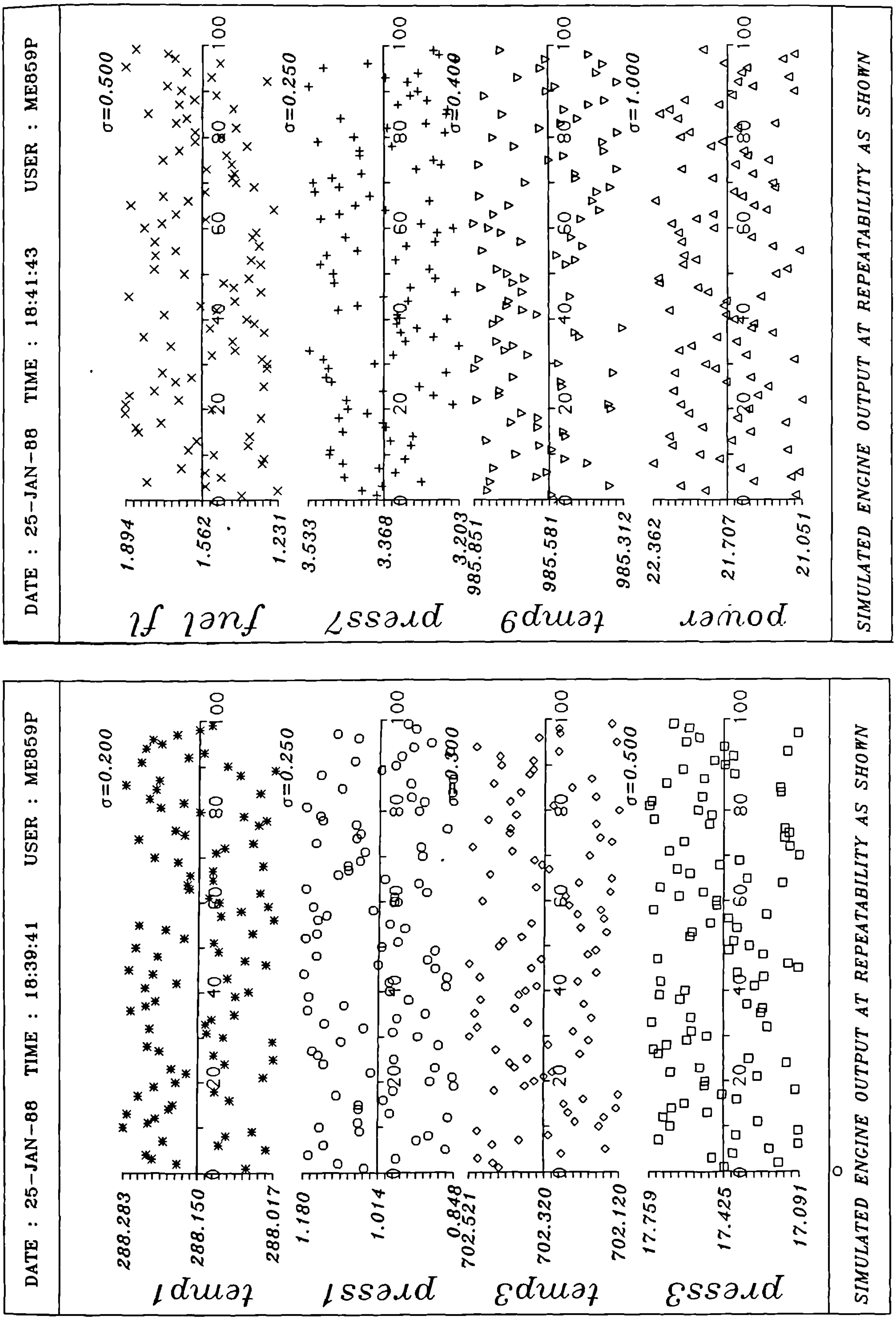
TF = 387.480
TF = 396.870
TF = 401.490
TF = 404.960
TF = 408.220
TF = 411.690
TF = 415.730
TF = 421.080
ENTHALPY DROP/TEMPERATURE
×10⁻³
NON-DIMENSIONAL RPM (CN)
×10⁻¹
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 8.3



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fuel fl
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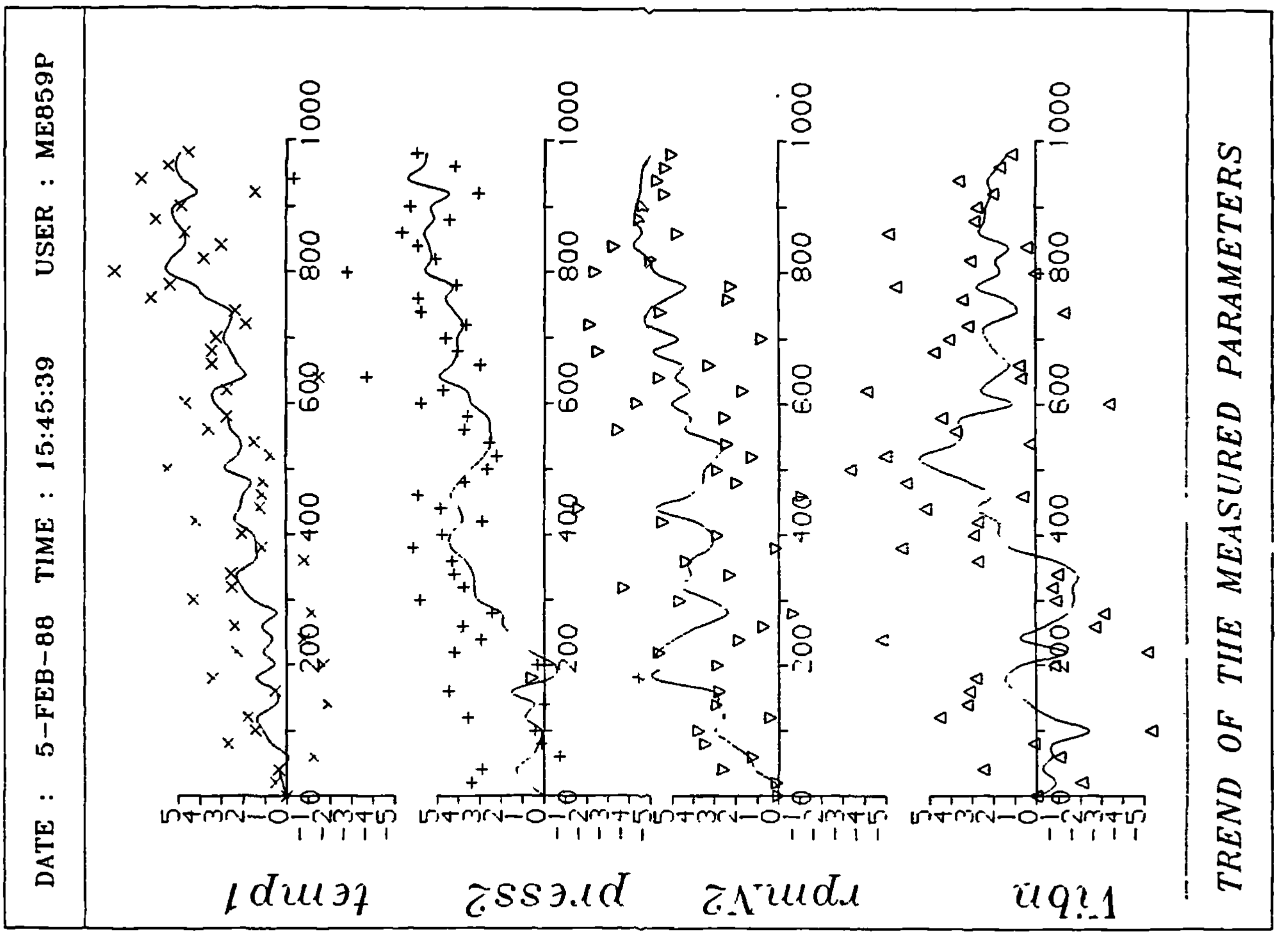
1.894
1.562
1.231
press7
σ=0.250
3.533
3.368
3.203
temp9
σ=0.400
985.851
985.581
985.312
power
σ=1.000
22.362
21.707
21.051
SIMULATED ENGINE OUTPUT AT REPEATABILITY AS SHOWN
DATE : 25-JAN-88 TIME : 18:39:41 USER : ME859P
temp1
σ=0.200
288.283
288.150
288.017
press1
σ=0.250
1.180
1.014
0.848
temp3
σ=0.300
702.521
702.320
702.120
press3
σ=0.500
17.759
17.425
17.091
SIMULATED ENGINE OUTPUT AT REPEATABILITY AS SHOWN

Fig 8.4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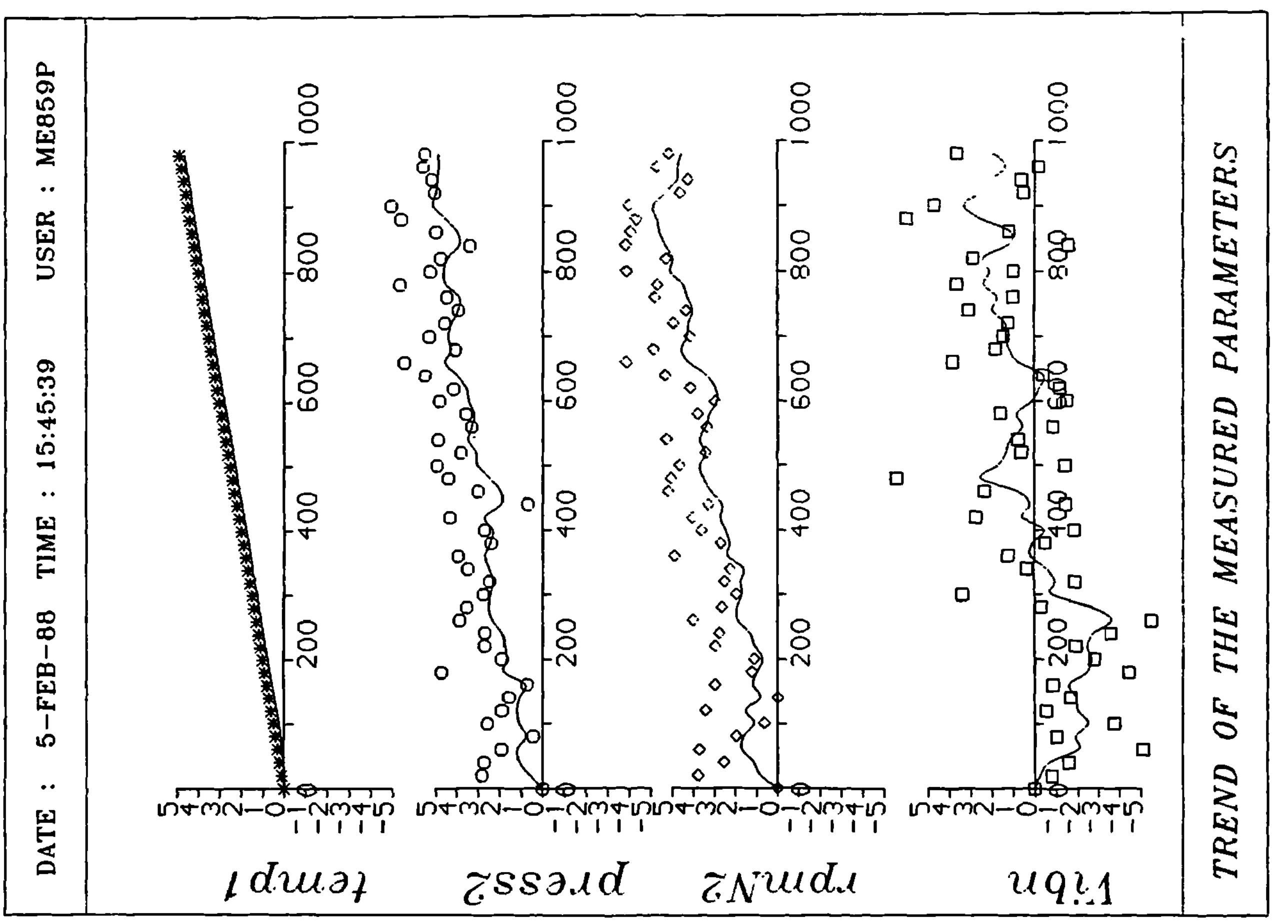
press2
rpmN2
Vibn
TREND OF THE MEASURED PARAMETERS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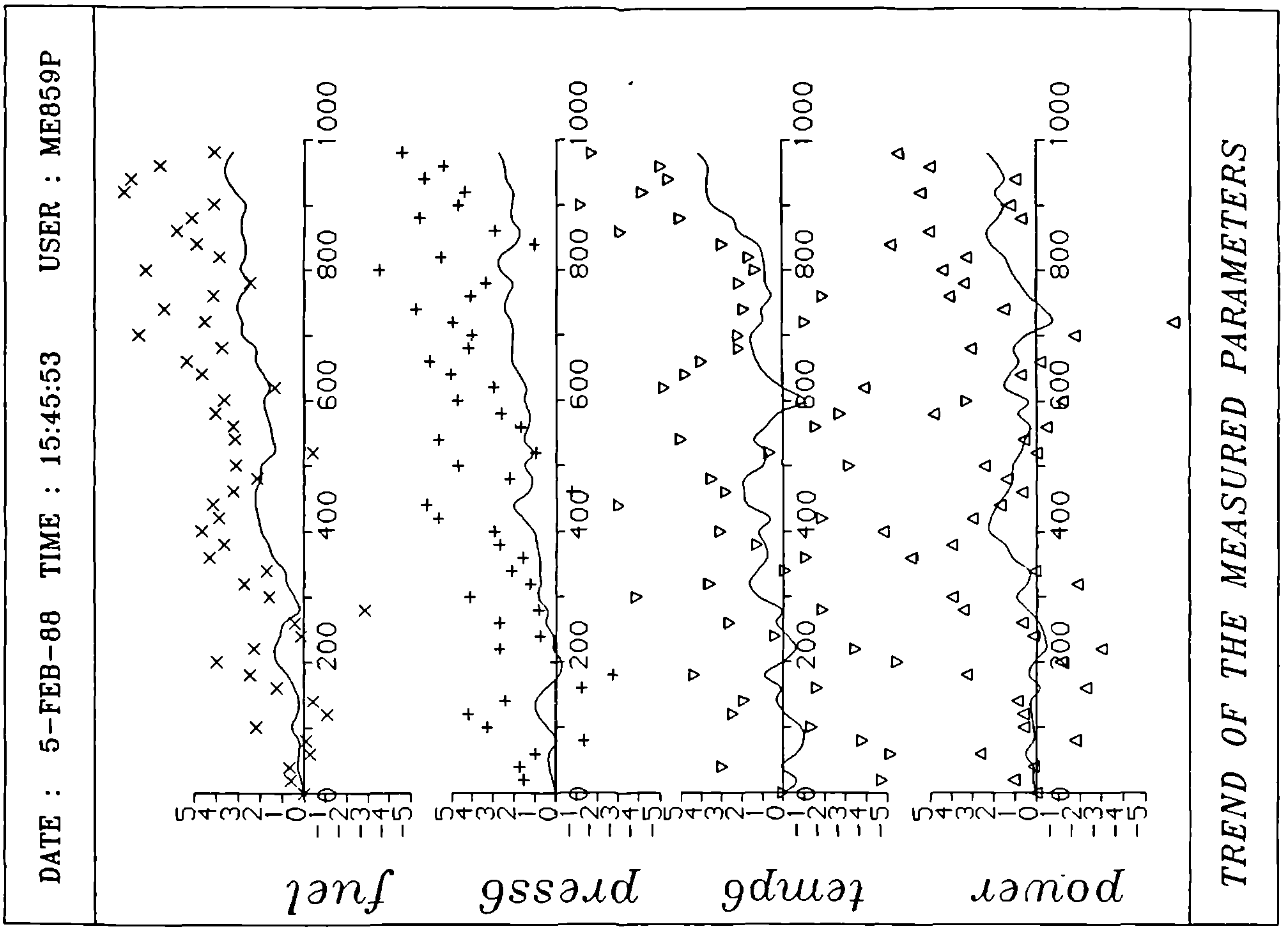
temp1
press2
rpmN2
Vibn
TREND OF THE MEASURED PARAMETERS

Fig 10.1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press6
temp6
power
TREND OF THE MEASURED PARAMETERS

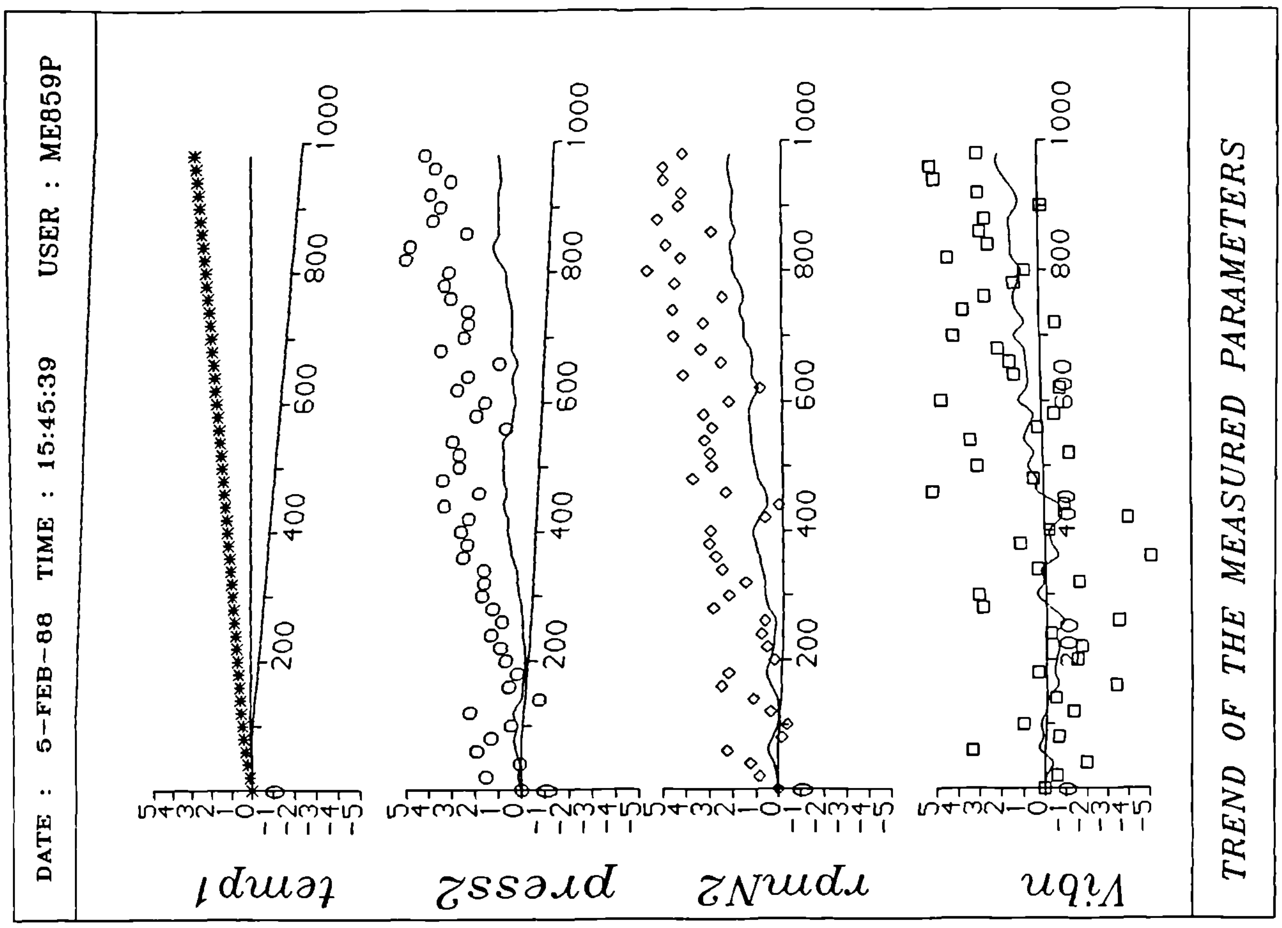

DATE : 5-FEB-88 TIME : 15:45:39 USER : ME859P
temp1
press2
rpmN2
Vibn
TREND OF THE MEASURED PARAMETERS

Fig 10.2

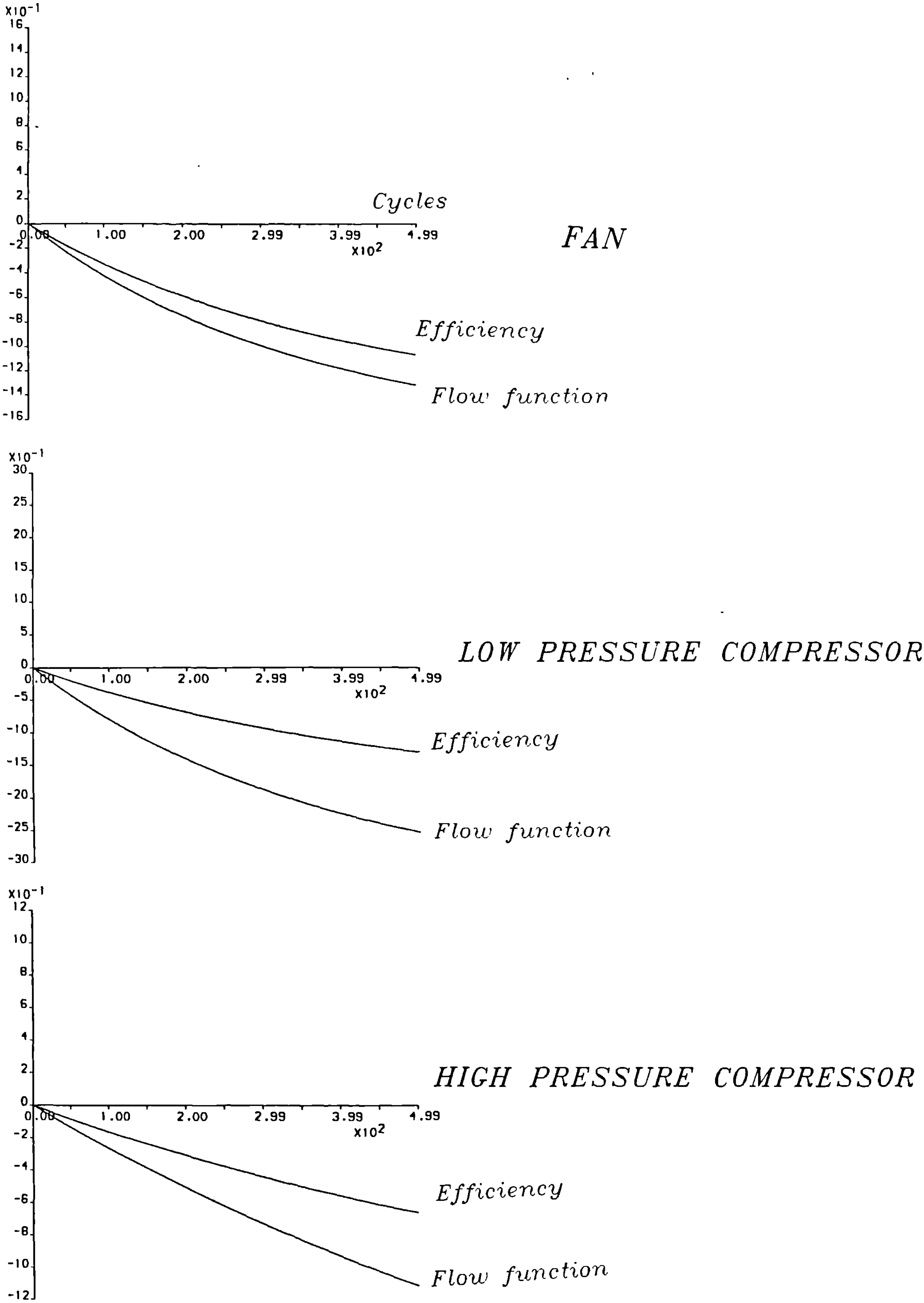
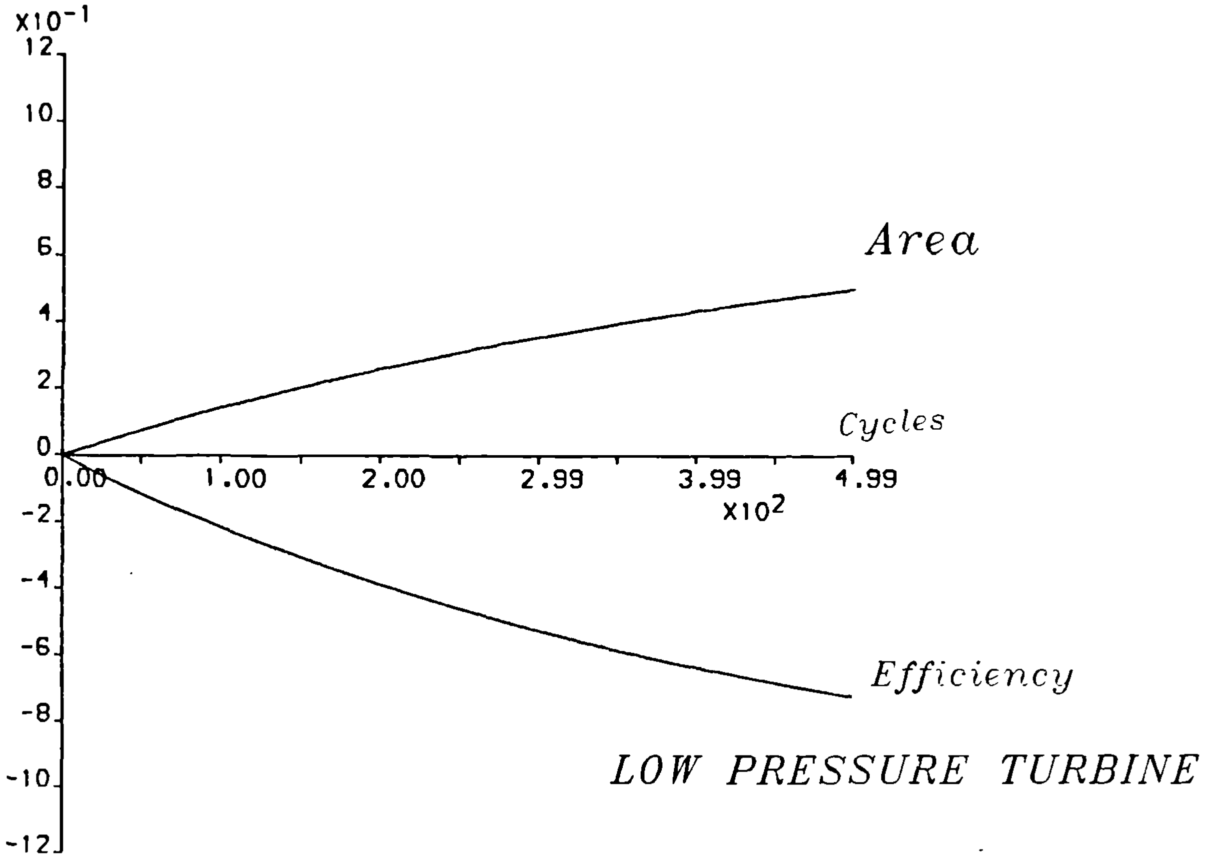


Fig 10.3 Hypothetical p.d.f



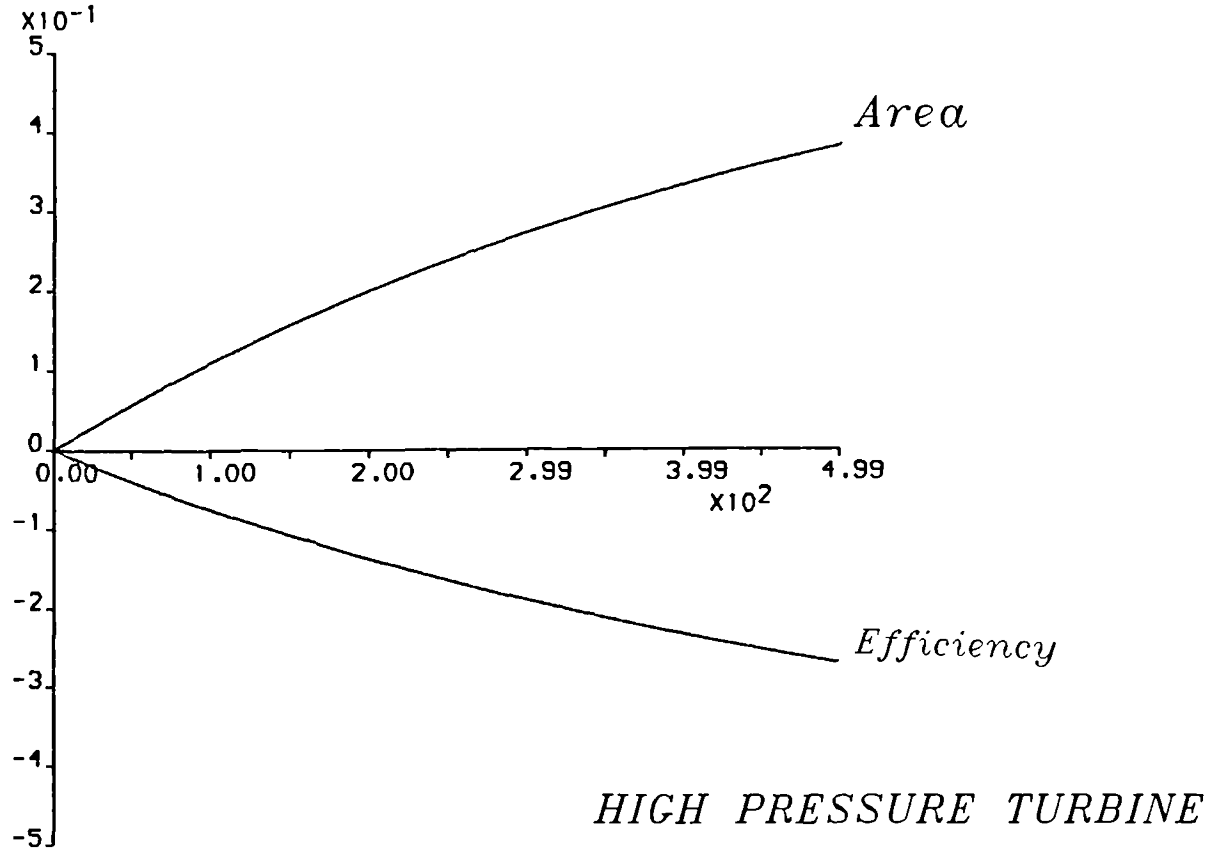
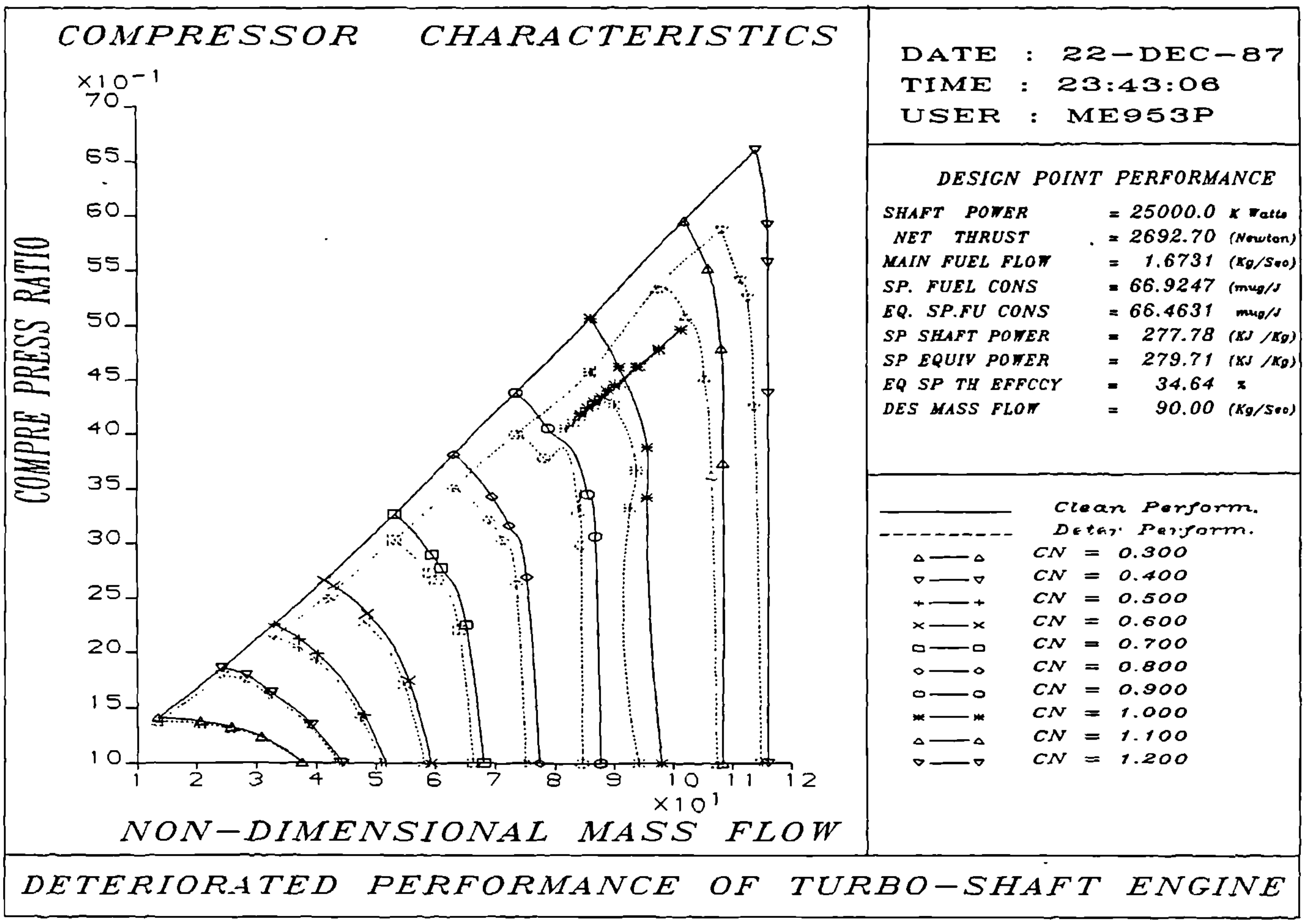


Fig 10.4 Hypothetical p.d.f


COMPRESSOR CHARACTERISTICS
x10⁻¹
COMPRE PRESS RATIO
NON-DIMENSIONAL MASS FLOW
x10¹
DATE : 22-DEC-87
TIME : 23:43:06
USER : ME953P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
CN = 0.800
CN = 0.900
CN = 1.000
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

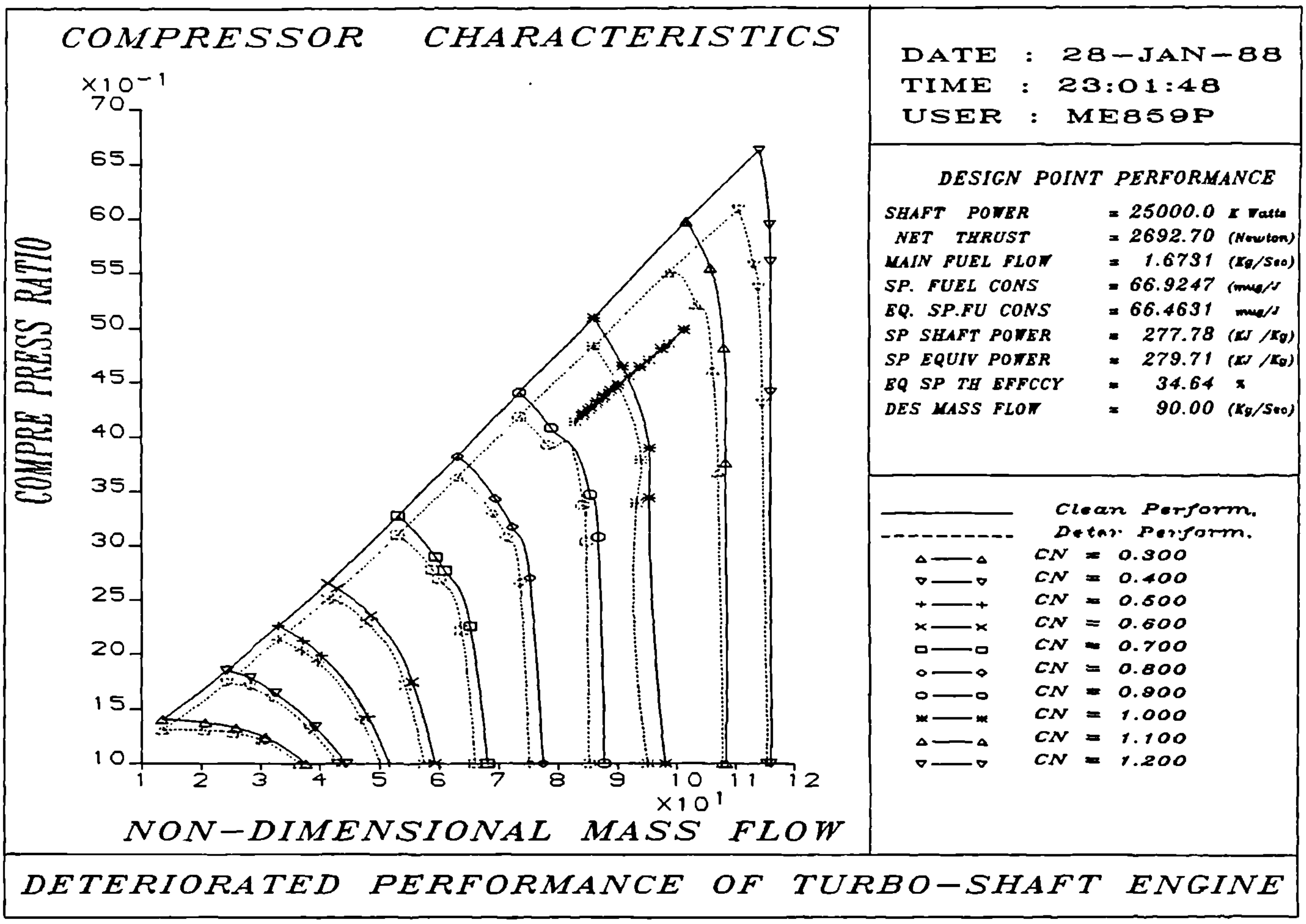
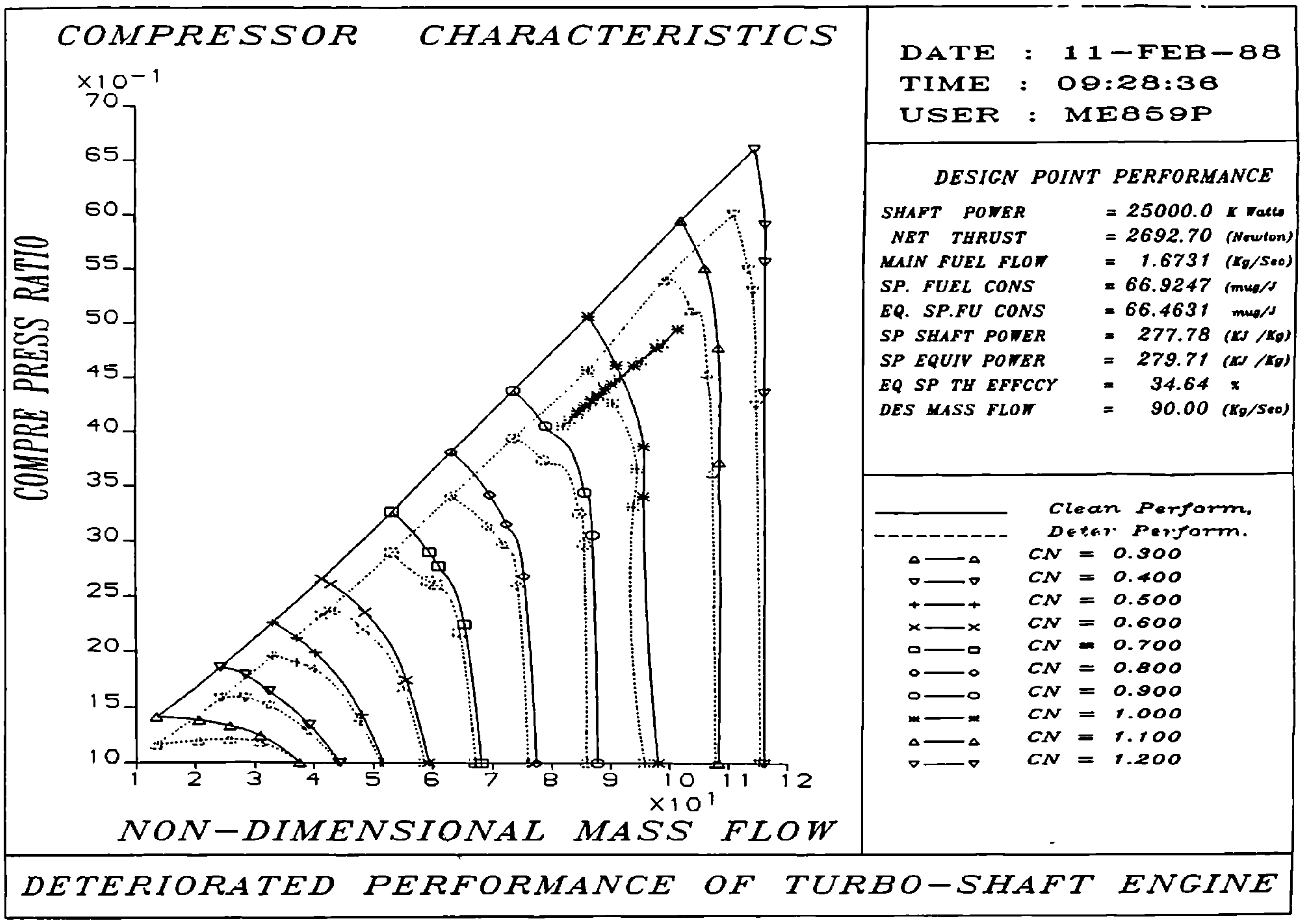

COMPRESSOR CHARACTERISTICS
x10⁻¹
COMPRE PRESS RATIO
NON-DIMENSIONAL MASS FLOW
x10¹
DATE : 28-JAN-88
TIME : 23:01:48
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
CN = 0.800
CN = 0.900
CN = 1.000
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 11.1


COMPRESSOR CHARACTERISTICS
x10⁻¹
70
65
60
55
50
45
40
35
30
25
20
15
10
COMPRE PRESS RATIO
1 2 3 4 5 6 7 8 9 10 11 12
x10¹
NON-DIMENSIONAL MASS FLOW
DATE : 11-FEB-88
TIME : 09:28:36
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
CN = 0.800
CN = 0.900
CN = 1.000
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

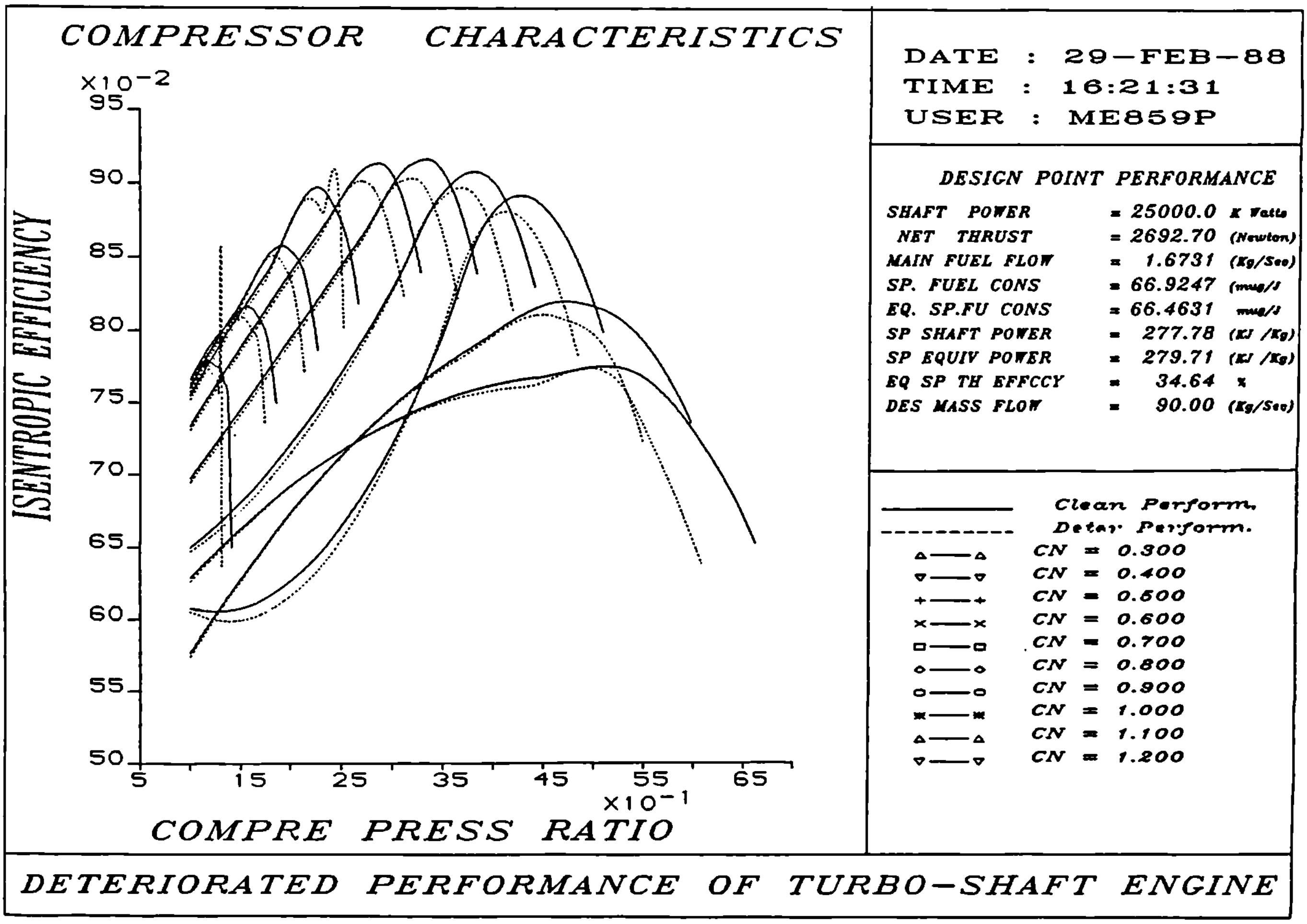
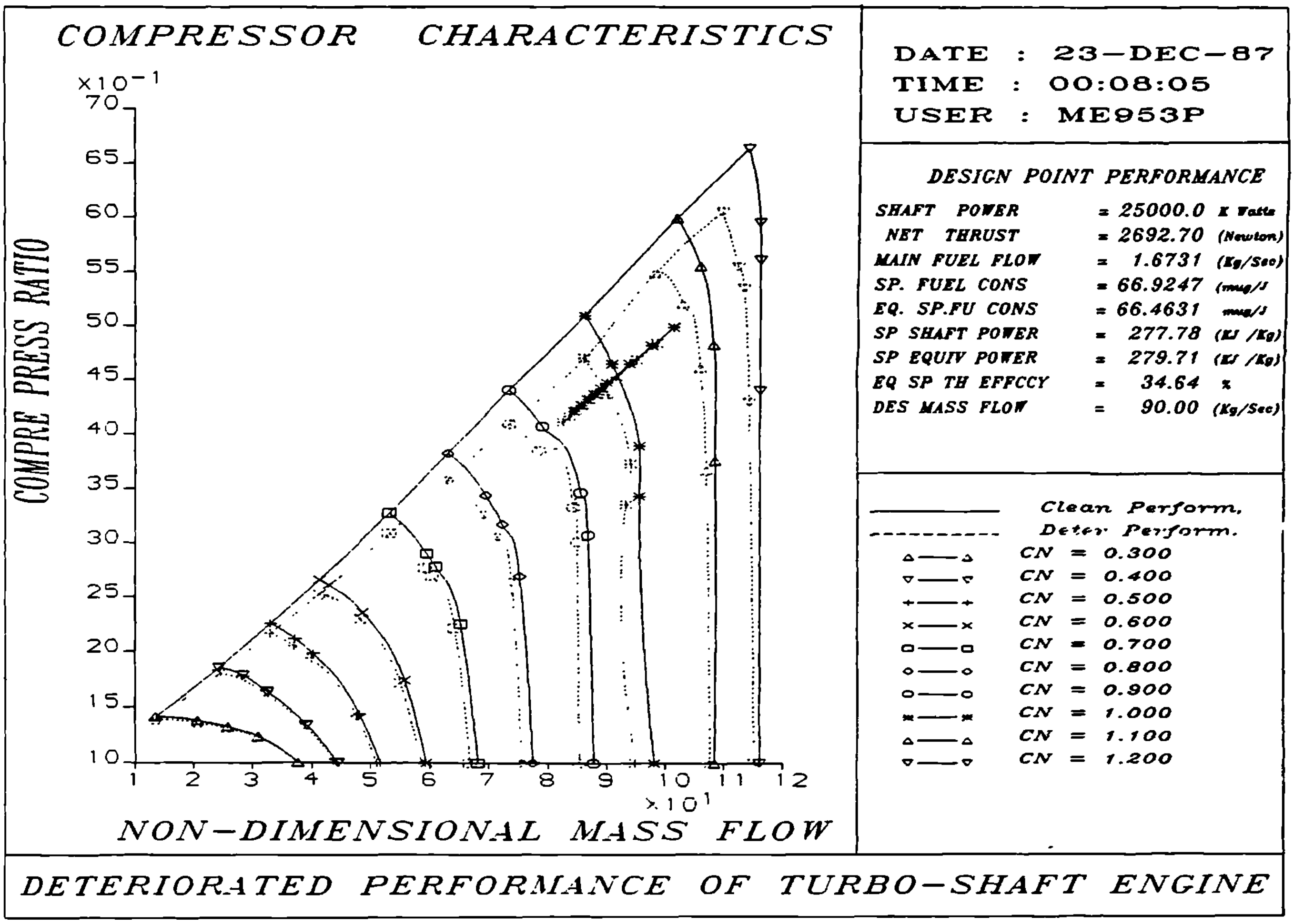

COMPRESSOR CHARACTERISTICS
x10⁻²
95
90
85
80
75
70
65
60
55
50
ISENTROPIC EFFICIENCY
5 15 25 35 45 55 65
x10⁻¹
COMPRE PRESS RATIO
DATE : 29-FEB-88
TIME : 16:21:31
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
CN = 0.800
CN = 0.900
CN = 1.000
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 11.2


COMPRESSOR CHARACTERISTICS
x10⁻¹
COMPRE PRESS RATIO
NON-DIMENSIONAL MASS FLOW
x10¹
DATE : 23-DEC-87
TIME : 00:08:05
USER : ME953P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
CN = 0.800
CN = 0.900
CN = 1.000
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

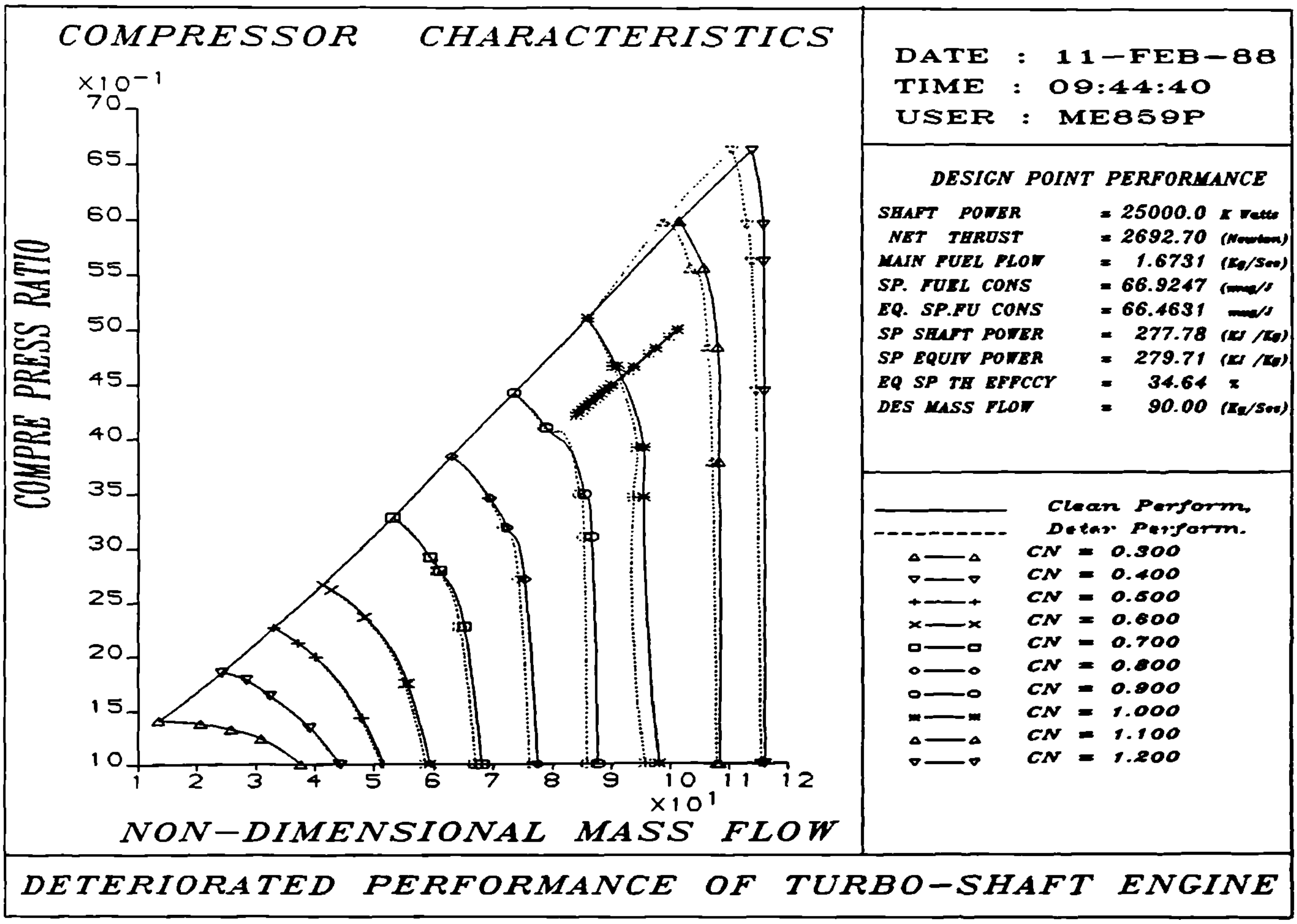
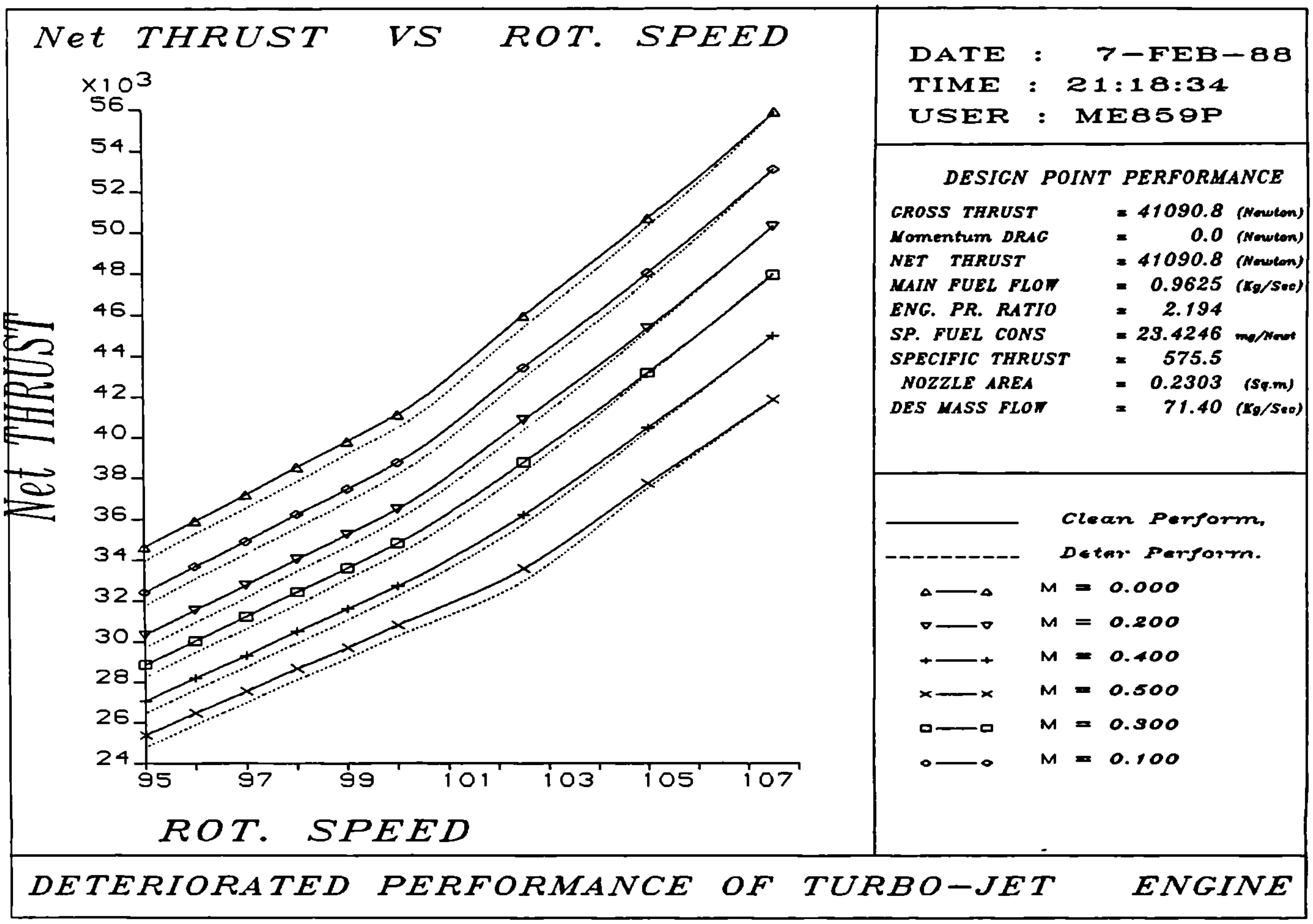

COMPRESSOR CHARACTERISTICS
x10⁻¹
COMPRE PRESS RATIO
NON-DIMENSIONAL MASS FLOW
x10¹
DATE : 11-FEB-88
TIME : 09:44:40
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
CN = 0.300
CN = 0.400
CN = 0.500
CN = 0.600
CN = 0.700
CN = 0.800
CN = 0.900
CN = 1.000
CN = 1.100
CN = 1.200
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 11.3


Net THRUST VS ROT. SPEED
x10^3
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
95
97
99
101
103
105
107
ROT. SPEED
Net THRUST
DATE : 7-FEB-88
TIME : 21:18:34
USER : ME859P
DESIGN POINT PERFORMANCE
GROSS THRUST = 41090.8 (Newton)
Momentum DRAG = 0.0 (Newton)
NET THRUST = 41090.8 (Newton)
MAIN FUEL FLOW = 0.9625 (Kg/Sec)
ENG. PR. RATIO = 2.194
SP. FUEL CONS = 23.4246 mg/Newt
SPECIFIC THRUST = 575.5
NOZZLE AREA = 0.2303 (Sq.m)
DES MASS FLOW = 71.40 (Kg/Sec)
Clean Perform.
Deter Perform.
M = 0.000
M = 0.200
M = 0.400
M = 0.500
M = 0.300
M = 0.100
DETERIORATED PERFORMANCE OF TURBO-JET ENGINE

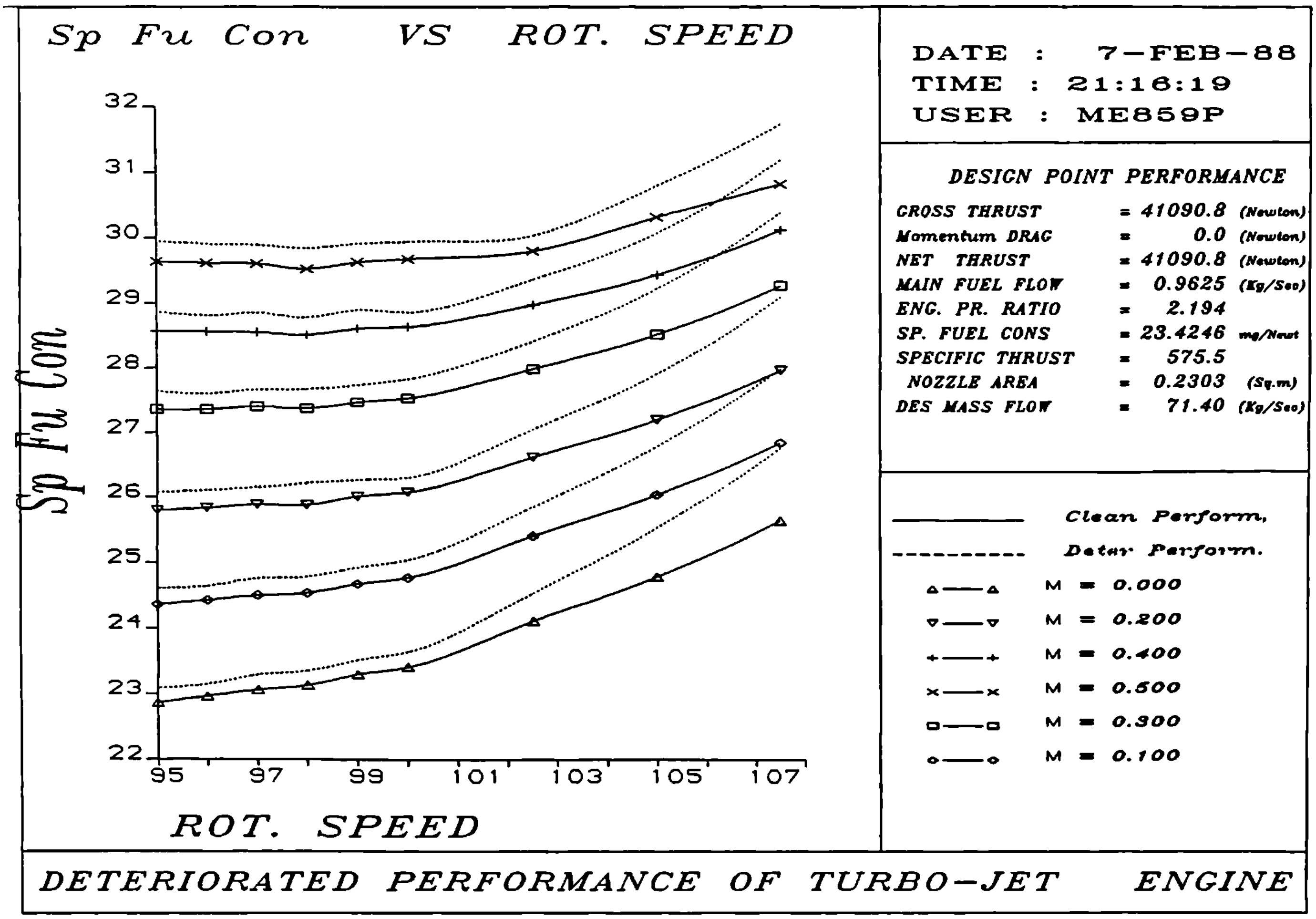
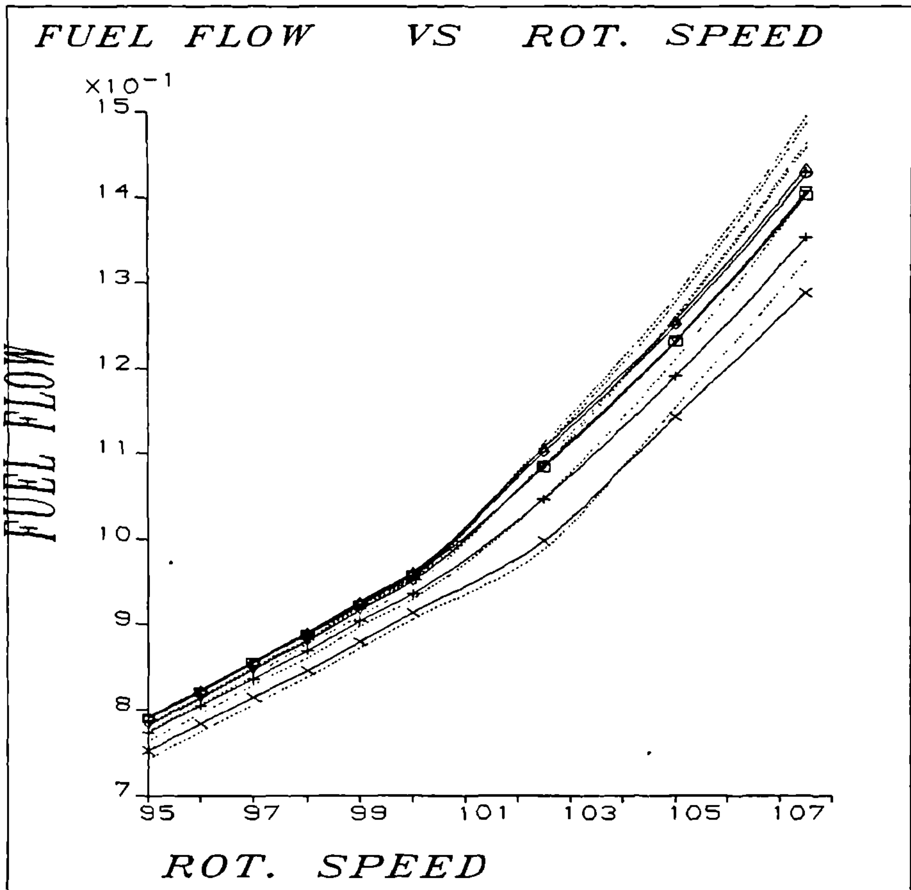

Sp Fu Con VS ROT. SPEED
32
31
30
29
28
27
26
25
24
23
22
95
97
99
101
103
105
107
ROT. SPEED
Sp Fu Con
DATE : 7-FEB-88
TIME : 21:16:19
USER : ME859P
DESIGN POINT PERFORMANCE
GROSS THRUST = 41090.8 (Newton)
Momentum DRAG = 0.0 (Newton)
NET THRUST = 41090.8 (Newton)
MAIN FUEL FLOW = 0.9625 (Kg/Sec)
ENG. PR. RATIO = 2.194
SP. FUEL CONS = 23.4246 mg/Newt
SPECIFIC THRUST = 575.5
NOZZLE AREA = 0.2303 (Sq.m)
DES MASS FLOW = 71.40 (Kg/Sec)
Clean Perform.
Deter Perform.
M = 0.000
M = 0.200
M = 0.400
M = 0.500
M = 0.300
M = 0.100
DETERIORATED PERFORMANCE OF TURBO-JET ENGINE

Fig 11.4(a)

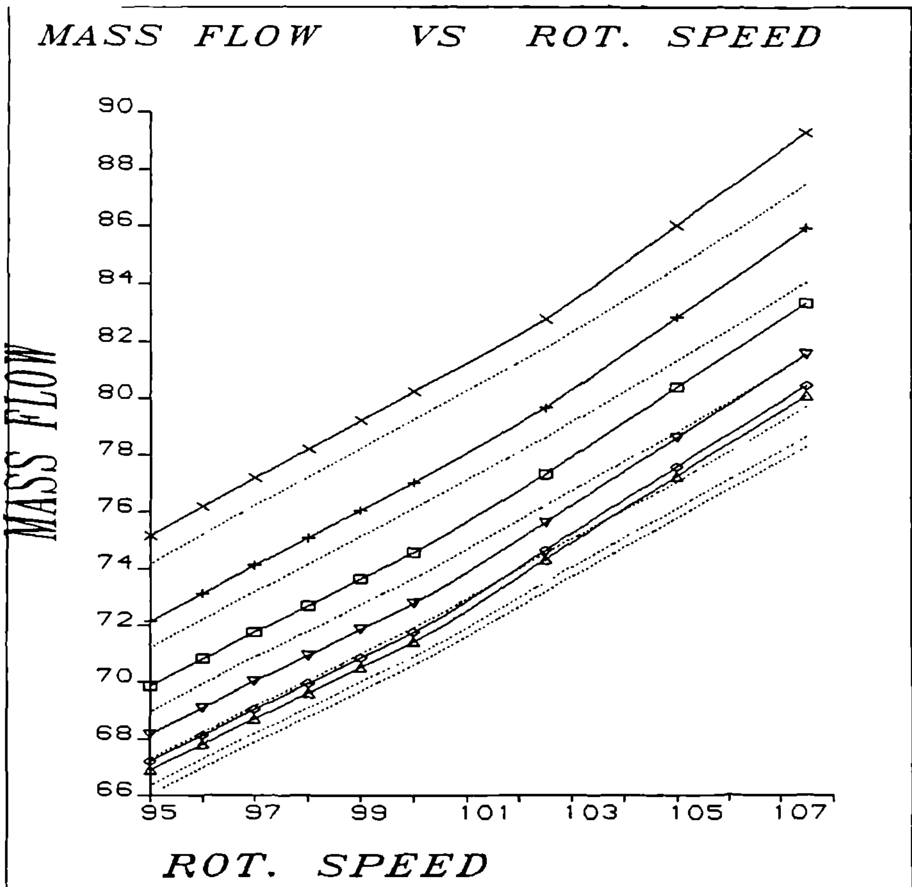


DATE : 7-FEB-88
TIME : 21:14:12
USER : ME859P

DESIGN POINT PERFORMANCE

GROSS THRUST	= 41090.8	(Newton)
Momentum DRAG	= 0.0	(Newton)
NET THRUST	= 41090.8	(Newton)
MAIN FUEL FLOW	= 0.9625	(Kg/Sec)
ENG. PR. RATIO	= 2.194	
SP. FUEL CONS	= 23.4246	mg/Newt
SPECIFIC THRUST	= 575.5	
NOZZLE AREA	= 0.2303	(Sq m)
DES MASS FLOW	= 71.40	(Kg/Sec)

DETERIORATED PERFORMANCE OF TURBO-JET ENGINE



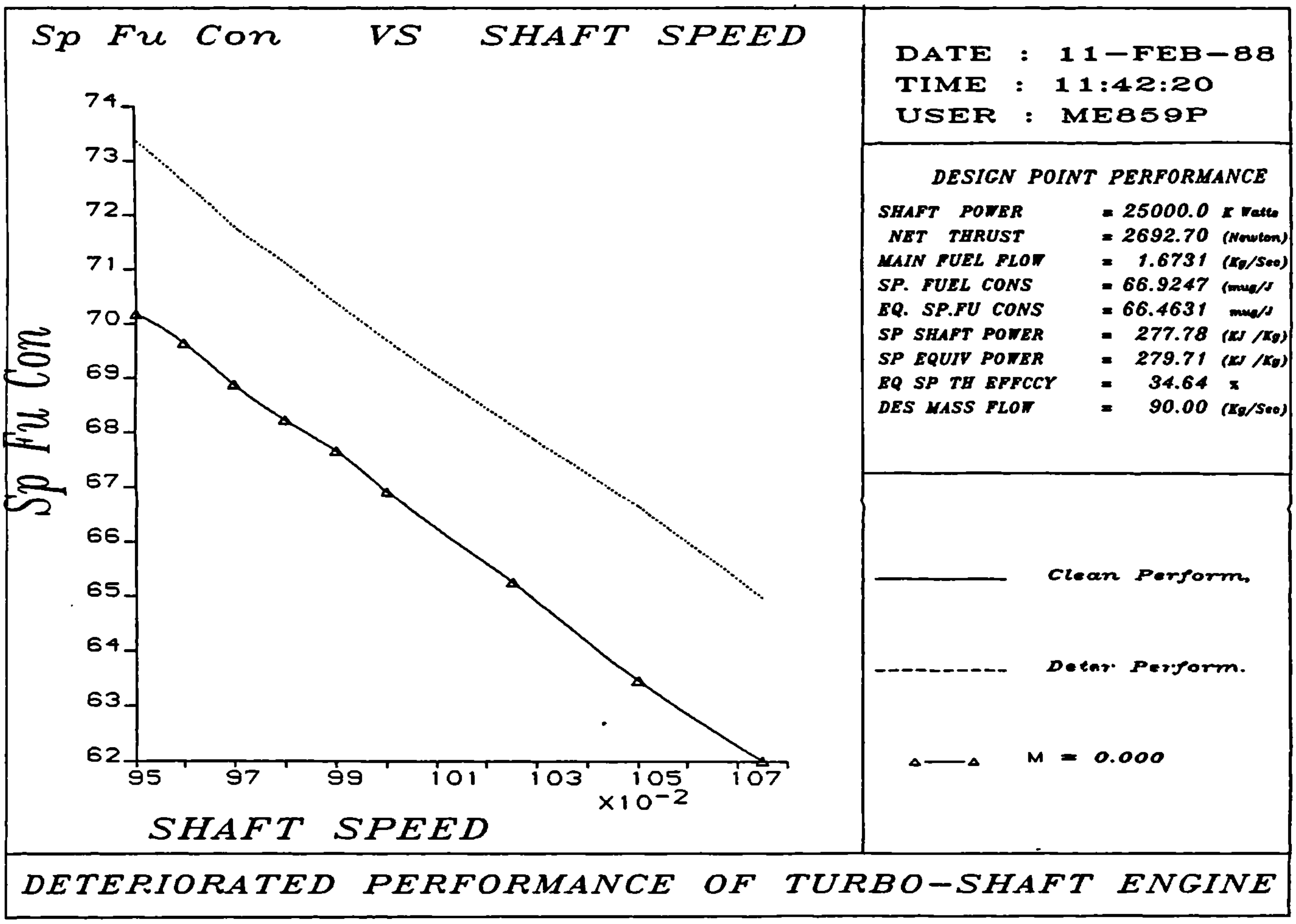
DATE : 7-FEB-88
TIME : 21:21:51
USER : ME859P

DESIGN POINT PERFORMANCE

GROSS THRUST	= 41090.8	(Newton)
Momentum DRAG	= 0.0	(Newton)
NET THRUST	= 41090.8	(Newton)
MAIN FUEL FLOW	= 0.9625	(Kg/Sec)
ENG. PR. RATIO	= 2.194	
SP. FUEL CONS	= 23.4246	mg/Newt
SPECIFIC THRUST	= 575.5	
NOZZLE AREA	= 0.2303	(Sq.m)
DES MASS FLOW	= 71.40	(Kg/Sec)

DETERIORATED PERFORMANCE OF TURBO-JET ENGINE

Fig 11.4(b)


Sp Fu Con VS SHAFT SPEED
DATE : 11-FEB-88
TIME : 11:42:20
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
M = 0.000
Sp Fu Con
74
73
72
71
70
69
68
67
66
65
64
63
62
95
97
99
101
103
105
107
X10-2
SHAFT SPEED
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

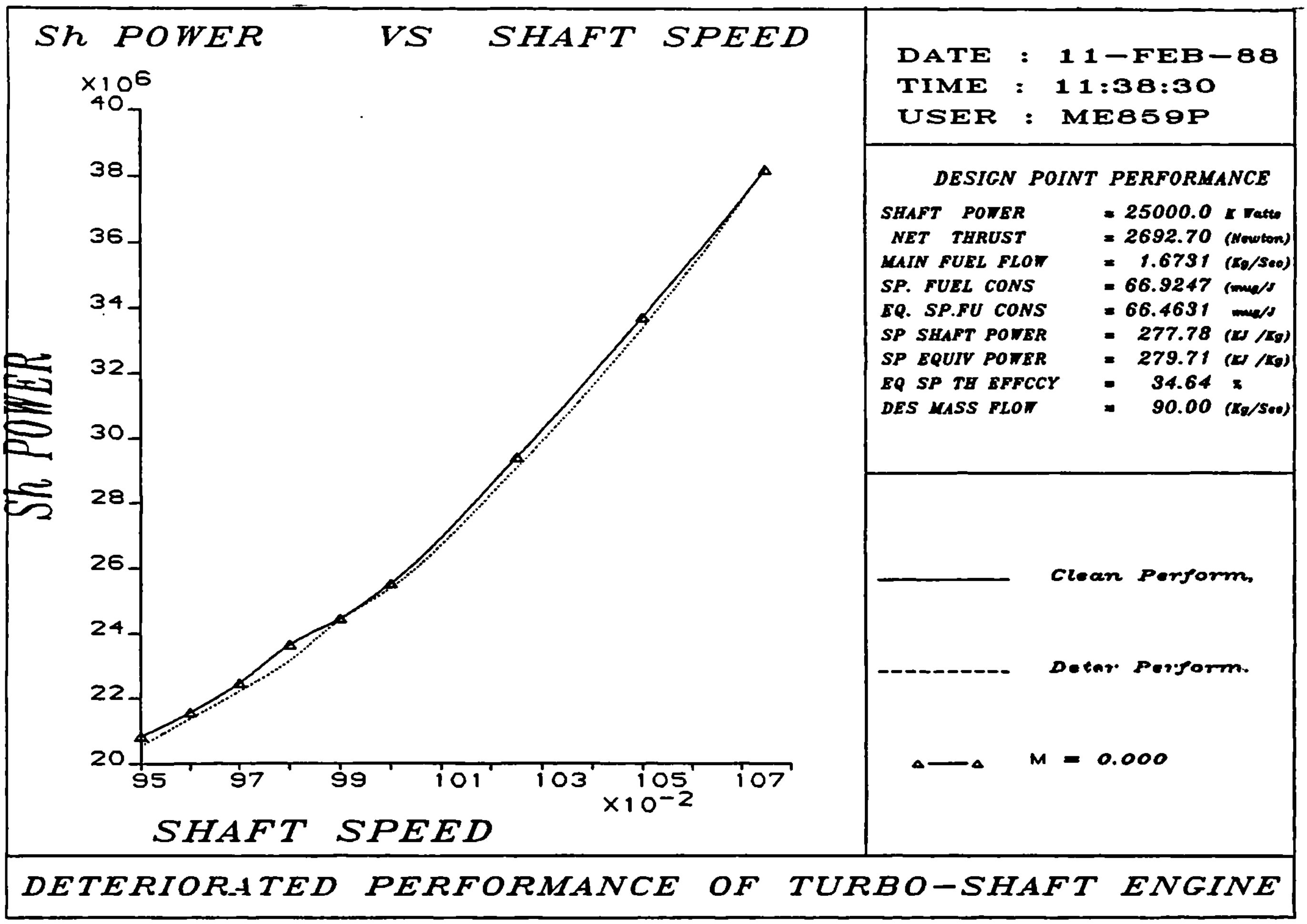
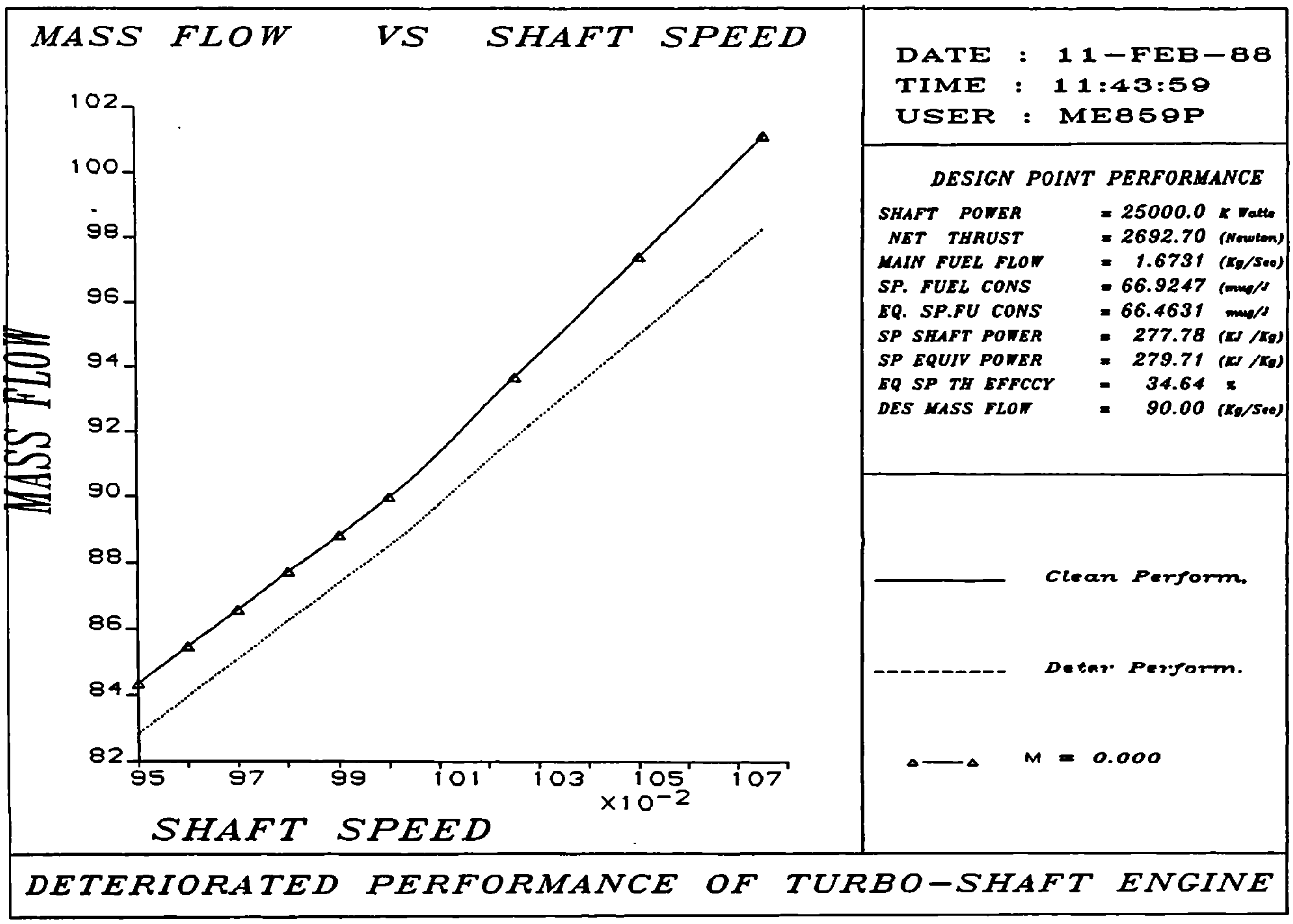

Sh POWER VS SHAFT SPEED
DATE : 11-FEB-88
TIME : 11:38:30
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
Clean Perform.
Deter Perform.
M = 0.000
Sh POWER
X10^6
40
38
36
34
32
30
28
26
24
22
20
95
97
99
101
103
105
107
X10-2
SHAFT SPEED
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 11.5(a)


MASS FLOW VS SHAFT SPEED
DATE : 11-FEB-88
TIME : 11:43:59
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
MASS FLOW
102
100
98
96
94
92
90
88
86
84
82
95
97
99
101
103
105
107
x10^-2
SHAFT SPEED
Clean Perform.
Deter Perform.
M = 0.000
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

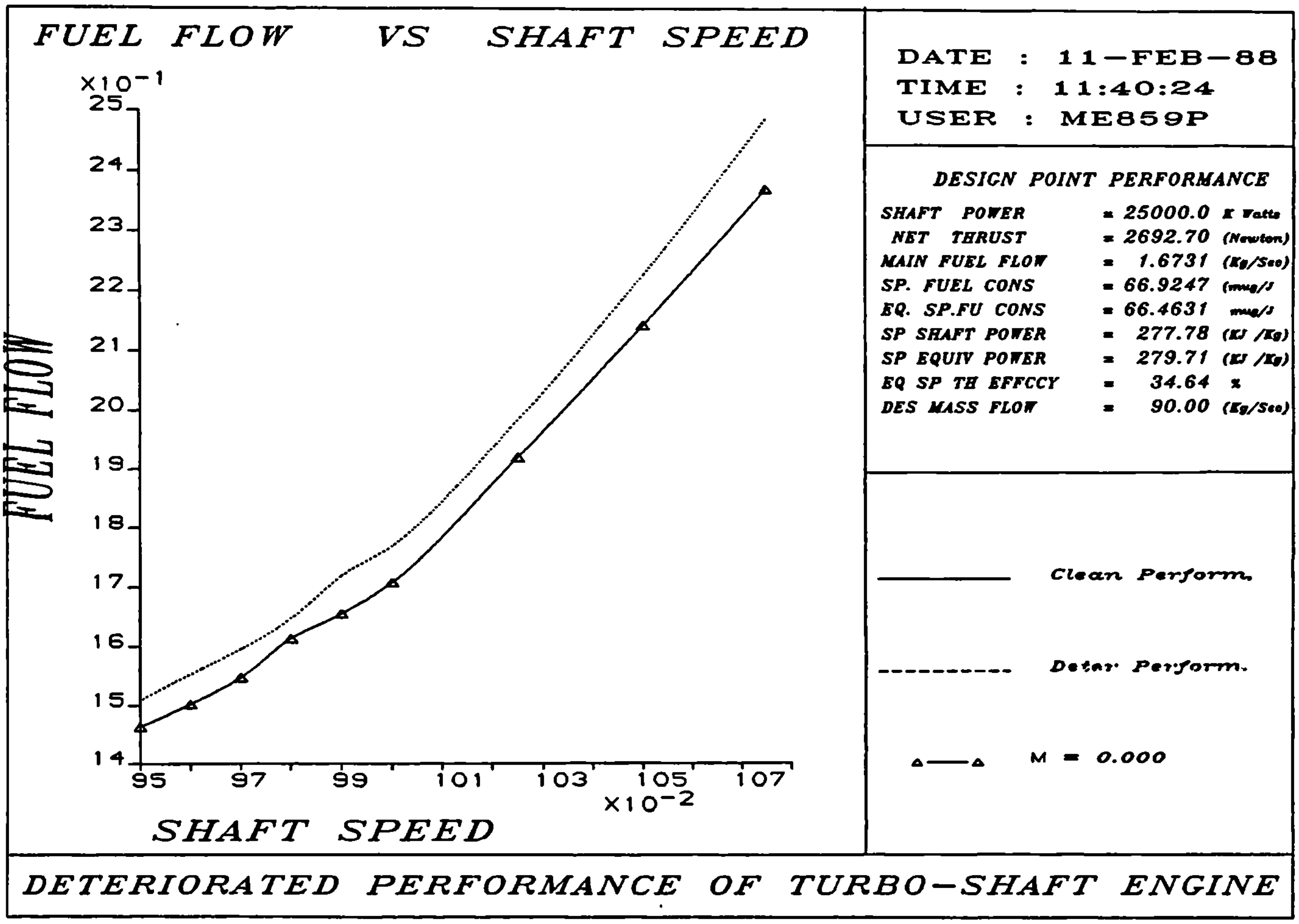
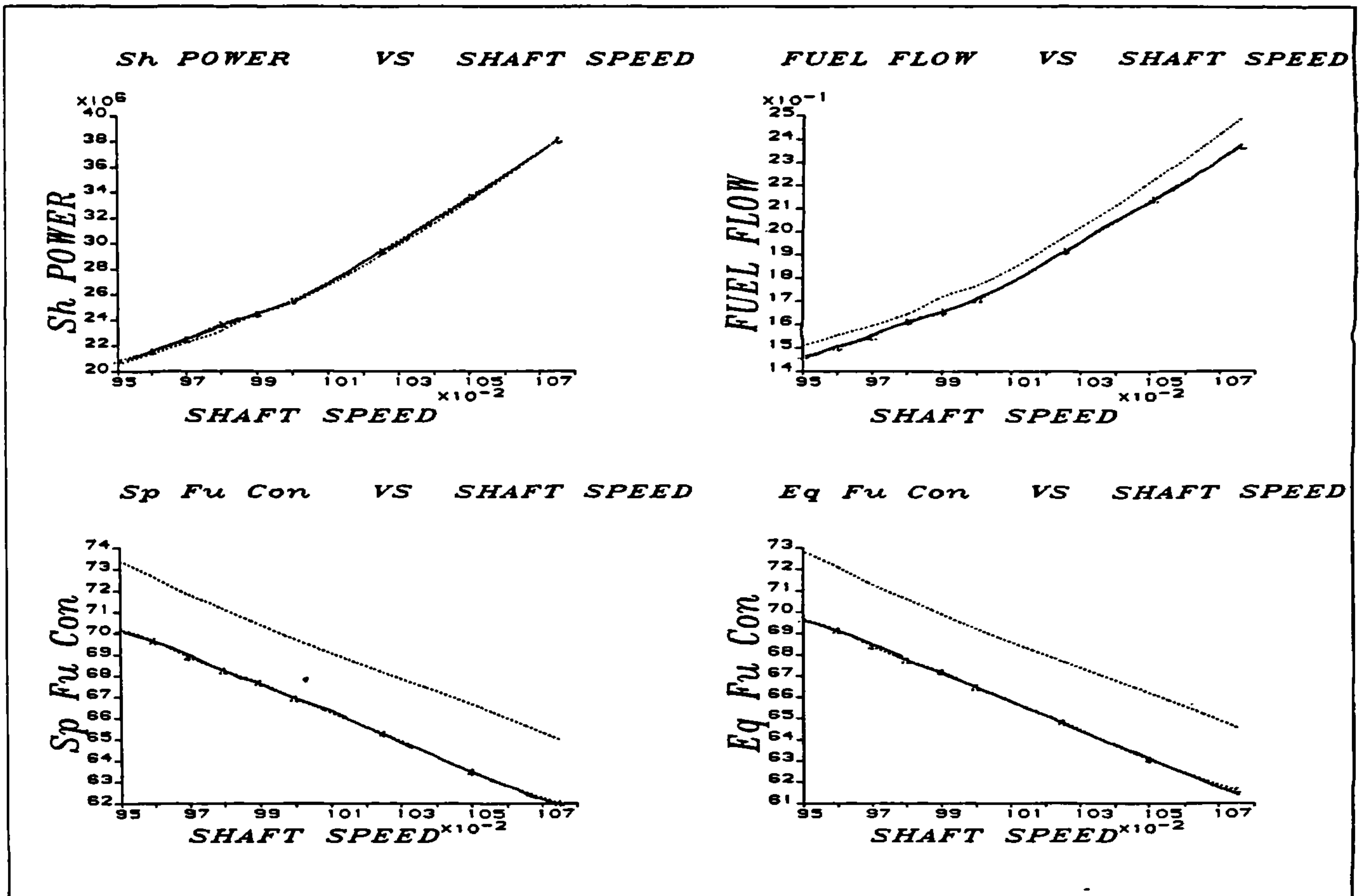
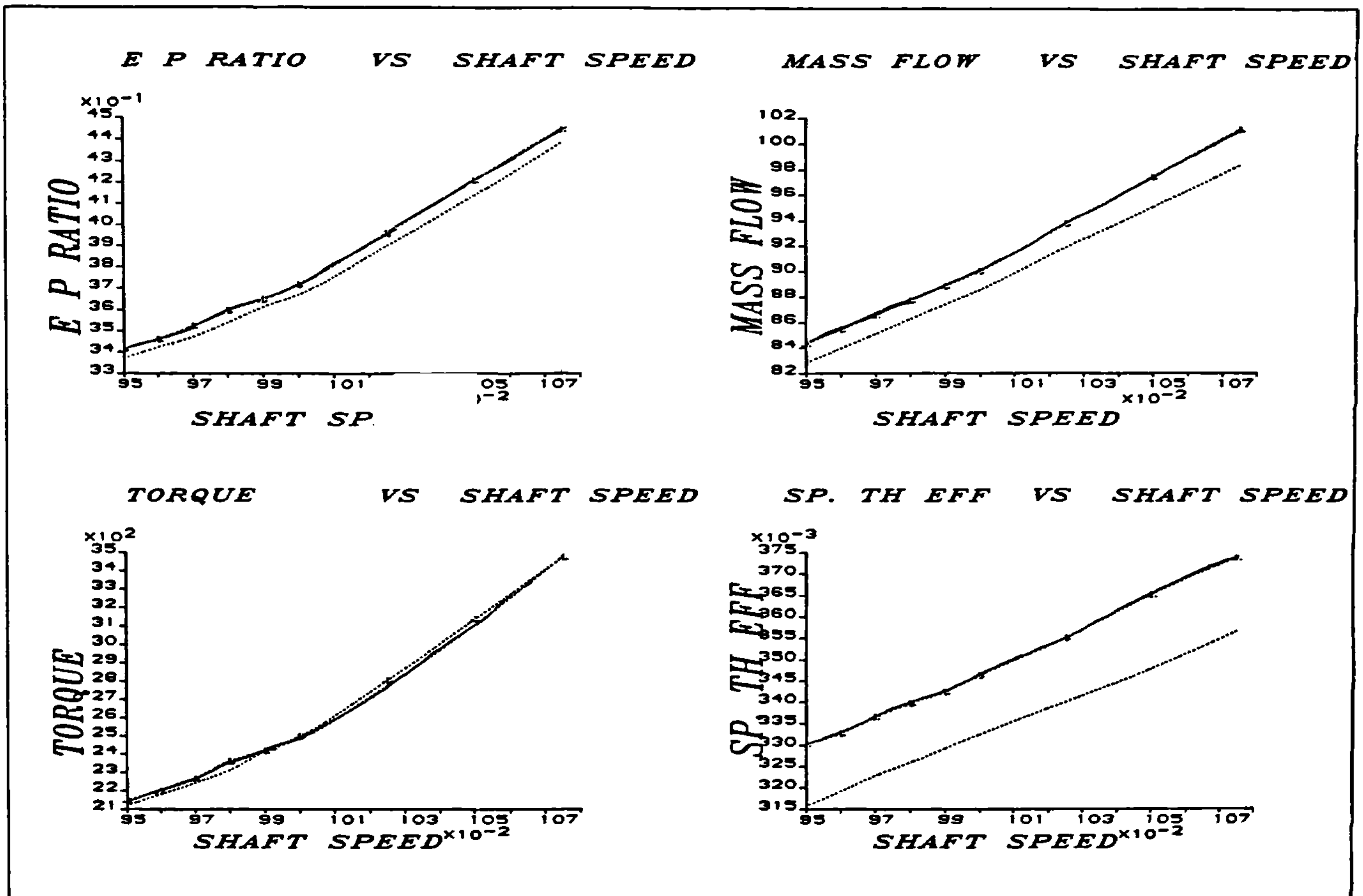

FUEL FLOW VS SHAFT SPEED
DATE : 11-FEB-88
TIME : 11:40:24
USER : ME859P
DESIGN POINT PERFORMANCE
SHAFT POWER = 25000.0 K Watts
NET THRUST = 2692.70 (Newton)
MAIN FUEL FLOW = 1.6731 (Kg/Sec)
SP. FUEL CONS = 66.9247 (mug/J
EQ. SP.FU CONS = 66.4631 mug/J
SP SHAFT POWER = 277.78 (KJ /Kg)
SP EQUIV POWER = 279.71 (KJ /Kg)
EQ SP TH EFFCCY = 34.64 %
DES MASS FLOW = 90.00 (Kg/Sec)
FUEL FLOW
x10^-1
25
24
23
22
21
20
19
18
17
16
15
14
95
97
99
101
103
105
107
x10^-2
SHAFT SPEED
Clean Perform.
Deter Perform.
M = 0.000
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

Fig 11.5(b)



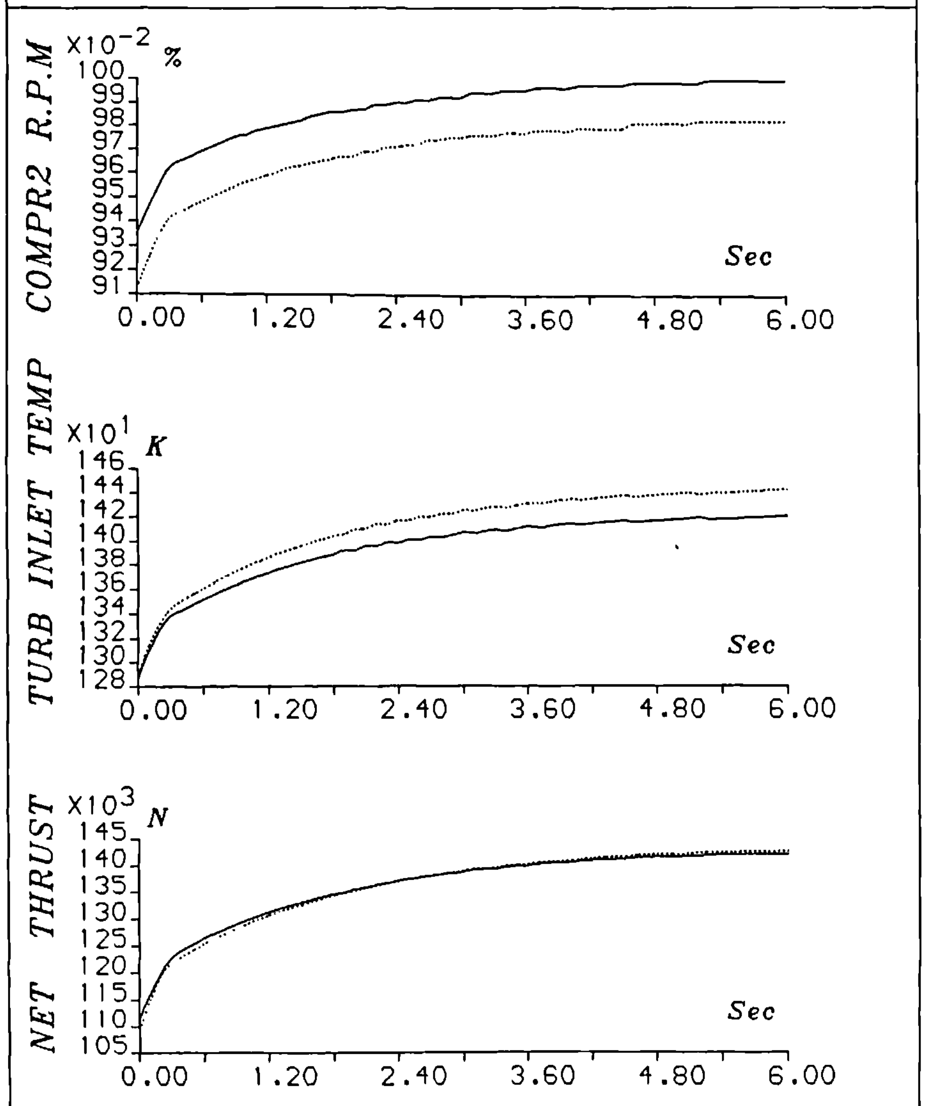
DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE



DETERIORATED PERFORMANCE OF TURBO-SHAFT ENGINE

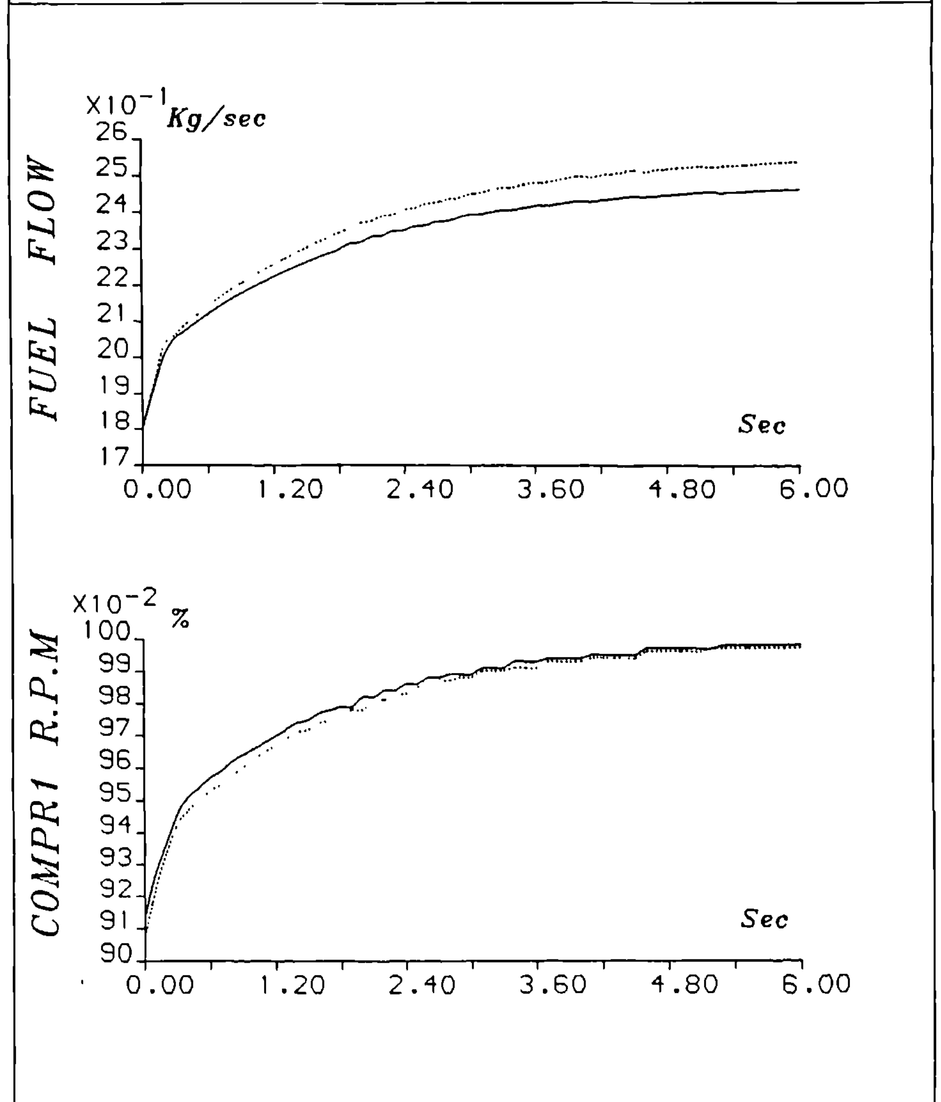
Fig 11.5(c)

DATE : 19-JAN-88 TIME : 21:11:11 USER : ME859P



EFFECTS OF DETERIORATION ON TRANSIENT PERFORMANCE

DATE : 19-JAN-88 TIME : 21:10:05 USER : ME859P



EFFECTS OF DETERIORATION ON TRANSIENT PERFORMANCE

Fig 11.6

INSTRUMENTATION NON REPEATABILITY ERRORS

SENSOR	ACCURACY % OF POINT	CORRECTED PARAMETER	ACCURACY % OF POINT
N1	0.02%	N1C2	0.09%
N2	0.02%	N2C2	0.13%
P2	0.13%	-	0.13%
P25	0.14%	P25	0.21%
P3	0.20%	P3C2	0.26%
Ps4	0.13%	Ps4C2	0.38%
P5	0.13%	P5	0.36%
P6	0.20%	P6	0.33%
P7	0.14%	P7	0.21%
DP/P25	1.00%	DP/P25	2.85%
DP/P4	1.00%	DP/P4	1.54%
T2	0.375%	T2	0.375%
T25	0.375%	T25	0.50%
T3	0.375%	T3	0.49%
T4	0.375%	T4	0.47%
T6	0.49%	T6	0.62%
T7	0.52%	T7	0.65%
T9	0.375%	T9	0.54%
mf	0.25%	mf	0.35%

TABLE II(a) TYPICAL MEASUREMENT NON-REPEATABILITIES

Raw Parameter % of Point		Corrected parameters % of point		Formula
ΔT2	0.20			
ΔP1	0.25			
ΔN1	0.10	N1C2	0.14	$\surd(0.1)^2+[0.5(0.2)^2]$
ΔT3	0.3	ΔT3C2	0.36	$\surd(0.3)^2 + (0.2)^2$
ΔP3	0.5	ΔP3C2	0.56	$\surd(0.5)^2 + (0.25)^2$
ΔMf	0.5	ΔWfC2	0.58	$\surd(0.5)^2+0.5(0.2)^2+(0.25)^2$
ΔP7	0.25	ΔP7/P2	0.35	$\surd(2(0.25)^2)$
ΔT9	0.4	ΔT9C2	0.45	$\surd((0.4)^2+(0.2)^2)$
ΔSHP	1.0	ΔSHPC2	1.03	$\surd((1)^2+(0.25)^2)$

TABLE II(b) CORRECTED PARAMETER UNCERTAINTY

MODULE	FAULT TYPE	INLET	LP COMPRESSOR			HP COMPRESSOR			HP TURBINE			LP TURBINE				POWER TURBINE			
		DP	PR	Q	N	PR	Q	N	PR	Q	N	PR	Q	N	B	PR	Q	N	B1
Inl	Increased Pr Drop	1.02																	
L	Fouling		.99	.988	.987														
P	Foreign Obj Damage		.98	.975	.98														
C	Tip Clea. Increase		.975	.944	.984														
H	Fouling					.99	.988	.987											
P	Foreign Object Dam					.98	.975	.98											
C	Tip Clearance Incr					.975	.944	.984											
H	Nozzle Erosion									1.005	.995								
	Nozzle Bowing									1.005	.995								
P	Fouling										.986								
T	Blade Damage										.985								
L	Nozzle Erosion												1.005	.995					
	Fouling													.986					
P	Tip Clearance Incr													.993					
T	Cool Airseal Leak													.98					
Po	Nozzle Erosion																1.005	.995	
T	Fouling																	.986	
u	Blade Damage																	.985	
r	Tip Clearance Incr																	.993	

TABLE III COMPONENT CHARACTERISTIC MODIFICATION FACTORS FT4 THREE-SPOOL TURBO-SHAFT ENGINE
[ref DUPUIS, 1986]

	GAMcomp	EFFcomp	AREAhpt	EFFhpt	AREApt	EFFpt
DELT3	0.3867	-0.2201	0.1707	-0.1489	0.0649	-0.0152
DELP3	1.3244	0.7923	0.5865	-0.5136	0.2236	-0.0523
DELmf	1.9971	0.3722	-0.5765	-2.2821	0.9951	-0.2319
DELT5	1.1589	0.7877	-0.1800	-0.4365	1.0389	-0.2421
DELP5	0.5808	-0.3956	-0.2880	-1.5681	0.6891	-0.1595
DELT6	0.4002	-0.5439	-0.3036	-1.5322	0.5238	-0.4043

	GAMlpc	EFFlpc	GAMhpc	EFFhpc	AREAhpt	EFFhpt	AREAlpt	EFFlpt	AREApt	EFFpt
DELP3	1.0236	0.8983	-0.3446	-0.5845	-0.2752	-0.8261	1.0886	0.3197	-0.5169	0.0391
DELT3	0.3200	-0.0165	-0.1072	-0.1817	-0.0856	-0.2565	0.3404	0.0997	-0.1607	0.0122
DELN2	0.4655	0.0721	-0.5190	-0.3322	0.3987	0.5933	-0.6818	-0.2012	0.5090	-0.0371
DELP4	1.5108	0.9552	-0.0360	-0.0755	0.9865	-0.0006	-0.7109	-0.4359	0.6156	-0.0639
DELT4	0.4668	0.0086	-0.1549	-0.3861	0.3284	0.0656	-0.4682	-0.2031	0.2332	-0.0315
DELmf	2.0341	0.7167	-0.3539	-0.5057	-0.2177	-0.7179	-1.7101	-1.7058	2.0081	-0.1675
DELP6	1.2938	0.7098	-0.0517	0.2756	-0.0394	0.0289	0.2529	-0.6767	0.7197	-0.0365
DELT6	0.5517	-0.1683	-0.2826	-0.3414	-0.1952	-0.5842	-0.6182	-0.8621	0.9425	-0.0708
DELP7	1.1910	0.6757	-0.0637	0.2277	-0.0246	0.0150	-0.7331	-0.6828	1.6240	-0.1139
DELT7	0.5399	-0.1775	-0.2944	-0.3602	-0.1941	-0.5931	-0.8727	-1.0495	1.1766	-0.0945

TABLE IV ENGINE FAULT COEFFICIENT MATRIX DETERMINED BY THE PROGRAM DETEM
(a) Two-spool Turbo Shaft Engine (upper)
(b) Three-spool Turbo Shaft Engine (lower)

	GAMfan	EFFfan	GAMlpc	EFFlpc	GAMhpc	EFFhpc	AREAhpt	EFFhpt	AREAlpt	EFFlpt
DELP3	0.1070	0.3661	0.9973	0.7716	-0.2363	-0.4657	-0.1236	-0.7294	0.6034	0.3376
DELT3	0.0187	0.0198	0.3337	0.1686	-0.0789	-0.1557	-0.0422	-0.2429	0.1999	0.1106
DELN2	0.4274	0.0947	-0.0812	-0.1321	-0.5293	-0.2479	0.3011	0.7501	-0.4277	-0.3288
DELP4	0.9100	0.5072	0.3501	0.2036	0.0056	0.0522	0.8916	0.1711	-0.3832	-0.6185
DELT4	0.3041	0.0705	0.0254	-0.0947	-0.2101	-0.4588	0.2979	0.1378	-0.3120	-0.3305
DELmf	2.0637	0.6608	-0.2586	-0.4231	-0.1269	-0.8181	-0.4151	-1.3641	-0.4357	-1.4076
DELP6	1.1930	0.5185	0.2630	0.1261	0.1083	0.1845	-0.0368	-0.0357	0.4765	-0.4385
DELT6	0.8792	0.1250	-0.3273	-0.4127	-0.2018	-0.6909	-0.3319	-1.1769	0.0122	-0.6104
DELP7	0.3211	-0.1038	-0.2704	-0.3716	0.1777	-0.2374	-0.3508	-0.6585	-0.4819	-0.5813
DELT7	0.7555	-0.0063	-0.4778	-0.5616	-0.2014	-0.8424	-0.4304	-1.4151	-0.2057	-1.0464

TABLE V THE INFLUENCE COEFFICIENT MATRIX DETERMINED BY DETEM - The columns Indicate The % changes in Measured quantities Brought by Changes in independent parameters marked in the first Row

	GAMfan	EFFfan	GAMlpc	EFFlpc	GAMhpc	EFFhpc	AREAhpt	EFFhpt	AREAlpt	EFFlpt
DELP3	0.1070	0.3661	0.9973	0.7716	-0.2363	-0.4657	-0.1236	-0.7294	0.6034	0.3376
DELT3	0.0187	0.0198	0.3337	0.1686	-0.0789	-0.1557	-0.0422	-0.2429	0.1999	0.1106
DELN2	0.4274	0.0947	-0.0812	-0.1321	-0.5293	-0.2479	0.3011	0.7501	-0.4277	-0.3288
DELP4	0.9100	0.5072	0.3501	0.2036	0.0056	0.0522	0.8916	0.1711	-0.3832	-0.6185
DELT4	0.3041	0.0705	0.0254	-0.0947	-0.2101	-0.4588	0.2979	0.1378	-0.3120	-0.3305
DELmf	2.0637	0.6608	-0.2586	-0.4231	-0.1269	-0.8181	-0.4151	-1.3641	-0.4357	-1.4076
DELP6	1.1930	0.5185	0.2630	0.1261	0.1083	0.1845	-0.0368	-0.0357	0.4765	-0.4385
DELT6	0.8792	0.1250	-0.3273	-0.4127	-0.2018	-0.6909	-0.3319	-1.1769	0.0122	-0.6104
DELP7	0.3211	-0.1038	-0.2704	-0.3716	0.1777	-0.2374	-0.3508	-0.6585	-0.4819	-0.5813
DELT7	0.7555	-0.0063	-0.4778	-0.5616	-0.2014	-0.8424	-0.4304	-1.4151	-0.2057	-1.0464

THE INFLUENCE COEFFICIENT MATRIX DETERMINED BY DETEM - The columns Indicate The % changes in Measured quantities Brought by Changes in independent parameters marked in the first Row. This part of the H matrix is the Fault Coefficient Matrix and hence identical to Table V

	P3SEN	T3SEN	N2SEN	P4SEN	T4SEN	mfSEN	P6SEN	T6SEN	P7SEN	T7SEN	N1SEN	SENP2	SENT2
DELP3	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.4617	-0.8488	0.7131
DELT3	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.6551	-0.1332	-0.7425
DELN2	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.9571	-0.0768	-0.1595
DELP4	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-3.0549	-0.8907	1.0339
DELT4	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.3359	-0.1423	-0.5790
DELmf	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	-5.3658	-1.0655	0.6488
DELP6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	-2.9830	-0.9187	0.9318
DELT6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	-2.0338	-0.1950	-0.6166
DELP7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	-2.2118	-1.2467	0.1264
DELT7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	-1.9779	-0.2852	-0.8504

TABLE VI THE SENSOR INFLUENCE COEFFICIENT MATRIX DETERMINED BY DETEM - The columns Indicate The % changes in Measured quantities Brought by Changes in instrument Sensitivities marked in the first Row

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3235	463.0483	0.9941	19.2147	740.3843	1.6282	6.9468	1145.8647	3.5861	992.1584

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-1.3485	-0.4218	-0.5900	-1.9598	-0.6047	-2.6836	-1.7370	-0.7527	-1.6078	-0.7364

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.99835	-0.00070	0.00555	-0.00069	-0.00248	-0.00115	-0.00293	-0.00039	-0.00300	0.00091

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3432	465.0866	0.9993	19.4116	744.8248	1.6611	7.0194	1156.4973	3.6200	1001.2935

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-0.8990	0.0165	-0.0700	-0.9552	-0.0086	-0.7172	-0.7101	0.1683	-0.6777	0.1775

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00037	-1.00062	-0.00517	0.00406	0.00015	0.00007	-0.00176	-0.00173	-0.00330	0.00368

Table VII(a) Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine Faults Imposed and Detected as Shown

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.4033	465.6949	1.0066	19.6109	746.3758	1.6806	7.0721	1158.7952	3.6461	1003.3046

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
0.4723	0.1473	0.6600	0.0617	0.1996	0.4483	0.0354	0.3673	0.0384	0.3787

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	L EFFIC	DEL AREA	DEL EFFIC
-0.00024	-0.00148	-0.99066	-0.00545	0.00257	-0.00060	0.00268	-0.00354	0.00235	0.02711

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.4082	465.8546	1.0033	19.6136	747.7648	1.6816	7.0501	1158.4966	3.6364	1003.1200

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
0.5841	0.1817	0.3300	0.0755	0.3861	0.5080	-0.2758	0.3414	-0.2277	0.3602

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00119	-0.00035	0.00277	-0.99959	-0.00256	-0.00022	-0.00170	-0.00010	-0.00410	-0.03153

Table VII(b) Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine Faults Imposed and Detected as Shown

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	+1.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3946	465.4080	0.9960	19.4055	742.4428	1.6768	7.0724	1156.8087	3.6456	1001.4592

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
0.2738	0.0856	-0.4000	-0.9863	-0.3284	0.2211	0.0396	0.1952	0.0247	0.1941

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00270	-0.00148	0.00199	0.00226	-1.00369	-0.00001	-0.00433	0.00017	-0.00369	0.00736

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
0.0	0.0	0.0	0.0	0.0	-1.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.4188	466.2026	0.9941	19.5989	744.4003	1.6851	7.0675	1161.2999	3.6441	1005.4473

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
0.8260	0.2565	-0.5900	0.0005	-0.0656	0.7172	-0.0297	0.5842	-0.0165	0.5931

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.00002	-0.00007	-0.00735	0.00468	0.00000	-1.00002	-0.00188	-0.00028	-0.00297	-0.00450

Table VII(c) Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine : Faults Imposed and Detected as Shown

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
0.0	0.0	0.0	0.0	0.0	0.0	+1.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3349	463.4271	1.0068	19.7381	748.3760	1.7017	7.0517	1161.6918	3.6714	1008.2425

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-1.0884	-0.3404	0.6800	0.7108	0.4682	1.7094	-0.2532	0.6182	0.7326	0.8727

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.00062	0.00013	0.00261	-0.00187	0.00084	-0.00048	-0.99847	-0.00069	-0.00011	-0.01555

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3685	464.5463	1.0020	19.6842	746.4017	1.7017	7.1174	1164.5079	3.6696	1010.0095

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-0.3217	-0.0997	0.2000	0.4357	0.2031	1.7094	0.6761	0.8621	0.6832	1.0495

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00306	-0.00208	0.00171	0.00303	-0.00438	-0.00028	-0.00530	-0.99837	-0.00387	0.00298

Table VII(d) Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine : Faults Imposed and Detected as Shown

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+1.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.4052	465.7570	0.9949	19.4782	743.1519	1.6395	7.0187	1143.6727	3.5855	987.7591

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
0.5157	0.1607	-0.5100	-0.6153	-0.2332	-2.0082	-0.7200	-0.9425	-1.6243	-1.1766

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00055	-0.00091	0.00337	-0.00173	0.00093	-0.00088	-0.00142	0.00016	-0.99586	0.06693

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3808	464.9532	1.0004	19.6113	745.1235	1.6759	7.0722	1155.3722	3.6488	1000.4642

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-0.0411	-0.0122	0.0400	0.0638	0.0315	0.1674	0.0368	0.0708	0.1125	0.0945

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	EL AREA	DEL EFFIC
0.00226	0.00121	0.02123	-0.02551	0.00645	-0.00417	-0.01775	0.00131	0.06291	-0.00599

Table VII(e) Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine : Faults Imposed and Detected as Shown

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
-0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3369	463.4949	0.9952	19.2966	741.3373	1.6384	6.9766	1148.0797	3.6006	994.0332

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-1.0428	-0.3258	-0.4800	-1.5419	-0.4768	-2.0740	-1.3155	-0.5608	-1.2100	-0.5489

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	L EFFIC	DEL AREA	DEL EFFIC
-0.78931	-0.00455	0.05151	-0.04872	0.00515	0.00646	0.06185	-0.01278	0.06817	-0.00584

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3328	464.0442	0.9968	19.3137	742.6111	1.6447	6.9825	1151.1724	3.6033	996.7195

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-1.1363	-0.2077	-0.3200	-1.4547	-0.3058	-1.6974	-1.2320	-0.2930	-1.1359	-0.2801

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.50078	-0.49811	-0.01060	0.01226	-0.00267	-0.00075	-0.01600	0.01206	-0.00062	0.00252

Table VIII Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine : Half Value Single and Multiple Faults

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
0.0	0.0	0.0	0.0	0.0	0.0	0.5	-0.7	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3472	463.8375	1.0058	19.7516	748.1803	1.7070	7.0794	1164.0111	3.6696	1010.3585

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-0.8077	-0.2521	0.5800	0.7796	0.4419	2.0262	0.1386	0.8191	0.6832	1.0844

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.05481	0.00914	-0.13193	0.12153	0.00211	-0.05346	-0.80413	-0.58274	-0.26406	0.01411

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
-1.0	0.0	0.0	-1.0	-1.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3637	464.3859	0.9931	19.0408	740.3215	1.6382	6.9357	1152.2784	3.5789	997.6566

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-0.4313	-0.1342	-0.6900	-2.8471	-0.6131	-2.0859	-1.8940	-0.1972	-1.8054	-0.1864

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	L EFFIC	DEL AREA	DEL EFFIC
-1.03224	-0.01609	-0.18552	-0.77437	-0.84889	-0.12704	0.12031	-0.03042	0.04925	-0.01441

Table IX Comparison of Faults Imposed and Detected by Fault Coefficient Method
For a Two Spool Turbo-shaft Engine

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
-1.0	-1.0	-1.0	-1.0	1.0	-1.0	1.0	-1.0	1.0	-1.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3147	464.1129	0.9985	19.2076	742.5381	1.6774	6.9374	1164.3059	3.5834	1010.1999

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-1.5493	-0.1929	-0.1500	-1.9960	-0.3156	0.2570	-1.8700	0.8446	-1.6819	1.0686

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.23116	-0.96259	-1.79901	1.77081	-1.12147	-1.00697	-1.90219	-0.67669	-1.83531	0.20835

Table X Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine
ALL FAULTS IN COMBINATION AND EACH 1% IN MAGNITUDE

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3235	463.0483	0.9941	19.2147	740.3843	1.6282	6.9468	1145.8647	3.5861	992.1584

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-1.3485	-0.4218	-0.5900	-1.9598	-0.6047	-2.6836	-1.7370	-0.7527	-1.6078	-0.7364

TURBINE ENGINE DIAGNOSTIC RESULTS

DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFI	DEL AREA	DEL EFFIC
-0.99835	-0.00070	0.00555	-0.00069	00248	-0.00115	-000293	-0.00039	-0.00300	0.00091

Table XI Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine
Beginning of the Looped faults No difference when compared with Table VII (a) values

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3428	465.0718	0.9994	19.4119	744.8356	1.6608	7.0177	1156.3236	3.6192	1001.1343

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-0.9104	0.0124	-0.0600	-0.9572	-0.0080	-0.7530	-0.7426	0.1449	-0.7024	0.1522

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFF	DEL AREA	DEL EFFIC
-0.00022	-0.99842	-0.02233	0.01930	0099	0.00024	-0.2895	0.02257	-0.02330	0.00549

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
4.3958	465.4459	0.9959	19.4145	742.5341	1.6779	7.0714	1157.3164	3.6458	1001.9448

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
0.3081	0.0957	-0.4200	-0.9550	-0.3228	0.2450	0.0170	0.2221	0.0055	0.2213

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFI	DEL AREA	DEL EFFIC
-0.00320	-0.00010	-0.02030	0.02127	96271	-0.07433	-001972	0.00188	-0.01830	0.00866

Table XII Comparison of Faults Imposed and Detected by Fault Coefficient Method
For a Two Spool Turbo-shaft Engine Faults in a Loop

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9
4.4204	466.2557	0.9934	19.5902	744.2542	1.6856	7.0734	1161.9161	3.6462

Note: the printed input data row carries a tenth value, 1005.9489, beneath DEL 9 position.

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
0.7269	0.2257	-0.4709	0.0531	-0.0382	0.6388	-0.2003	0.4868	-0.1807	0.4960

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.03409	0.00380	-0.22745	0.22028	-0.01769	-1.00823	-0.27407	0.05140	-0.27455	0.02243

Table XIII Comparison of Faults Imposed and Detected by Fault Coefficient Method
For a Two Spool Turbo-shaft Engine Faults in a Loop

Notes : The parameters Monitored for the three spool turboshaft engines were

P3 ,T3 ,N2 ,P4 ,T4 ,fuel flow ,P6 ,T6 ,P7 ,T7 Total = 10

When only 9 parameters were monitored P6 was dropped out

In the loop the initial point was determined by rematching to design conditions and the characteristics of 4 components (compressor 1 mass flow, compressor 1 efficiency , Turbine 1 Area and Turbine 1 effeciency) was changed one at a time by a value of 1 %. The results are as shown.

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9
4.3235	463.0483	0.9941	19.2147	740.3843	1.6282	1145.8647	3.5861	992.1584

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9
-1.3485	-0.4218	-0.5900	-1.9598	-0.6047	-2.6836	-0.7527	-1.6078	-0.7364

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL AREA	L EFFIC	DEL AREA	DEL EFFIC	
-0.99820	-0.00057	0.00933	-0.00472	-0.00176	0.00592	0.00472	-0.01194	-0.00345	0.00867

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3n
-1.0	-1.0	-1.0	-1.0	1.0	-1.0	1.0	-1.0	1.0	-1.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9
4.3507	465.3423	1.0031	19.2166	745.4194	1.6898	1171.7712	3.5833	1016.7838

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9
-0.7279	0.0715	0.3100	-1.9501	0.0712	0.9981	1.4912	-1.6846	1.7273

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1					
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL				
-0.30698	-1.02631	-2.52367	1.19868	-1.09194	-1.73155	-2.24216	0.27906	-1.60834	-2.50578

Table XIV Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine (9 parameters monitored)

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00070	-1.00051	-0.00145	-0.00027	0.00092	0.00743	0.00620	-0.01378	-0.00361	0.01411

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00016	-0.00095	-0.03682	-0.96676	-0.00735	-0.06634	-0.07411	0.10449	0.00918	0.05773

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00327	-0.00174	-0.00356	0.00742	-1.00460	-0.00598	-0.01005	0.00990	-0.00672	-0.05026

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	0.0	-1.0	0.0	0.0	0.0	0.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00191	0.00055	0.04664	-0.04073	0.00658	-0.90152	0.10722	-0.15623	-0.02948	-0.23370

Table XV Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine CHANGED INSTRUMENTATION

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00122	0.00081	0.06431	-0.05110	0.00772	0.10555	-0.88133	-0.16772	-0.02779	-0.25817

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	0.0	0.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
0.00027	-0.00365	-0.10738	0.09194	-0.01719	-0.18223	-0.20494	-0.71097	0.03518	0.28936

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.00013	-0.00152	-0.02044	0.01865	-0.00225	-0.03590	-0.03891	0.05599	-0.99465	0.02770

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.00

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.99754	-0.00031	0.02608	-0.02231	0.00114	0.04496	0.04823	-0.07488	-0.01494	-0.08362

Table XV (contd.) Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine CHANGED PARAMETERS OF MEASURE

FAULTS IMPOSED

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1	EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
-1.0	-1.0	-1.0	-1.0	1.0	-1.0	1.0	-1.0	1.0	-1.00

--- INPUT DATA ---

MON 1	MON 2	MON 3	MON 4	MON 5	MON 6	MON 7	MON 8	MON 9	MON 10
4.3611	465.6958	1.0027	19.3186	746.4420	1.7033	1174.5286	3.6011	1019.3020	1.0331

--- MEASURED DELTAS ---

DEL 1	DEL 2	DEL 3	DEL 4	DEL 5	DEL 6	DEL 7	DEL 8	DEL 9	DEL 10
-0.4906	0.1475	0.2700	-1.4297	0.2085	1.8050	1.7300	-1.1963	1.9792	0.0097

TURBINE ENGINE DIAGNOSTIC RESULTS

COMPRESSOR1		COMPRESSOR2		TURBINE 1		TURBINE 2		TURBINE 3	
DEL MASS	DEL EFFIC	DEL MASS	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC	DEL AREA	DEL EFFIC
-0.00196	-0.98544	-1.12509	-0.32313	-0.81405	0.55868	0.29325	-3.69338	-1.53970	3.15931

Table XVI Comparison of Faults Imposed and Detected by Fault Coefficient Method For a Two Spool Turbo-shaft Engine

ALL THE FAULTS IMPOSED TOGETHER , EACH OF MAGNITUDE 1%

Notes : The parameters Monitored for the three spool turboshaft engines were

P3 ,T3 ,N2 ,P4 ,T4 ,fuel flow ,T6 ,P7 ,T7, P8 Total = 10

	GAMfan	EFFfan	GAMlpc	EFFlpc	GAMhpc	EFFhpc	AREAhpt	EFFhpt	AREAlpt	EFFlpt	P3SEN	T3SEN
DELP3	0.1070	0.3661	0.9973	0.7716	-0.2363	-0.4657	-0.1236	-0.7294	0.6034	0.3376	1.0000	0.0000
DELT3	0.0187	0.0198	0.3337	0.1686	-0.0789	-0.1557	-0.0422	-0.2429	0.1999	0.1106	0.0000	1.0000
DELN2	0.4274	0.0947	-0.0812	-0.1321	-0.5293	-0.2479	0.3011	0.7501	-0.4277	-0.3288	0.0000	0.0000
DELP4	0.9100	0.5072	0.3501	0.2036	0.0056	0.0522	0.8916	0.1711	-0.3832	-0.6185	0.0000	0.0000
DELT4	0.3041	0.0705	0.0254	-0.0947	-0.2101	-0.4588	0.2979	0.1378	-0.3120	-0.3305	0.0000	0.0000
DELmf	2.0637	0.6608	-0.2586	-0.4231	-0.1269	-0.8181	-0.4151	-1.3641	-0.4357	-1.4076	0.0000	0.0000
DELP6	1.1930	0.5185	0.2630	0.1261	0.1083	0.1845	-0.0368	-0.0357	0.4765	-0.4385	0.0000	0.0000
DELT6	0.8792	0.1250	-0.3273	-0.4127	-0.2018	-0.6909	-0.3319	-1.1769	0.0122	-0.6104	0.0000	0.0000
DELP7	0.3211	-0.1038	-0.2704	-0.3716	0.1777	-0.2374	-0.3508	-0.6585	-0.4819	-0.5813	0.0000	0.0000
DELT7	0.7555	-0.0063	-0.4778	-0.5616	-0.2014	-0.8424	-0.4304	-1.4151	-0.2057	-1.0464	0.0000	0.0000

TABLE XVII THE INFLUENCE COEFFICIENT MATRIX DETERMINED BY DETEM - The columns Indicate The % changes in Measured quantities Brought by Changes in independent parameters marked in the first Row

	N2SEN	P4SEN	T4SEN	mfSEN	P6SEN	T6SEN	P7SEN	T7SEN	N1SEN	SENP2	SENT2
DELP3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.4617	-0.8488	-0.7131
DELT3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.6551	-0.1332	-0.7425
DELN2	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.9571	-0.0768	-0.1595
DELP4	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-3.0549	-0.8907	1.0339
DELT4	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.3359	-0.1423	-0..5790
DELmf	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	-5.3658	-1.0655	0.6488
DELP6	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	-2.9830	-0.9187	0.9318
DELT6	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	-2.0338	-0.1950	-0.6166
DELP7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	-2.2118	-1.2467	0.1264
DELT7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	-1.9779	-0.2852	-0.8504

TABLE XVII THE SENSOR INFLUENCE COEFFICIENT MATRIX DETERMINED BY DETEM - The columns Indicate The % changes in Measured quantities Brought by Changes in instrument Sensitivities marked in the first Row

Number Of data Points 500
number of monitored parameters10
weight index 0

	GAMfan	EFFfan	GAMlpc	EFFlpc	GAMhpc	EFFhpc	AREAhpt	EFFhpt
GAMfan	0.3042633	0.1137433	0.1133683	0.2197702	0.0575292	0.0969885	-0.0438698	0.0634078
EFFfan	0.1137433	0.3738952	0.1392292	0.2700480	0.0705744	0.1189488	-0.0538696	0.0778779
GAMlpc	0.1133683	0.1392292	0.3727021	0.2690934	0.0705883	0.1190462	-0.0537618	0.0776842
EFFlpc	0.2197702	0.2700480	0.2690934	0.7223143	0.1365058	0.2301156	-0.1041257	0.1505096
GAMhpc	0.0575292	0.0705744	0.0705883	0.1365058	0.1897378	0.0607682	-0.0273326	0.0394670
EFFhpc	0.0969885	0.1189488	0.1190462	0.2301156	0.0607682	0.3203096	-0.0461011	0.0665565
AREAhpt	-0.0438698	-0.0538696	-0.0537618	-0.1041257	-0.0273326	-0.0461011	0.1442529	-0.0300656
EFFhpt	0.0634078	0.0778779	0.0776842	0.1505096	0.0394670	0.0665565	-0.0300656	0.2084368
AREAlpt	-0.0334500	-0.0410775	-0.0409890	-0.0793958	-0.0208343	-0.0351387	0.0158647	-0.0229229
EFFlpt	0.0235087	0.0288622	0.0288163	0.0557953	0.0146589	0.0247284	-0.0111544	0.0161145
P3SEN	0.0000274	0.0000303	0.0000378	0.0000631	0.0000245	0.0000435	-0.0000151	0.0000207
T3SEN	0.0706111	0.0865463	0.0867340	0.1675014	0.0443492	0.0749051	-0.0335957	0.0484853
N2SEN	-0.0001351	-0.0001646	-0.0001672	-0.0003199	-0.0000871	-0.0001477	0.0000649	-0.0000934
P4SEN	0.0015389	0.0019345	0.0018300	0.0036792	0.0008608	0.0014241	-0.0007015	0.0010289
T4SEN	0.2476855	0.3049575	0.3025234	0.5883692	0.1525497	0.2568037	-0.1169703	0.1692804
mfSEN	0.0024147	0.0029697	0.0029534	0.0057340	0.0014942	0.0025172	-0.0011424	0.0016522
P6SEN	0.0000987	0.0001214	0.0001205	0.0002343	0.0000607	0.0001020	-0.0000466	0.0000675
T6SEN	1.3436077	1.6504152	1.6458830	3.1894028	0.8358649	1.4094556	-0.6369643	0.9205080
P7SEN	-0.0001178	-0.0001405	-0.0001494	-0.0002771	-0.0000826	-0.0001420	0.0000585	-0.0000831
T7SEN	1.1387815	1.3992922	1.3943780	2.7034776	0.7073749	1.1924816	-0.5395567	0.7799054
N1SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
P2SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
T2SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

TABLE XVIII VARIANCE - COVARIANCE MATRIX OF 10 ENGINE FAULTS, 10 DEPENDENT MEASUREMENTS FAULTS AND 3 SENSORS OF CONTROL/STANDARDISATION FOR A HYPOTHETICAL TWO SPOOL TURBOFAN ENGINE sheet 1 of 2

	AREAlpt	EFFlpt	P3SEN	T3SEN	N2SEN	P4SEN	T4SEN
GAMfan	-0.0334500	0.0235087	0.0000274	0.0706111	-0.0001351	0.0015389	0.2476855
EFFfan	-0.0410775	0.0288622	0.0000303	0.0865463	-0.0001646	0.0019345	0.3049575
GAMlpc	-0.0409890	0.0288163	0.0000378	0.0867340	-0.0001672	0.0018300	0.3025234
EFFlpc	-0.0793958	0.0557953	0.0000631	0.1675014	-0.0003199	0.0036792	0.5883692
GAMhpc	-0.0208343	0.0146589	0.0000245	0.0443492	-0.0000871	0.0008608	0.1525497
EFFhpc	-0.0351387	0.0247284	0.0000435	0.0749051	-0.0001477	0.0014241	0.2568037
AREAhpt	0.0158647	-0.0111544	-0.0000151	-0.0335957	0.0000649	-0.0007015	-0.1169703
EFFhpt	-0.0229229	0.0161145	0.0000207	0.0484853	-0.0000934	0.0010289	0.1692804
AREAlpt	0.1099788	-0.0085038	-0.0000114	-0.0256042	0.0000494	-0.0005373	-0.0892233
EFFlpt	-0.0085038	0.0773290	0.0000085	0.0180258	-0.0000349	0.0003713	0.0626153
P3SEN	-0.0000114	0.0000085	0.0009286	0.0000703	-0.0000003	0.0000014	0.0000166
T3SEN	-0.0256042	0.0180258	0.0000703	0.2381707	-0.0001167	0.0011926	0.1852671
N2SEN	0.0000494	-0.0000349	-0.0000003	-0.0001167	0.0005316	-0.0000008	-0.0003235
P4SEN	-0.0005373	0.0003713	0.0000014	0.0011926	-0.0000008	0.0137555	0.0061216
T4SEN	-0.0892233	0.0626153	0.0000166	0.1852671	-0.0003235	0.0061216	0.8335569
mfSEN	-0.0008712	0.0006119	0.0000010	0.0018564	-0.0000035	0.0000620	0.0066992
P6SEN	-0.0000356	0.0000249	0.0000016	0.0001649	-0.0000005	0.0000322	0.0004631
T6SEN	-0.4856537	0.3413787	0.0004740	1.0292639	-0.0019963	0.0254577	3.6228398
P7SEN	0.0000443	-0.0000318	-0.0000005	-0.0001173	0.0000003	0.0000126	-0.0001203
T7SEN	-0.4114128	0.2891222	0.0002888	0.8658050	-0.0016619	0.0222113	3.0867112
N1SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
P2SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
T2SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

	mfSEN	P6SEN	T6SEN	P7SEN	T7SEN	N1SEN	P2SEN	T2SEN
GAMfan	0.0024147	0.0000987	1.3436077	-0.0001178	1.1387815	0.0000000	0.0000000	0.0000000
EFFfan	0.0029697	0.0001214	1.6504152	-0.0001405	1.3992922	0.0000000	0.0000000	0.0000000
GAMlpc	0.0029534	0.0001205	1.6458830	-0.0001494	1.3943780	0.0000000	0.0000000	0.0000000
EFFlpc	0.0057340	0.0002343	3.1894028	-0.0002771	2.7034776	0.0000000	0.0000000	0.0000000
GAMhpc	0.0014942	0.0000607	0.8358649	-0.0000826	0.7073749	0.0000000	0.0000000	0.0000000
EFFhpc	0.0025172	0.0001020	1.4094556	-0.0001420	1.1924816	0.0000000	0.0000000	0.0000000
AREAhpt	-0.0011424	-0.0000466	-0.6369643	0.0000585	-0.5395567	0.0000000	0.0000000	0.0000000
EFFhpt	0.0016522	0.0000675	0.9205080	-0.0000831	0.7799054	0.0000000	0.0000000	0.0000000
AREAlpt	-0.0008712	-0.0000356	-0.4856537	0.0000443	-0.4114128	0.0000000	0.0000000	0.0000000
EFFlpt	0.0006119	0.0000249	0.3413787	-0.0000318	0.2891222	0.0000000	0.0000000	0.0000000
P3SEN	0.0000010	0.0000016	0.0004740	-0.0000005	0.0002888	0.0000000	0.0000000	0.0000000
T3SEN	0.0018564	0.0001649	1.0292639	-0.0001173	0.8658050	0.0000000	0.0000000	0.0000000
N2SEN	-0.0000035	-0.0000005	-0.0019963	0.0000003	-0.0016619	0.0000000	0.0000000	0.0000000
P4SEN	0.0000620	0.0000322	0.0254577	0.0000126	0.0222113	0.0000000	0.0000000	0.0000000
T4SEN	0.0066992	0.0004631	3.6228398	-0.0001203	3.0867112	0.0000000	0.0000000	0.0000000
mfSEN	0.0083046	0.0000131	0.0367033	0.0000026	0.0314115	0.0000000	0.0000000	0.0000000
P6SEN	0.0000131	0.0046279	0.0046350	0.0000097	0.0043414	0.0000000	0.0000000	0.0000000
T6SEN	0.0367033	0.0046350	4.4796165	0.0000919	17.1105107	0.0000000	0.0000000	0.0000000
P7SEN	0.0000026	0.0000097	0.0000919	0.0025890	0.0005170	0.0000000	0.0000000	0.0000000
T7SEN	0.0314115	0.0043414	17.1105107	0.0005170	3.8245750	0.0000000	0.0000000	0.0000000
N1SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
P2SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
T2SEN	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

TABLE XVIII VARIANCE - COVARIANCE MATRIX OF 10 ENGINE FAULTS, 10 DEPENDENT MEASUREMENTS FAULTS AND 3 SENSORS OF CONTROL/STANDARDISATION FOR A HYPOTHETICAL TWO SPOOL TURBOFAN ENGINE 1 OF 2

	P3C2	T3C2	N2C2	P4C2	T4C2	Mfc2	P6C2	T6C2	P7C2	T7C2
GAMF	-0.0562	0.0166	0.0890	0.0608	-0.0224	0.1781	0.2922	0.0431	-0.0095	-0.1101
ETAF	0.1014	-0.1263	-0.0406	0.0949	-0.0526	0.1890	0.0458	-0.0613	-0.1432	-0.1227
GAMLC	0.2989	0.2073	0.0096	0.1038	0.0814	-0.0682	0.0377	-0.1022	0.1343	-0.0500
ETALC	0.3107	-0.0356	-0.0563	0.1029	-0.0966	0.1053	0.0501	-0.1865	-0.0370	-0.1840
GAMHP	-0.0784	-0.0368	-0.3488	0.0864	0.0017	0.0555	0.0928	-0.1211	0.1799	-0.1159
ETAHP	-0.1846	-0.0552	-0.1976	0.1201	-0.3625	-0.0046	0.2195	-0.1058	0.0537	-0.1245
AREAHP	-0.0955	0.0055	-0.0436	0.3528	0.1423	-0.1727	-0.1539	0.1243	-0.1156	0.1272
ETAHPT	-0.1064	-0.0380	0.2904	-0.0734	0.1376	-0.0054	0.1247	-0.1260	-0.0720	-0.1574
AREALP	-0.0145	0.0307	-0.0490	-0.1561	-0.0138	-0.1416	0.2039	0.1620	-0.2168	0.1230
ETALPT	0.0391	0.0123	-0.0205	-0.0814	-0.0267	0.0241	-0.0221	0.0745	-0.0773	-0.1276

THE ENGINE FAULT COEFFICIENT MATRIX (MAXIMUM A-POSTERIORI SOLUTION)

P3SEN	0.0010	-0.0009	0.0005	-0.0002	-0.0001	-0.0002	-0.0002	-0.0001	0.0005	0.0001
T3SENS	-0.0013	0.0058	0.0001	0.0001	-0.0002	0.0002	0.0001	-0.0003	0.0001	-0.0003
N2SENS	0.0005	0.0002	0.0026	-0.0005	-0.0012	-0.0004	0.0000	0.0002	0.0005	0.0003
P4SENS	-0.0002	0.0000	-0.0006	0.0030	-0.0008	-0.0009	-0.0010	0.0006	0.0002	0.0007
T4SENS	0.0000	-0.0003	-0.0027	-0.0011	0.0081	-0.0001	0.0015	-0.0007	0.0003	-0.0011
mfsens	-0.0008	0.0007	-0.0027	-0.0058	-0.0019	0.0193	-0.0098	-0.0096	-0.0062	-0.0093
P6SENS	-0.0004	0.0000	0.0002	-0.0013	0.0011	-0.0022	0.0041	0.0002	0.0008	0.0014
T6SENS	0.0003	-0.0012	0.0004	0.0043	-0.0024	-0.0074	0.0016	0.0279	-0.0014	-0.0142
P7SENS	0.0020	0.0003	0.0020	0.0004	0.0004	-0.0028	0.0016	-0.0007	0.0142	-0.0026
T7SENS	0.0026	-0.0011	0.0011	0.0056	-0.0043	-0.0078	0.0083	-0.0157	-0.0066	0.0243
N1SENS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
P2SENS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
T2SENS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

THE SENSOR FAULT COEFFICIENT MATRIX (MAXIMUM A-POSTERIORI SOLUTION)

TABLE IX "INVERTED" ENGINE/SENSOR FAULT COEFFICIENTS
(MAXIMUM A-POSTERIORY SOLUTION FOR THE PDF's By Fig 10.3 and 10.4)

TABLE 20

$\Delta\Gamma$	$\Delta\eta$	$\Delta\left(\frac{P_3}{P_2}\right)$	$\Delta\left(\frac{N_2}{\sqrt{T_2}}\right)$	$\Delta\left(\frac{P_4}{P_2}\right)$	$\Delta\left(\frac{m_f}{P_2\sqrt{T_2}}\right)$	$\Delta\left(\frac{T_6}{T_2}\right)$	$\Delta\left(\frac{P_6}{P_2}\right)$	$\Delta\left(\frac{T_7}{T_2}\right)$	$\Delta\left(\frac{P_7}{P_2}\right)$
0.00	5.00	↓	↑	↑	↑	↑	↑	↑	↑
1.00	4.00	↓	↑	↑	↑	↑	↑	↑	↑
2.00	3.00	↓	↑	↓	↑	↑	↓	↑	↓
3.00	2.00	↓	↓	↓	↓	↓	↓	↑	↓
4.00	1.00	↓	↓	↓	↓	↓	↓	↓	↓
1.00	1.00	↓	↓	↓	↓	↓	↓	↓	↓
2.00	2.00	↓	↑	↓	↓	↑	↓	↑	↓
3.00	3.00	↓	↑	↓	↑	↑	↓	↑	↓
4.00	1.00	↓	↓	↓	↓	↓	↓	↓	↓
5.00	0.00	↓	↓	↓	↓	↓	↓	↓	↓

Two Spool Turbo-jet Engine

DEVIATIONS OBSERVED DUE TO LP COMPRESSOR FAULT

TABLE 21

ΔA	$\Delta\eta$	$\Delta\left(\frac{P_3}{P_2}\right)$	$\Delta\left(\frac{N_2}{\sqrt{T_2}}\right)$	$\Delta\left(\frac{P_4}{P_2}\right)$	$\Delta\left(\frac{m_f}{P_2\sqrt{T_2}}\right)$	$\Delta\left(\frac{T_6}{T_2}\right)$	$\Delta\left(\frac{P_6}{P_2}\right)$	$\Delta\left(\frac{T_7}{T_2}\right)$	$\Delta\left(\frac{P_7}{P_2}\right)$
0.00	3.00	↓	↓	↓	↑	↑	↓	↑	↓
1.00	3.00	↓	↓	↓	↑	↑	↓	↑	↓
1.00	2.00	↓	↓	↓	↑	↑	↓	↑	↓
2.00	2.00	↓	↓	↓	↑	↑	↓	↑	↓
3.00	3.00	↓	↓	↓	↑	↑	↓	↑	↓
1.00	1.00	↓	↓	↓	↑	↑	↓	↑	↓
3.00	0.00	↓	↓	↓	↑	↑	↓	↑	↓
3.00	1.00	↓	↓	↓	↑	↑	↓	↑	↓
0.00	1.00	↓	↓	↓	↑	↑	↓	↑	↓
2.00	0.00	↓	↓	↓	↑	↑	↓	↑	↓

Two Spool Turbo-jet Engine

DEVIATIONS OBSERVED DUE TO HP TURBINE FAULTS

TABLE 22			
Module	**parameter**	**Imposed Fault**	**Detected Fault**
comp1	Γ	2.500	2.503
	η	2.900	2.900
comp2	Γ	1.800	1.799
	η	1.700	1.703
turb1	A	0.980	0.969
	η	1.100	1.116
turb2	A	1.300	1.020
	η	1.200	0.869
turb3	A	1.450	1.300
	η	1.500	0.956

A COMPARISON OF IMPOSED AND DETECTED FAULTS

TABLE 23			
Module	**parameter**	**Imposed Fault**	**Detected Fault**
comp1	Γ	1.100	1.073
	η	1.300	1.308
comp2	Γ	1.400	1.370
	η	1.100	1.070
turb1	A	0.000	0.007
	η	0.000	0.080
turb2	A	0.450	0.394
	η	0.560	0.614
turb3	A	0.960	0.900
	η	0.380	0.450

A COMPARISON OF IMPOSED AND DETECTED FAULTS

TABLE XXIV COMPARISON OF FAULTY ENGINE AND SIMULATED ENGINE

***** DESIGN POINT ENGINE CALCULATIONS *****

PROGRAM RUN ON 26-JAN-88 AT 12:27:07 Hrs

***** AMBIENT AND INLET PARAMETERS *****

Alt. = 0.0	I.S.A. Dev. = 0.000	Mach No. = 0.00
Etar = 0.9800	Momentum Drag = 0.00	
Specific Humidity = 0.00000		

***** COMPRESSOR 1 PARAMETERS *****

PRSF = 0.34039E+01	ETASF = 0.10482E+01	WASF = 0.51600E+00
Z = 0.85000	PR = 4.472	ETA = 0.87000
PCN = 1.0000	CN = 1.00000	COMWK = 0.16105E+08

***** COMPRESSOR 2 PARAMETERS *****

PRSF = 0.34039E+01	ETASF = 0.10482E+01	WASF = 0.14603E+00
Z = 0.85000	PR = 4.472	ETA = 0.87000
PCN = 1.0000	CN = 1.00000	COMWK = 0.26542E+08

***** COMBUSTION CHAMBER 1 PARAMETERS *****

ETASF = 0.10000E+01		
ETA = 1.00000	DLP = 0.9799	WFB = 1.6731

***** TURBINE 1 PARAMETERS *****

CNSF = 0.10675E+03	ETASF = 0.10216E+01	TFSF = 0.23386E+01
DHSF = 0.53129E+04		
TF = 401.640	ETA = 0.88000	CN = 2.819
AUXWK = 0.00000E+00		

***** TURBINE 2 PARAMETERS *****

CNSF = 0.95786E+02	ETASF = 0.10216E+01	TFSF = 0.92989E+00
DHSF = 0.37625E+04		
TF = 401.640	ETA = 0.88000	CN = 2.819
AUXWK = 0.00000E+00		

***** TURBINE 3 PARAMETERS *****

CNSF = 0.89123E-02	ETASF = 0.10216E+01	TFSF = 0.50508E+00
DHSF = 0.66129E+04		
TF = 401.640	ETA = 0.88000	CN = 2.819
AUXWK = 0.25000E+08		

Additional Free Turbine Parameters:-

Speed = 100.0%	Power = 0.25000E+08

***** CONVERGENT NOZZLE 1 PARAMETERS *****

Area = 6.5407	Exit Velocity = 30.28
Gross Thrust = 2692.70	Nozzle Coeff. = 0.97005E+00

Scale Factor on above Mass Flows, Areas, Thrusts & Powers = 1.0000

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	90.000	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	90.000	******	0.98000	******	288.15	******	******
3	0.00000	90.000	******	4.38256	******	465.01	******	******
4	0.00000	90.000	******	19.59881	******	744.89	******	******
5	0.00000	82.770	******	19.59881	******	744.89	******	******
6	0.02021	84.443	******	18.61887	******	1434.00	******	******
7	0.02021	84.443	******	7.06958	******	1179.10	******	******
8	0.01897	89.866	******	7.06958	******	1154.55	******	******
9	0.01897	89.866	******	3.64468	******	1004.40	******	******
10	0.01859	91.673	******	3.64468	******	999.52	******	******
11	0.01859	91.673	******	1.03303	******	762.25	******	******
12	0.01859	91.673	******	1.00204	******	762.25	******	******
13	0.01859	91.673	1.00000	1.00204	761.86	762.25	30.3	6.5407
14	0.00000	7.230	******	19.59881	******	744.89	******	******
15	0.00000	5.422	******	19.59881	******	744.89	******	******
16	0.00000	1.808	******	19.59881	******	744.89	******	******

Shaft Power = 25000000.00
Net Thrust = 2692.70
Equiv. Power = 25173618.00
Fuel Burnt = 1.6731
s.f.c. = 66.9247
equiv.s.f.c. = 66.4631
Sp. Sh. Power = 277777.78
Sp. Eq. Power = 279706.84
Sh. Th. Effy. = 0.3464

***** OFF DESIGN ENGINE CALCULATIONS. Converged after 8 Loops *****

***** AMBIENT AND INLET PARAMETERS *****
Alt. = 0.0 I.S.A. Dev. = 0.000 Mach No. = 0.00
Etar = 0.9800 Momentum Drag = 0.00
Specific Humidity = 0.00000

***** COMPRESSOR 1 PARAMETERS *****
Z = 0.89420 PR = 4.428 ETA = 0.85009
PCN = 1.0000 CN = 1.00000 COMWK = 0.15906E+08

***** COMPRESSOR 2 PARAMETERS *****
Z = 0.88268 PR = 4.397 ETA = 0.85694
PCN = 1.0050 CN = 1.00228 COMWK = 0.26000E+08

ETA = 1.00000 DLP = 0.9586 WFB = 1.6859

***** TURBINE 1 PARAMETERS *****
TF = 405.434 ETA = 0.86974 CN = 2.808
AUXWK = 0.00000E+00

***** TURBINE 2 PARAMETERS *****
TF = 405.759 ETA = 0.87292 CN = 2.790
AUXWK = 0.00000E+00

***** TURBINE 3 PARAMETERS *****
TF = 406.882 ETA = 0.86204 CN = 2.788
AUXWK = 0.23961E+08
Additional Free Turbine Parameters:-
Speed = 100.0% Power = 0.23961E+08

***** CONVERGENT NOZZLE 1 PARAMETERS *****
Area = 6.5407 Exit Velocity = 30.56
Gross Thrust = 2645.64 Nozzle Coeff. = 0.97002E+00

***** OFF DESIGN ENGINE CALCULATIONS. Converged after 4 Loops *****

***** AMBIENT AND INLET PARAMETERS *****
Alt. = 0.0 I.S.A. Dev. = 0.000 Mach No. = 0.00
Etar = 0.9800 Momentum Drag = 0.00
Specific Humidity = 0.00000

***** COMPRESSOR 1 PARAMETERS *****
Z = 0.89422 PR = 4.428 ETA = 0.85009
PCN = 1.0000 CN = 1.00000 COMWK = 0.15906E+08

***** COMPRESSOR 2 PARAMETERS *****
Z = 0.88284 PR = 4.398 ETA = 0.85692
PCN = 1.0050 CN = 1.00227 COMWK = 0.26003E+08

***** COMBUSTION CHAMBER 1 PARAMETERS *****
ETA = 1.00000 DLP = 0.9584 WFB = 1.6865

***** TURBINE 1 PARAMETERS *****
TF = 405.390 ETA = 0.86961 CN = 2.808
AUXWK = 0.00000E+00

***** TURBINE 2 PARAMETERS *****
TF = 405.755 ETA = 0.87275 CN = 2.790
AUXWK = 0.00000E+00

***** TURBINE 3 PARAMETERS *****
TF = 406.882 ETA = 0.88884 CN = 2.788
AUXWK = 0.24697E+08

Additional Free Turbine Parameters:-
Speed = 100.0% Power = 0.24697E+08
***** CONVERGENT NOZZLE 1 PARAMETERS *****
Area = 6.5407 Exit Velocity = 30.27
Gross Thrust = 2621.08 Nozzle Coeff. = 0.97006E+00

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	87.571	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	87.571	******	0.98000	******	288.15	******	******
3	0.00000	87.571	******	4.33926	******	467.63	******	******
4	0.00000	87.571	******	19.08210	******	749.22	******	******
5	0.00000	80.535	******	19.08210	******	749.22	******	******
6	0.02094	82.222	******	18.12369	******	1460.02	******	******
7	0.02094	82.222	******	6.88530	******	1204.64	******	******
8	0.01965	87.499	******	6.88530	******	1178.97	******	******
9	0.01965	87.499	******	3.54244	******	1027.38	******	******
10	0.01926	89.258	******	3.54244	******	1022.20	******	******
11	0.01926	89.258	******	1.03251	******	782.74	******	******
12	0.01926	89.258	******	1.00232	******	782.74	******	******
13	0.01926	89.258	1.00000	1.00232	782.26	782.74	30.3	6.5407
14	0.00000	7.036	******	19.08210	******	749.22	******	******
15	0.00000	5.277	******	19.08210	******	749.22	******	******
16	0.00000	1.759	******	19.08210	******	749.22	******	******

Shaft Power = 24697112.00
Net Thrust = 2621.08
Equiv. Power = 24866112.00
Fuel Burnt = 1.6865
s.f.c. = 68.2886
equiv.s.f.c. = 67.8245
Sp. Sh. Power = 282023.13
Sp. Eq. Power = 283952.97
Sh. Th. Effy. = 0.3394
****

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	87.574	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	87.574	******	0.98000	******	288.15	******	******
3	0.00000	87.574	******	4.33918	******	467.63	******	******
4	0.00000	87.574	******	19.07904	******	749.18	******	******
5	0.00000	80.538	******	19.07904	******	749.18	******	******
6	0.02093	82.224	******	18.12046	******	1459.74	******	******
7	0.02093	82.224	******	6.88470	******	1204.38	******	******
8	0.01965	87.501	******	6.88470	******	1178.72	******	******
9	0.01965	87.501	******	3.54213	******	1027.12	******	******
10	0.01925	89.260	******	3.54213	******	1021.95	******	******
11	0.01925	89.260	******	1.03153	******	789.79	******	******
12	0.01925	89.260	******	1.00104	******	789.79	******	******
13	0.01925	89.260	1.00000	1.00104	789.58	789.79	30.6	6.5407
14	0.00000	7.036	******	19.07904	******	749.18	******	******
15	0.00000	5.277	******	19.07904	******	749.18	******	******
16	0.00000	1.759	******	19.07904	******	749.18	******	******

```
Shaft Power    =  23961464.00
Net Thrust     =  2645.64
Equiv. Power   =  24132046.00
Fuel Burnt     =  1.6859
     s.f.c.    =  70.3605
equiv.s.f.c.   =  69.8631
Sp. Sh. Power  =  273613.44
Sp. Eq. Power  =  275561.31
Sh. Th. Effy.  =  0.3294
```

****

PARAMETERS MEASURED AND COMPARED

4.3392	467.6302	1.0050	19.0790	749.1803
1.6859	6.8847	1178.7211	3.5421	1021.9505

***** DEGRADED ENGINE CALCULATIONS. Converged after 7 Loops of Iteration*

```
NLOOP,K,KOUNT          7             1             3
yfoul 1 to 5     2.503502      1.799316      0.0000000E+00  0.0000000E+00
 0.0000000E+00
zfoul 1 to 5     2.899582      1.702591      0.0000000E+00  0.0000000E+00
 0.0000000E+00
atfoul 1 to 5    0.9690552     1.019615      1.300049       0.0000000E+00
 0.0000000E+00
etfoul 1 to 5    1.115601      0.8689957     -0.9556580     0.0000000E+00
 0.0000000E+00
```

The Last Value of the Variables was

97.4965	97.1004	98.2007	98.2974	100.9691
98.8844	101.0196	99.1310	101.3000	100.9557

THE ANALYSED RESULT IS

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	Atur1
-2.5035	-2.8996	-1.7993	-1.7026	0.9691

EFFtur1	Atur2	EFFtur2	Atur3	EFFtur3
-1.1156	1.0196	-0.8690	1.3000	0.9557

TABLE 25

Module	parameter	Imposed Fault	Detected Fault
comp1	Γ	0.500	0.497
	η	0.300	0.302
turb1	A	0.480	0.484
	η	0.350	0.342
turb2	A	0.210	0.191
	η	0.400	0.395

A COMPARISON OF IMPOSED AND DETECTED FAULTS

TABLE 26

Module	parameter	Imposed Fault	Detected Fault
comp1	Γ	1.500	1.342
	η	1.300	1.108
turb1	A	0.000	0.012
	η	0.000	0.003
turb2	A	1.100	0.950
	η	0.750	1.100

A COMPARISON OF IMPOSED AND DETECTED FAULTS

APPENDIX A

THE MILITARY AIRCRAFT ENGINE CONDITION MONITORING SYSTEMS

UK	
EUMS Mk II	JAGUAR HAWK AV-8A HARRIER PHANTOM/SPEY
USA	
Engine Health Monitoring System	T38/J85
Engine Monitoring System	F109
Engine Monitoring System	F110
Engine Monitoring System	F-15/F100
Engine Diagnostic System	F100/J57
Engine Diagnostic System	F109- PW - 220
C A P M S	LM2500
Turbine Engine Monitoring System	F108/KC-135R
Turbine Engine Monitoring System	A-10/TF34
Turbine Engine Monitoring System	F108/KC-135R
T E M S /CEMS IV	A-10/TF34-100
In flight ECMS	F-18/F404
Central Integrated Test Sys	B1-B/F101
ADEMS II	TF39/C-5A

TABLE A1 Military Aircarft Engine Health Monitoring UK/USA

LM 2500 INSTRUMENTATION

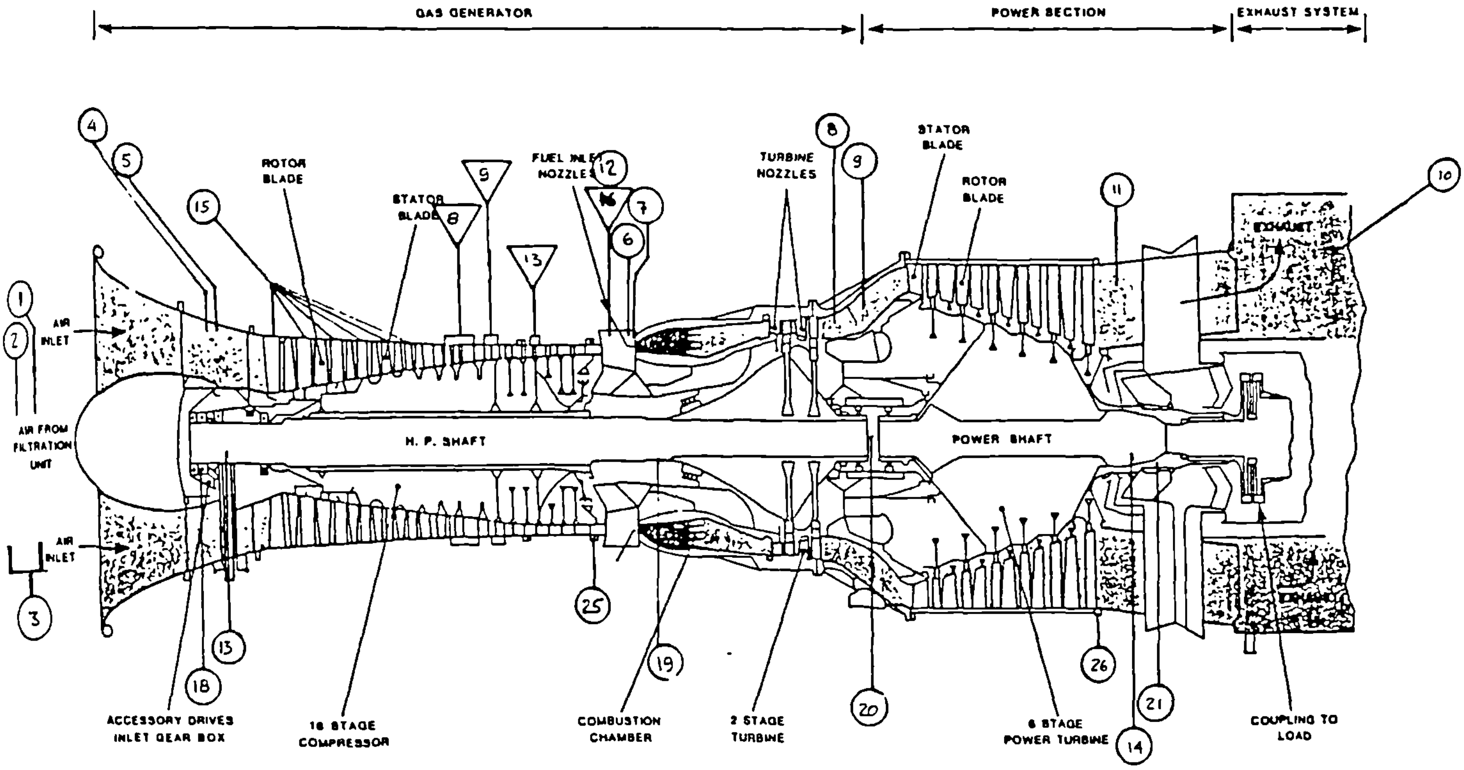


FIG A 1 - LM 2500 Typical Instrumentation

1.0 Measured Parameters - Aerothermal

(numbers below refer to diagram above)

1.	Ambient Pressure	Pa
2.	Ambient Temperature	Ta
3.	Pressure Drop-Filters	dP
4.	Compressor Inlet Pressure	P2
5.	Compressor Inlet Temperature	T2
6.	Compressor Discharge Pressure	P3
7.	Compressor Discharge Temperature	T3
8.	PT Inlet Temperature	T5.4
9.	PT Inlet Pressure	P5.4

10.	PT Exhaust Temperature	T9
11.	PT Exhaust Pressure	P9
12.	Compressor Bleed Flow	On/Off
13.	Gas Generator Speed	Ngg
14.	Power Turbine Speed	Npt
15.	VSV Position	deg
16.	Fuel Supply Pressure	Wpf
17.	Fuel Supply Temperature	Wtf

1.1 Measured Parameters - Mechanical

18. Scavenge Oil Temperature - Sump A + gr.box
19. Scavenge Oil Temperature - Sump B
20 Scavenge Oil Temperature - Sump C
21. Scavenge Oil Temperature - Sump D
22. Lube Supply Temperature - Pump
23. Scavenge Oil Pressure
24. Fuel Manifold Pressure
25. Vibration - GG
26. Vibration - PT
27. Lube Oil Supply Temperature
28. Lube Oil Supply Pressure
29. Fuel Supply Temperature
30. Fuel Supply Pressure

1.2 Calculated Parameters

(All corrected to ISO standards)

1. Air Mass Flow
2. Compressor Efficiency
3. HPT Efficiency

4. PT Efficiency
5. Thermal Efficiency
6. GG Speed Corrected
7. PT speed Corrected
8. EGT Time above 1475 deg F
9. EGT Time above 1455-1475 deg F
10. EGT Time below 1455 deg F
11. Heat Rate
12. SFC
13. Horsepower (IGHP)
14. Total power = comp + turbine + Lpt = Driven equipment
15. Trend Temperature - Sump A
16. Trend Temperature - Sump B
17. Trend Temperature - Sump C
18. Trend Temperature - Sump D
19. Trend Temperature - Sump Gear Box
20. Turbine Inlet Temperature
21. Calculation of EGT profile
22. Correction of output power to inlet conditions
23. Trend compressor efficiency
24. Trend turbine efficiency
25. Trend power turbine efficiency
26. Trend vibration in 3 speedbands (gg)
27. Trend vibration in 3 speedbands (pt)
28. Plot of EGT vs gg speed(corr) & EPR
29. Plot of CDP vs gg speed(corr) & EPR
30. Plot of SFC/Heat rate vs gg speed(corr) & EPR
31. Plot of EGT profile
32. Plot of output (kW) vs gg speed (corr) & EPR

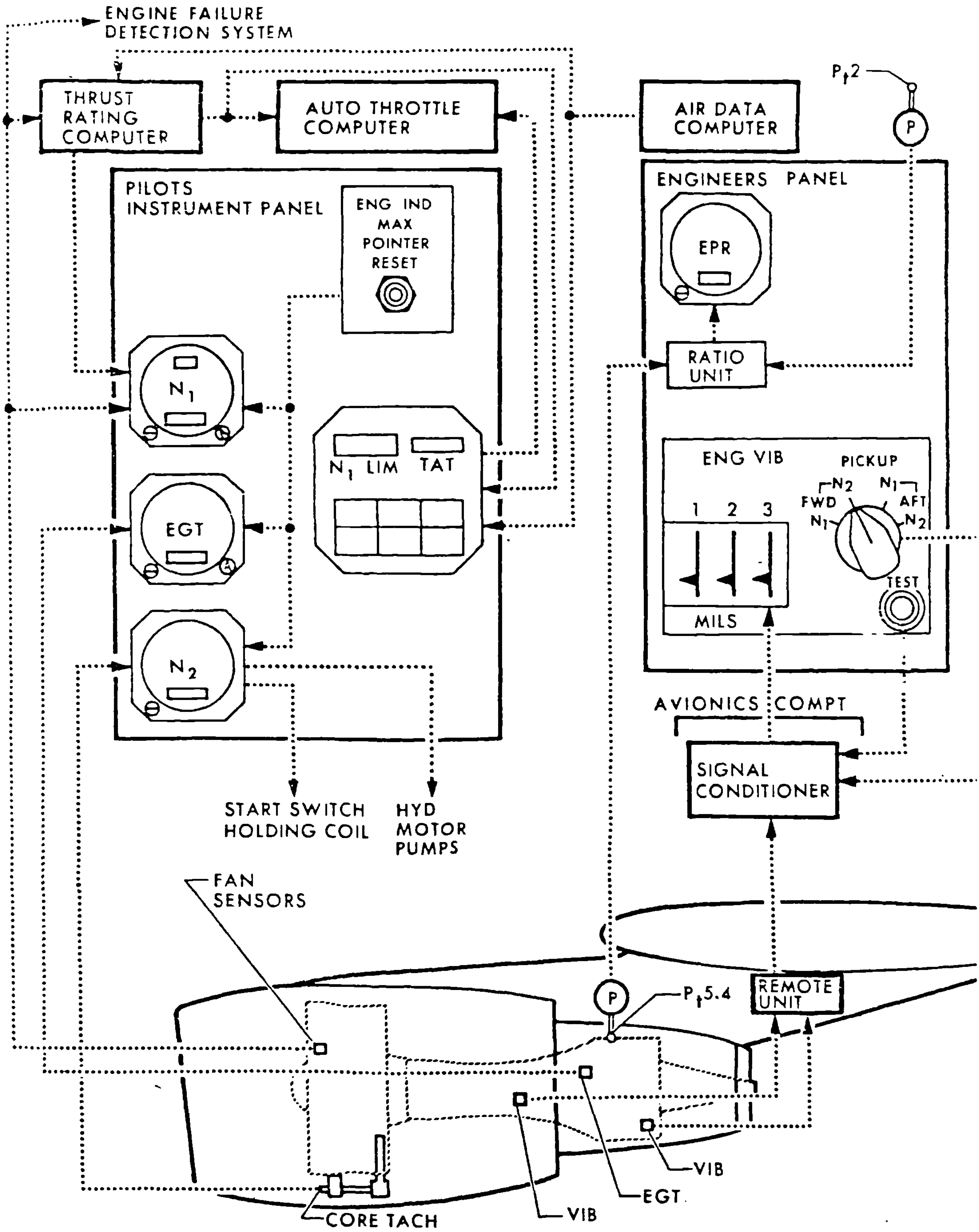
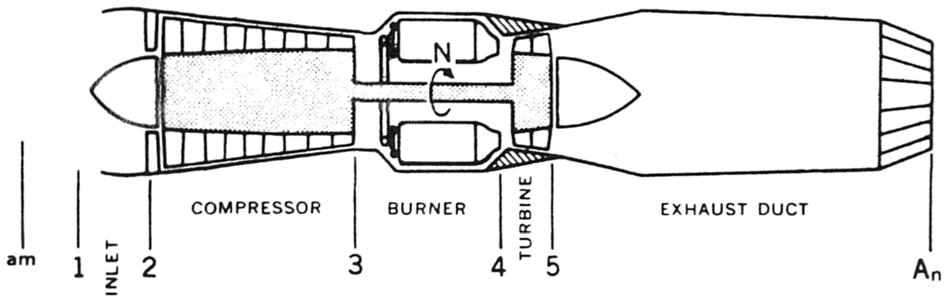


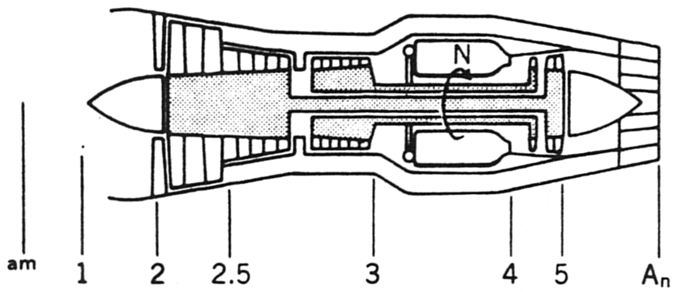
Fig A2 DC-10 - Engine Indicating Functional Diagram.

(A)



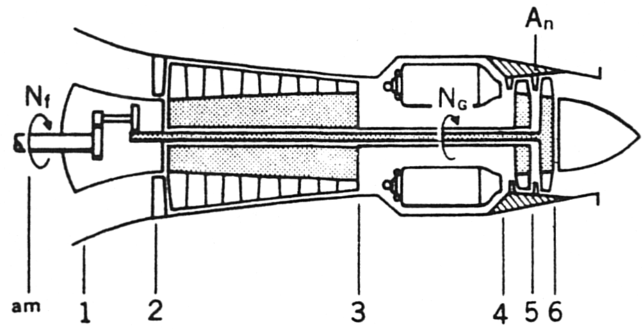
SINGLE ROTOR TURBOJET ENGINE

(B)



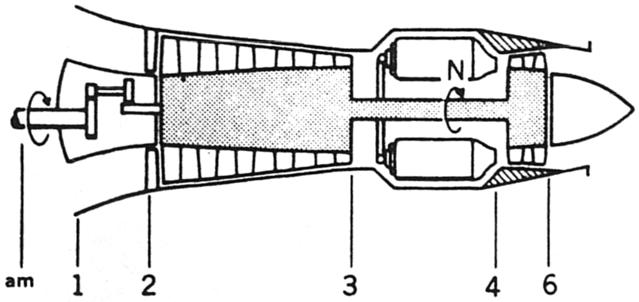
DUAL ROTOR TURBOFAN ENGINE

(C)



FREE POWER TURBINE ENGINE

(D)



FIXED SHAFT POWER TURBINE ENGINE

Fig A 3 **SCHEMATICS OF TYPICAL GAS TURBINE ENGINES**

APPENDIX B

MECHANICAL CONDITION MONITORING TECHNIQUES

Introduction

Monitoring techniques that determine the mechanical condition (health) of the gas turbines and ensure safe operations are reviewed in this Appendix. To be cost effective the engine condition monitoring system must be a totally integrated diagnostic system with a proper balance of emphasis on all of the condition monitoring techniques. Techniques of (1) **oil condition and debris monitoring**, (2) **vibration monitoring** (3) **engine life usage** and (4) **visual inspection** have been explained in the Appendix

General

A failure can be defined as a state when the machine is unable to yield the same performance as when new. Failures occur mainly because of design deficiencies, material defects, processing and manufacturing deficiencies, assembly errors, unintended service, maintenance deficiencies (eg. neglecting some of the procedures), improper operation or abuse. Various stages of a failure can be classified as, damage, deterioration, distress, incipient damage and incipient failure. The gas path analysis is an analytical technique, capable of detecting only those degradations that imply measureable changes of the measured variable. Most of the faults arising in the modules of the gas path do generate detectable changes of temperatures and pressures which permits GPA to identify the faulty modules. Hence a large portion of the potential faults related to engine performance parameters are amenable to detection by gas path analysis.

Certain faults occurring in the gas turbine are not possible to be implicitly detected by the analytical technique because of the neglegible effects caused by these on the measurable parameters of the engine. Detection of these faults, such as fatigue crack, corrosive attack, bearing failure, combustor liner crack, fuel injector coking etc, is important. Similarly determination of the engine life used, problems of rotating components and condition of accessories are necessary.

This ensures an efficient and an economical use of the engine but the concept of "safe operation" is equally important. Symptoms of the mechanical condition (and failure) may be present in the gas stream, but the complexity of the flows, limited number of sensors, errors and uncertainty of the measurements have inhibited their identification by the GPA. Detecting and preditction of the failure of these components that are present in the gas path, but do not induce detectable changes in the measured parameters, is as important as the determination of the deterioration of the engine performance. In addition to these, there are a few components that are not washed by the gas, and hence may not influence any changes in the measured parameters .The GPA cannot predict behaviour of such components that are not washed by the gas eg. bearings, shafts, auxiliaries, support system etc until their deterioration has reached such a level so as to cause a noticeable change in the measured parametrs.

The purpose of any gas turbine engine condition monitoring system is to permit meaningful conclusions on the engine status to be drawn from measurable data in a cost effective manner. Certain monitoring techniques that determine mechanical integrity of the engine to ensure safe operation must be installed on the engine along with GPA. A totally integrated diagnostic system must serve the measured data from gas path, rotating parts and accessories, in a fashion, mutually complementary to each other to diagnose the problem. As engines have become more capable, complex and costly, sophisticated maintenance has developed. When the engine goes for maintenance, complete knowledge of the engine health, its performance and the scope of work needed to restore its performance, is required to be known without stripping the engine. This involves monitoring the mechanial condition of the engine by other techniques in addition to the gas path analysis. Detectable faults due to wear, component degradation, corrosion, erosion, abnormal use etc. can be determined by these mechanical diagnostic methods.

Following are the prominent mechanical condition monitoring techniques employed on today's gas turbine engines

- **Oil system monitoring technique**
- **Vibration monitoring techniques**
- **Engine usage monitoring techniques**
- **Visual condition monitoring techniques**
- **Exhaust gas spread**
- **Limited transient monitoring**
- **Acoustic monitoring**

OIL SYSTEM MONITORING TECHNIQUE

There are certain components in gas turbine engines, eg. bearings, gears, splines etc. which rub against each other, are in constant motion and hence produce friction. Oil is pumped to lubricate (decrease the friction) and cool these parts. The high temperature of the components changes the physical properties of the oil and some of this oil is consumed in the process. A sudden rise in, or increased level of oil usage can be an indication of internal deterioration of the lubricated mechanical parts or the whole engine. The technique of monitoring oil consumption and condition (visual) has been the oldest technique used in gas turbine engine health monitoring. The engine components, usually, do not fail suddenly. Before actual failure, there is a period in which wear particles are released at a greater rate than normal. By observing and analyzing these particles, failures can be predicted. The term oil analysis has become synonymous with wear particle analysis .

Oil system monitoring, on-line as well as off-line, is classified into three categories [TAUBER,1983].

1. **Oil condition monitoring** (monitoring physical condition of the oil itself).

2. **Oil debris monitoring** (monitoring the condition of oil-wetted engine components via the oil system).

3. **Oil system operation monitoring** (monitoring the oil system for proper operation).

Fig B1 shows schematiclly the techniques and the hardware used for the three catagories mentioned above. A brief description of the first two is given in succeeding paragraphs.

Oil Condition Monitoring

In the gas turbine engines the deterioration rate of the physical/chemical properties of the oil is dependent on aeration, temperature, oil consumption, oil system capacity and oil formulation. A change in the engine operating conditions resulting in increased aeration or higher oil temperature such as after seal wear, can cause significant increase of oil degradation and/or oil consumption. Tests for oxidation, additive depletion, solids content, fuel dilution, viscosity and total acid number are performed to ascertain

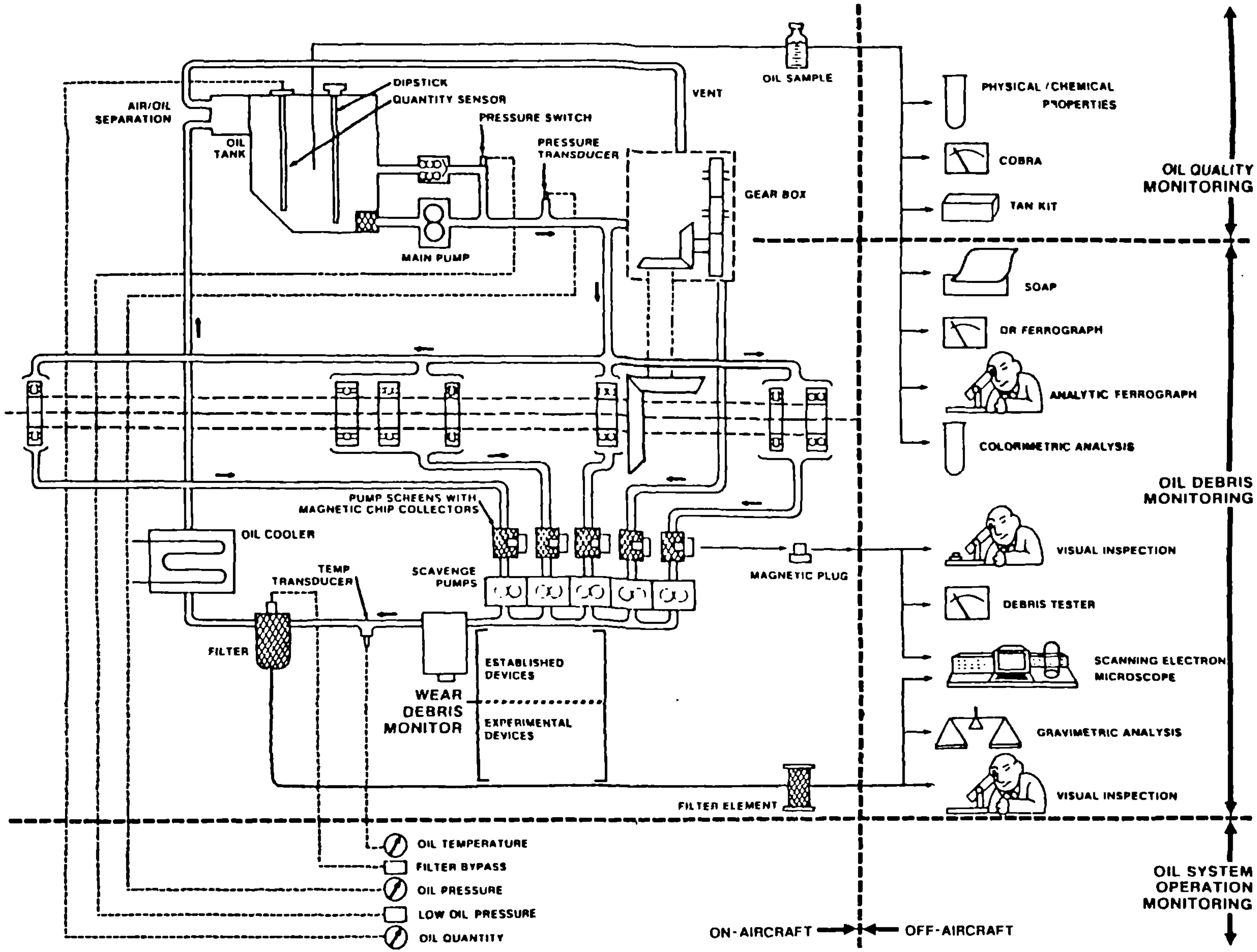


Fig B1 Oil Condition Monitoring (AIR 1828) the lubricant serviceability. This is an off-line process in which samples of oil are withdrawn from the engine and tested for continued serviceability of the oil, either on-spot or in a laboratory.

Spot checks are usually conducted in field and consist of :-

1 **Blotting Paper Test** is a visual check of the clarity and the condition of the oil. An oil drop is deposited onto a filter paper, the oil filters through leaving the contents behind. These can be analyzed. (the condition and engine components responsible are determined primarily by comparison or experience.)

2 **Viscosity test** The change in viscosity of the oil indicates the change in its composition primarily due, to temperatures it is subjected to, presence of foreign materials as solution in the oil, and changes in chemical composition.

3 **Capacitance test** The presence of water,methane debris or acidic oxidation products will reduce the capacitance, which is an indication of the condition of the oil in the engine. Thus determining capacitance enables us to determine the contamination of the oil.

Rigorous tests can be undertaken under laboratory conditions and exact changes in the oil composition (physical and chemical) determined. However it is not instantaneous as on-the-spot tests, requires skilled manpower and is expensive. The techniques commonly used are :-

1 **Emission spectroanalysis** uses a high energ excitation of the oil debris to determine the concentrations of submicroscopic wear metal particles in the oil. Part per-million concentrations can be measured of such wear metals as Iron, Silver, Aluminium, Chromium, Copper, magnesium, Nickel, Lead, Tin and Titanium . Other elements like Sodium, Barium and Zinc which derive from oil are also measured.

2 **Infrared spectroanalysis** measures the contamination and the degradation of the oil. Difference between the infrared spectra of the sample and a reference spectra of the same oil represents contamination or chemical change in the oil. Contaminants commonly detected through infrared analysis include water, blowby products, unburnt fuel etc. Degradation of the oil through nitration and oxidation, polymerisation

can be measured directly.

3 **Viscosity measurement** is obtained with an oscillation viscometer and the values are compared with reference viscosity and density to ascertain presence *of contaminants and change in chemical composition of* the oil.

All the three tests viz. Emission, Infrared and Viscosity, are run independently and concurrently and oil condition report printed out with recommendations and warnings (if abnormalities exist and are beyond a specified limit).

Oil Debris Monitoring

Wear Analysis

'**Wear**', the removal of material by mechanical action, is categorised as abrasion, erosion, fretting, scuffing and contact fatigue which relate to the nature, velocity and load intensity of a particular system. This wear is minimized by the lubricating oil which also serves as a transport medium for debris generated by the rolling and sliding surfaces subject to wear. Based on the rate of removal of the material from the surface, wear can be classified as normal wear, accelerated wear or incipient failure. The debris generated in those processes contain very valuable and detailed information about the condition of the wear surfaces.

Characteristics of the particles, generated during wear can identify the wear. The wear particles of platelets form indicate normal wear, rubbing or adhesive (permissible). Cutting or abrasive wear particles are in miniature spirals and loops. Steel spherical particles are a characteristic feature associated with fatigue crack propagation in rolling contacts. Specific regimes of wear have been classified by the nature of the particles produced by the surfaces in sliding contact. Particles of compounds can result from oxidising or corrosive environment.

Monitoring and trending of the wear debris combined with debris identification techniques allows diagnosis of an impending failure. Quantity, rate of production, material, particle shape, size, distribution and colour are the basis of the debris assessment. Fig B2 shows a typicl wear debris accumulation upto an incipient failure. Various debris monitoring methods differ with respect to the parameters observed and the range of measure. Depending upon the accumulated wear or incipient failure mode, debris production may increase dramatically in one size range. As a result, the timeliness of detection can vary from method to method.

The debris monitoring method is based on the types of potential wear/failure modes, their criticality versus their probability, the required deterioration point (timeliness) and the cost effectiveness. Most of the debris monitoring methods incorporate trending capability which can provide essential information to eliminate spurious indications. Trending also helps in determining the criticality of the wear/failure mode under investigation.

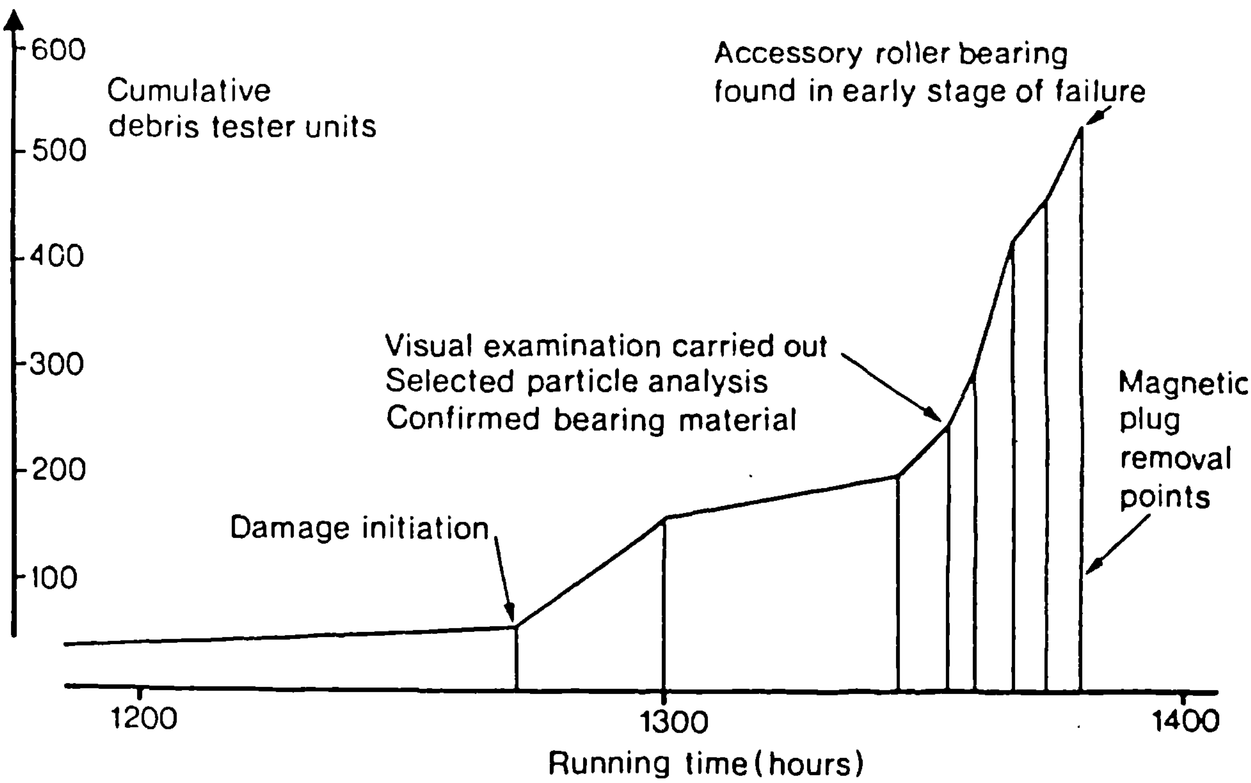


Fig B2 Growth of Wear Debris Rate

The critical characteristics defined for selecting a suitable testing of a wear are the quantity, size, elemental composition and the morphology of the particles. The amount and size of debris particles remains unchanged under normal conditions of wear. As a failure develops, debris particles produced increase in number and size. The debris production rate curve gives no information about the particle size which identifies the failure mode. Various sensors/techniques used are sensitive to a range of debris particle size. Hence, wear debris monitoring sensors need to be matched to the wear mode. Following are the main techniques available for use in debris monitoring :-

Spectrometric Oil Analysis (S.O.A): Generally applicable to wear debris particles of < 10 um size. The oil and its containment are vaporised and the elements present are identified by the spectrometric analysis of the radiation emitted by the solids left behind. Depending upon their energy state, the atoms and the ions absorb or emit characteristic spectra which is unique to the element. The elements present are thus identified by the wave length emitted/ absorbed while the intensity of absorption or emission indicates the quantity. Various techniques of S.O.A are described below.

Atomic Emission Spectroscopy: The oil debris particles are excited by a high voltage which causes the metallic particles to emit their characteristic radiations. The radiation emitted is analyzed to detect the elements present. This is a costly, off line method, but is fast and automatic.

Atomic Absorption Spectroscopy: A hollow cathode discharge lamp emits the source light which is absorbed in certain spectrum depending upon the elements present in the debris. The frequencies absent in the reflected spectra indicate the presence of the element. The process is cheaper but time consuming since concentration of only one element at a time is determined.

Plasma Arc : To improve sample consistency, large particles are filtered or centrifuged. This leaves fine particles of metal or metal oxide and dissolved organometallics, reaction products between metal and oil. This sample of oil and its contents is then excited and analysis of the emitted spectra gives state of the oil and contaminations. The results is more consistent and reliable but at a higher cost.

SOA Program, detects the changes in the metal concentrations but does not determine the absolute figures or the source of the debris. The state of the component can be concluded through experience only. Experience generally shows that each individual engine generates different metal rejection rates which necessitates establishing the engine's own metal base line. Additionally the volume of the oil in the associated engine oil tank can have effect on the sensitivity of the analysis procedure. The sensitivity decreasing with increasing volume. These shortcomings have reduced S.O.A to a technique of continuous monitoring the debris, with the individual SOA analysis of little value. Overall SOAP has been assessed by various users as between 90% to 98% reliable depending upon type of equipment and the experience of the operator but the high cost has forced the test out of practice [Hunter,1975].

Ferrography Usually applied for the wear debris particles of size 1 to 100 μm. The oil is run across a slide placed in a magnetic field, any magnetic containment in the oil (ferrous) is deposited on the slide. The simple concept uniquely reveals the nature of the wear and is very sensitive to the changes in wear rate. This technique is extensively used in gas turbines to monitor the bearing deterioration.

The main areas of development of the technique are Analytical Ferrography, Direct Reading Ferrography and on-line Ferrography.

In **Analytical Ferrography** the ferromagnetic wear debris in oil sample are magnetically isolated on to a slide using a high gradient magnetic field. Large particles, size > 25 um are precipitated in a heap at the entry, where the oil first contacts the slide. Smaller particles are precipitated progressively down the slope of the slide. To improve the particle precipitation, the oil sample is diluted. The slide, known as ferrogram, when dry, is examined by optical or the electron microscopy. Although ferrography is primarily for the observation of the steel particles, non-ferrous materials also precipitate, because either they become weakly magnetic due to small inclusions of steel, or are trapped by the precipitated steel particles. The presence of these non metallic particles can be distinguished from the metallic particles by the colour of the reflected light, eg. copper and its alloys. The particle morphology can be studied under a microscope to identify type of wear or failure. From a single ferrogram, the type or types of wear taking place in the system and often the individual component wearing can be identified.

In **Direct Reading Ferrography** the diluted solvent is passed through an upsloping glass tube (rather than a slide), the ferromagnetic wear particles are precipitated in the tube, at a position dependent upon their size. The tube is thus covered with particles of different sizes along its length. Provided the concentration of the wear particles is not too high, there is very little overlap of the deposited particles and the light blockage is proportional to their cross sectional area. The DR ferrography quantifies the amount and approximate size distribution of wear particles whereas the morphology is difficult because of the size of the tube. It is an inexpensive technique, which can be operated by less skilled personnel and gives immediate results. The most satisfactory method is to use the Direct Reading Ferrography to monitor a severity of wear index and when this becomes large then the Analytical Ferrography can, from particle morphology, determine the type of wear.

Use of **temper colours** as a means of extracting further information from a ferrogram is the latest advancement in ferrographic technique. Simple heat treatment of ferrograms on a hot-plate can provide useful means of identifying the different materials present. Based on Iron or Nickel alloys present, the magnetic particles generate temper colours that divide them into four types viz. Carbon Steels, Cast Iron, Nickel and Stainless Steel. The majority of non magnetic engineering alloys such as Aluminium, Magnesium, Chromium, Cadmium and Silver do not form colours. The Copper base alloys may form temper colour but can, of course, be readily identified by their yellow bronze colours prior to the heat treatment. This grouping of debris particles, permit identification of the particular component wearing and the wear process.

The **on-line ferrography** is installed on the engine for fast response and minimal logistic requirements. An on-line debris monitor relies on the debris transport characteristics of the oil system. Most respond to debris in a size range considerably larger than the separation capability of the oil filter and are therefore installed upstream of the filter. Various devices used include magnetic plug, burn-off magnetic plug, electric chip collector, pulsed electric chip detector, screen-type full-flow debris monitor. In addition there are a variety of devices under development e.g. electro-optical debris monitor, inductive debris monitor, on-line ferrograph, capacitative debris monitor, degaussing chip detector, indicating screen etc. The probability of detecting an incipient failure in real time depends on the on-line ferrography's capability to sense the accumulation of the debris. Hence the magnetic field is graduated and the sensing device is duplicated so that both the large and the small particles may be investigated.

Magnetic Chip Detection and Magnetic Plugs are used for detection of wear debris particles of the order of 50 to 100 μm. A magnetic stub is introduced into the oil flow in such a way that it continuously attracts magnetic materials from the oil. The debris is commonly wiped on to a transparent tape and viewed under a microscope or else the debris can be measured for total ferrous contents.

Electrical Chip detectors have proved to be a very reliable indicators of the incipient failure and are widely used on gas turbine engines and helicopter transmissions. They have replaced conventional magnetic plugs and use of SOA as a health monitoring tool for wear debris analysis. A magnet attracts the ferrous debris, shed into the lubrication system by the failing components and retains it for analysis.

The debris particles accumulate across the gap between two electrodes and act as a switch activating a chip warning. Conventional chip detectors are subjected to a large number of false indications (58% due to 'wear fuzz', 25% due to electrical failure, 7% due to other metal etc.) Wear debris generated due to fatigue-type (bearing or gear spalling) consists particles of all sizes up to 50 microns. In the lube system very fine filters remove particles of 3 to 10 micron size. With coarse filtration higher diameter particles accumulate slowly in the oil and are deposited on the chip detector. This process gives rise to 'wear fuzz', the main contributory cause for nuisance indications, not present on oil system with very fine filters. The chip detector responds to an indication each time the chip gap is bridged regardless of whether the gap consists of large quantities of small or small quantities of large particles.

The problem was resolved by sending a strong current pulse through the chip gap every time there is electrical continuity. This interrupts the current path and melts the particles responsible for false indications. The debris particles with substantial cross section conduct the current and are not affected. The chip light going off indicates generation of fine debris in normal wear, but if light does not go off, it implies debris saturation warning impending failure.

Quantitative debris monitor (QDM) technique eliminates the subjective nature of engine diagnostics by measuring the ferrous debris production rate and the particle size, combining them in a decision matrix to provide information on severity of an impending failure and recommend maintenance action. It has proved a very valuable tool and has been widely used in turbine engines and transmissions. QDM is designed to operate on 'first-pass debris capture' of the oil borne ferrous debris i.e. before it can be trapped in the lubrication system filter. The sensor retains ferrous debris for subsequent off line analysis.

Perturbations of the magnetic field, caused by the capture of the ferrous magnetic debris on the magnetic pole face exposed to the oil stream, change the magnetic flux within a sensing coil. The output voltage is proportional to the flux change rate, hence to the mass of the particles captured. A data processor is the heart of QDM system and performs size discrimination, debris count, totalisation and computes rate of debris generation. The data processor circuitry classifies the incoming pulses into two categories

1 particles greater than 5 micrograms (equivalent to 200 microns size bearing spall flake).
2 particles greater than 40 micrograms (equivalent to

1000 microns size bearing spall flake).

This classification is used to determine the rate of pulse occurrence for each size category and determine cumulative debris. Debris generation rate is the indicator of failure progression rate while debris count is an indication of the damage severity. The system is designed with two levels of warnings designated 'maintenance alert' and 'mission alert'. A majority of the fatigue failures will give first indications at the maintenance level, thus providing adequate time for more detailed mechanical diagnosis and corrective maintenance action. The mission alert level serves to guard against rapidly progressing failures which could be catastrophic. The debris data processor is designed to operate either as a stand-alone unit or to interface with a computerised event monitoring system. Presently the data is transferred, after an operation, to a base computer, for detailed analysis. In 'stand-alone' mode the individual exceedance flag outputs are displayed for operator information, maintenance or engine shut down action. Fig B3 shows the detection range of wear particle sizes for the techniques described above.

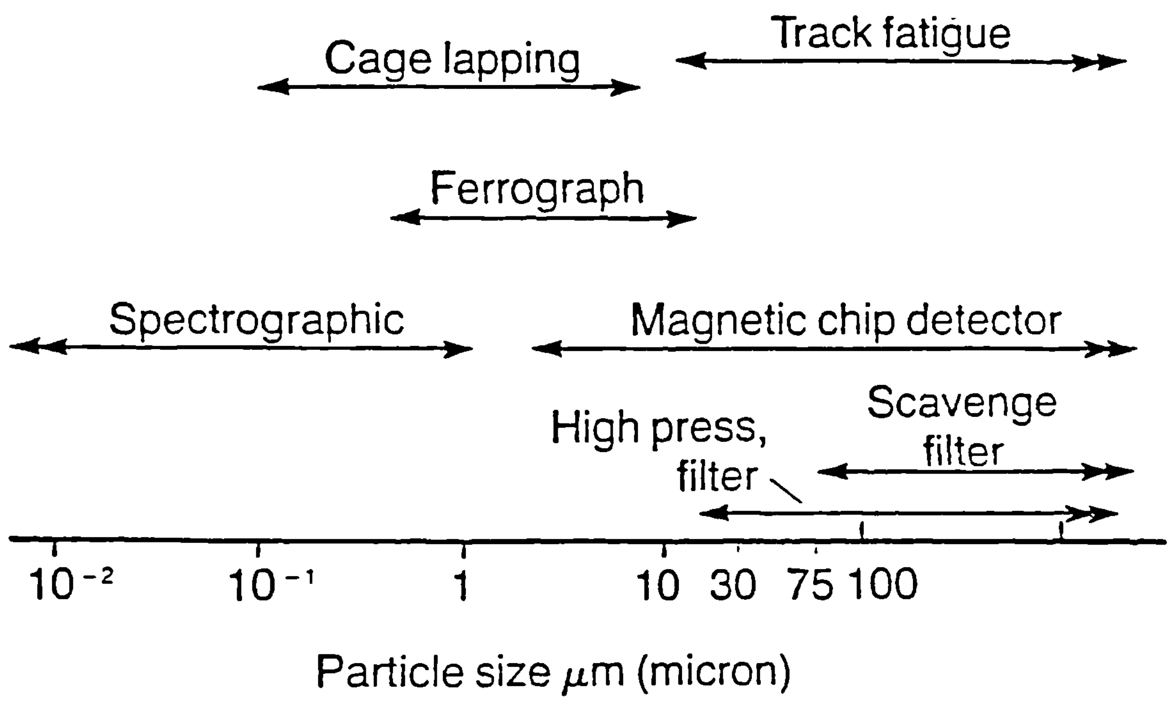


Fig B3 Detection Range of Wear Particles

<u>Non Oil Washed Component Monitoring</u>

Health monitoring of the components, that are not washed by the lubricant, has been carried out by ferrographic analysis of the particles collected from the exhaust gases. Some of the particles carried by the gas, impinge on the walls of the tail pipe and on the thermocouples. These can be removed by an adhesive tape for ferrographic analysis. Composition of such particles can be obtained by X-ray energy analysis. Ferrography of the particles collected from the tail pipe and other accessible components in the gas stream has indicated useful information on inaccessible components of a jet engine.

To detect and identify component distress, **Gas Path Particle Analysis** technique uses removable targets located between the gas stream. These targets entrap debris particles for subsequent analysis [LLOYD,1987]. GAPPA technique best applied not as a routine analytical facility, but as an aid (diagnostic) to assist with the solution of specific engine problems.

The **surface layer activation technique (SLA)** is the on-line monitoring of wear health of components to predict imminent failures. High energy particle beam bombarding a selected area of the component wearing surface, causes nuclear transmutation of a few of the atoms in the material into radio active elements i.e. makes it radio active. The radionuclide is unstable and decays emitting gamma rays, which have the capability of penetrating matter. Employing a nuclear detector in the general vicinity of the activated spot the amount of radiation (gamma rays) can be monitored. Each radionuclide has unique set of gamma rays which are used as finger print of the specific activated part. A sharp drop in the intensity of the signal received indicates the loss of surface material or abnormal wear [SIOSHANSI,1984]. It has the following desirable features.

- Can measure wear on line, in site, under normal operating conditions
- does not need mechanical access or even line-of sight to the part for wear determination
- is accurate
- can operate under hostile environment (shock, high temperature, vibrations etc)
- is a direct measurement, hence not dependent on the debris collection or fluid circulation system etc
- can be easily automated

On the bearing one or more sensitive spot would be activated for SLA measurements. The bearing are subsequently installed in the engine and the strength of radio activity monitored. Wear rate computation and fine control corrections is carried out by a microcomputer. Other areas where SLA monitoring technique could be used in aircraft are turbine blade tips, gear transmission, and helicopters.

Oil System Monitoring

Oil temperature and pressure are usually measured to monitor proper functioning of the oil system and to diagnose the faults in the oil system itself.

VIBRATION MONITORING

The use of **Vibration monitoring** to provide early diagnostic information with regard to the engine rotors, bearings and accessory case has long been recognized as an accurate reflection of the condition of dynamic components. It detects significant portion of faults in a gas turbine engine that are not amenable to detection by other condition monitoring techniques. These faults may or may not influence gas path parameters e.g. blade fracture in compressors or turbines, misaligned coupling, bearing defect, malfunction of gears, imbalance and other defects of engine or auxiliary components. In many circumstances, the vibration analysis can detect faults that would otherwise have gone undetected and/or led to a breakdown.

Most of these prblems initially manifest as vibrations which can be detected at early stages if vibration monitoring systems are installed on the engine. Undetected vibrations due to imbalance or misalignement etc, can progressively increase and eventually result into catastrophic failures. There are, however, instances when impending failure gives no advanced warning and identification of the failing component is not in the observed frequency domain, bearing and seal rub, or the onset of hydrodynamic instability, are examples.

The principle components that cause vibrations in a gas turbine engine rotating system are the rotors, blades, discs, bearings and gears. Depending on the level of sophistication used and background experience available, vibration monitoring can detect :-

1. Basic out of balance of rotating components
2. Outright or incipient failures of rotating components
3. Bearing or bearing support problems
4. Oil leakage into compressor drums
5. Corrosion, erosion or dirt build up of gas path components

Vibrations can be expressed in terms of displacement, velocity and acceleration. Although there are transducers available that will measure vibration in each of these terms, there exists a correlation between them, [COLLACOT] which allows the vibration to be measured in one parameter only. Vibration can be measured with noncontact shaft displacement sensors, velocity pick-ups or accelerometers. The rolling element bearing construction of turbine engines (especially aero-derivative) limits vibration measurements to the use of seismic type of transducers, usually accelerometers, although velocity probes were used in the near past.

The transducers placed onto the stator casing pick up the acceleration caused by pressure fluctuations when ever a blade is passing by. The frequency would naturally be blade passing frequency. In case the stator vanes have the natural frequency close to this frequency, then the transducers will pick up stator vane resonance as well. The transducers should be placed close to the stage (of compressor or turbine) where the vibration is to be measured otherwise there is likelihood of wrong stage signals to be picked up. The problem of measurement of signals becomes complex when number of stators and blades are different and generate lobes, rotating at the blade passing frequency, which supplement the acceleration.

Each compressor and turbine rotor has its own imbalance, mass and bearing support stiffness. The natural frequencies of the rotors, at which the vibration amplitudes are large, are therefore usually different, so the identity of the rotor causing a particular vibration problem is indicated by the speed at which the peak occurs. The bearing support structure is usually flexible enough to keep the natural frequency low, often below the idle speed [HARMAN]. This may involve a spring mounted housing, a housing mounted in a lightly clamped plate which provides damping as it orbits, or a squeeze film which provides oil damping.

Fixed wake excitation, self excitation (flutter),disc movement, rotating stall, blade rub or shaft whirling cause blade vibrations in compressors and turbines [MARKWELL,1985]. Vibrations in the bearings are caused by misalignment, wear, rub or loss of the oil film. Fretting or corrosion in the inner or outer races and rolling elements may also cause bearing vibrations. Spalling and foreign material damage are some of the additional causes for vibration in bearings. Changes in teeth profile, wear and high clearances cause vibrations of the gears.

Signals obtained from complex rotating machines, such as gas turbine engine, normally are made up of a collection of signals generated from a number of component parts with-in the machine. Each component emits its own signal plus noise, but is correlated in some way to the main rotor speed. Hence the noise is not entirely random, and some form of time locking or synchronisation must be used. Signatures, as a general rule, are greatly improved when synchronised with the rotational speed of the machine.

Spectral mapping is used to assist identification of the engine orders (ratio of component frequency to fundamental frequency of rotation of the main shaft). The engine vibration spectrum can be theoretically predicted from the engine design specifications. It is basically a three dimensional display generated by collection of power spectral density plots drawn above each other for different engine speeds as shown in Fig B4 [WEBB,1983]. This mapping indicates resonance conditions, can identify the component responsible for generating the vibration response and locate the source of excitation.

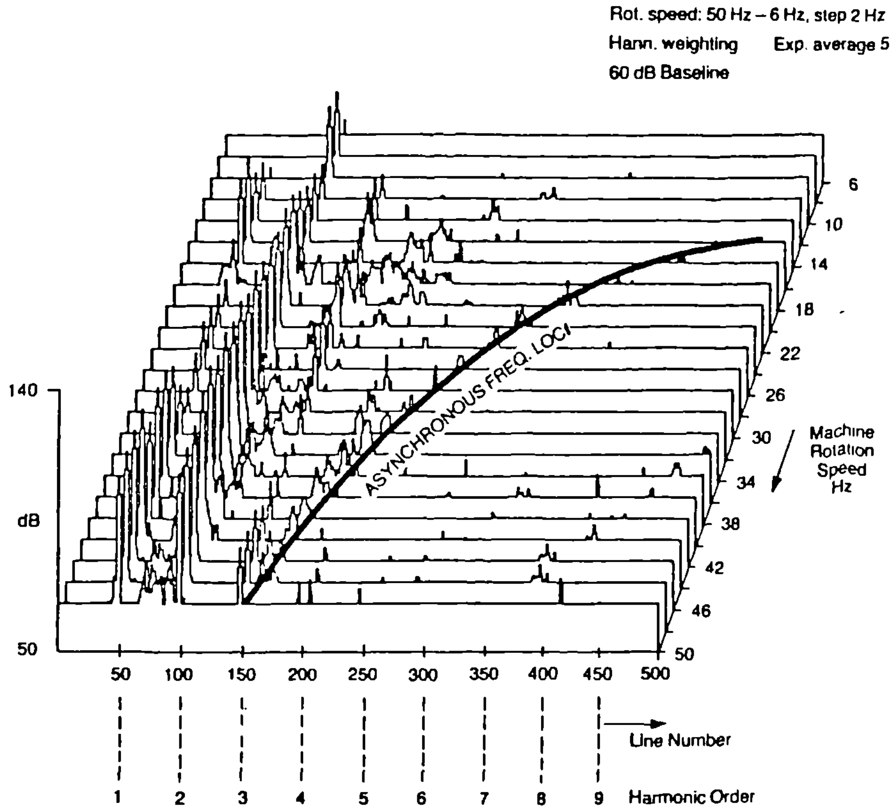


Fig B4 Spectra Of a Turbine

A vibration monitoring system comprises of transducers, display and/or recording unit. Mountings of transducers on the engine depends upon the type of engine, its installation, vibration monitoring method and vibration experience on the engine. Accelerometers use a quartz crystal element which has the effect of a particularly stiff and mechanically ideal spring with no moving parts, high mechanical and thermal stability, good reproducibility, high efficiency over wide range and no risk of resonance in the low frequency range [BREDIN,1983].

Both ground and in-flight vibration measurements are essential in determining the normal vibration amplitudes and the energy spectrum of all major rotating componets for each engine. Thus establishing a vibration "signature" for each engine leads to the individual base line data against which the trending technique would be meaningful.

Three types of measurement viz. entry/return to service, on-load, run-down, are necessary to provide sufficient data base for efficient diagnosis of the problem. During the overhaul the components can undergo major structural changes that can change the base line vibration spectra. It is therefore essential to obtain data in a repeatable form, when the engine is first installed. This is true even when the engine installations are changed. This defines the state of the machine on return to service and provides data that can be used to compare the state of machine vibrations acquired later. The nature of measurement may vary from location to location depending upon the type of engine and the nature and frequency of associated vibrational problems.

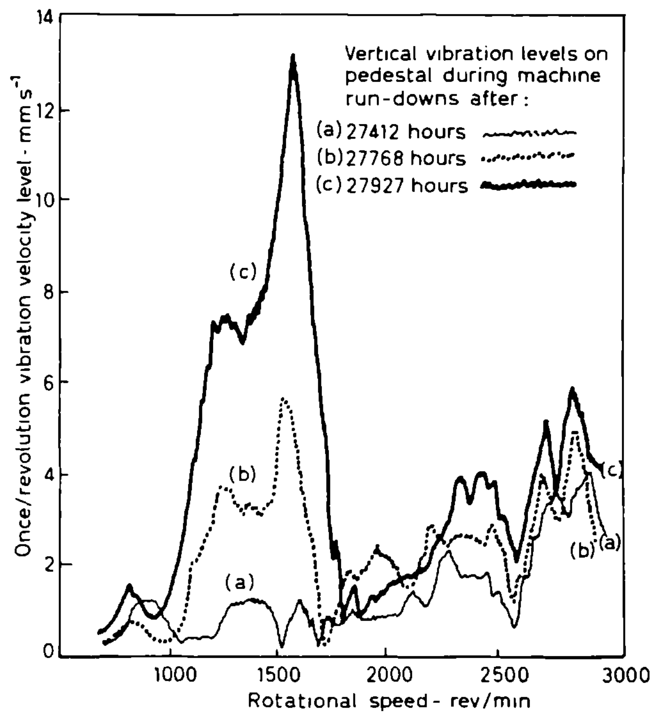


FIG B5 Run Down Spectra of a Shaft That Enabled the Detection of a Crack in the Shaft

The purpose of On-load measurement is to assess the actual in service behaviour of the engine and ensure that a history of this is available for problem diagnostics. It should consist of periodic measurements of the overall level and once and twice per rev. amplitudes and phases of all the bearing vibrations made at consistent engine conditions [THOMAS,1984]. The frequency of conducting the test depends on the vibration history of the engine and its location, ideally it should be weekly but not less than once a month.

During the engine **run down** the vibration signature contains the response to a wide range of exciting frequencies. Thus vibration analysis during run down contains much more information than the on-load fingerprint. Over period of time experience in analysis and interpretation of run-down data must be build up. Recording all run downs is desirable but this does not justify the removal of the engine from service. Fig B5 shows run down spectra of a shaft which could lead to detection of a crack in the shaft.

Threshold vibration levels in excess of which an engine is regarded in a bad condition have been recommended by various bodies empirically. Engine component failure is preceeded by an increase in its vibration level in more than 90% of the cases. All machines vibrate and a good correlation exists between characteristic vibration signatures of the machine and their relative condition. A practical method of judging vibration severity is to establish baseline signature in the installation for a machine in good condition (not necessarily new) and to monitor changes in these signature with time. Various criterion have been used [COLLACOT] to determine acceptable limit of change. Different manufacturers of gas turbine engines have laid such limits for their engines. Graphic representation of the spectra for comparison are also different eg. IRD Mechanalysis or Octave band analysis. One such signature for a gas turbine engine in 1/3 octave limits is shown in Fig B6 [RAO,1986]

A vibration problem is usually first detected when the prescribed limits are exceeded under normal operation conditions or significant departure from normal behaviour is observed. Probability of a correct and speedy diagnosis is increased with detailed recording of particular vibrational behaviour obtained with the test equipment built in a systematic manner.

On detection of a fault the monitoring system may have to respond immediately if safety limits are exceeded. Action such as reducing load, shut down might require to be taken for safety. This control divides the vibration monitoring as **off-line** and **on-line** processes. Off-line vibration monitoring makes best use of specialist staff and a central computer. This method is currently used by most of the operators when diagnosis is carried out in a centralised place normally away from the engine (eg. for off shore engines). This introduces time delay in the transmission of the data, usually through a recorded tape, requires a selection of run ups and run downs specially for vibration data acquisition. The tape recorders normally record 14 parameters, hence the experts analysing the spectrum do not have approach to additional information and hence correlation to any occurrence other than recorded is not possible. The alarm and action to prevent incipient failure is delayed and can prove catasrophic.

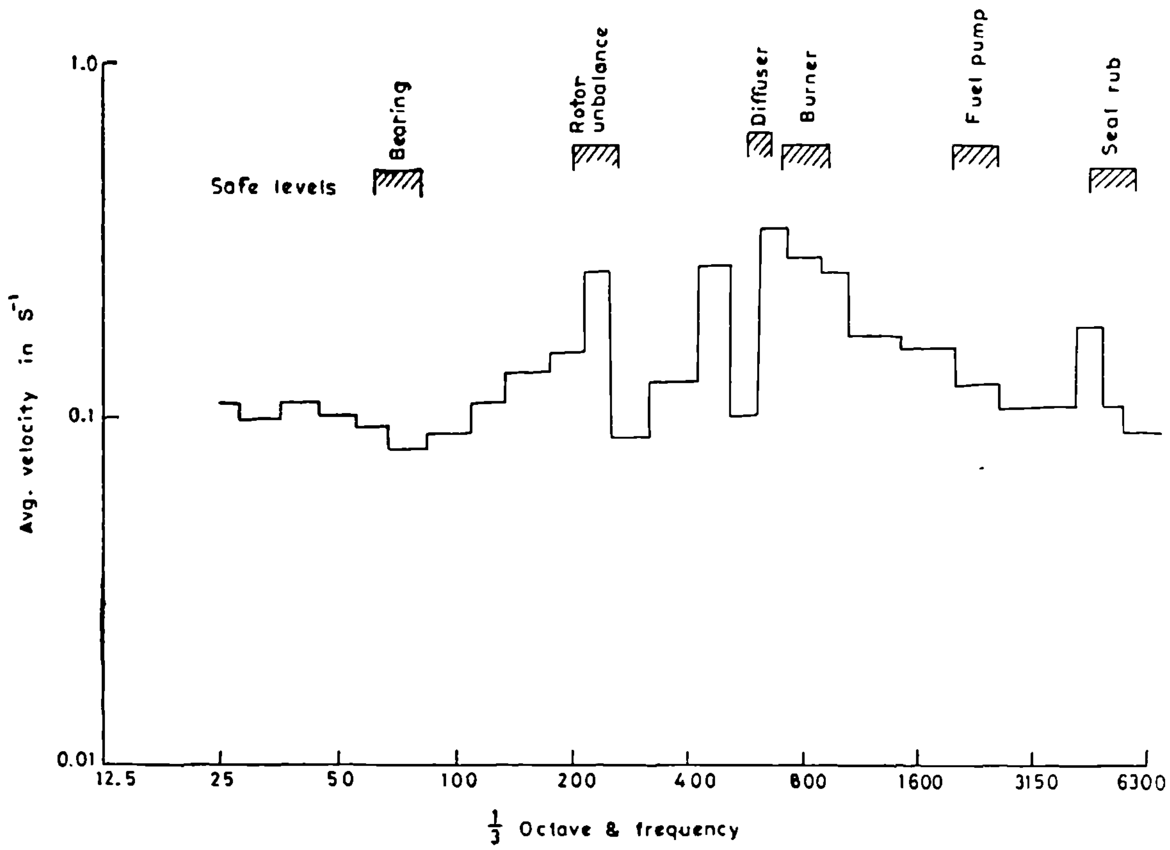


Fig B6 The Octave Band Analysis of a Gas Turbine Engine

Correlation with other data, sophisticated alarm, automatic recording of data, trending and correlation of the trend and alarm in on-line vibration monitoring technique, give an improved off line capability. The analysis is immediate but not by experts. Analogue data is not stored (usually) in a form other than trending. The real time alarm raising and automatic control have made on-line monitoring a success as gas turbine vibration monitoring technique.

Until recently, periodic, on-line monitoring was a labour intesive task that often could not be justified especially for installations with high fleet of small engines. This required extensive and expensive wiring or carrying the laboratory instruments to hostile industrial environments. The situation has improved with introduction of portable automated systems for periodic condition monitoring. This consists of a portable micro-computer, software for comparison and analysis, a data base and a portable data collecting probe [MITCHELL,1983]

Graphic time trends of overall vibration levels and of individual spectral component levels indicate slow changes in a way that is easy to interpret. Trends of pressure, temperature and fuel flow can be correlated when analysing the vibration trends. In modern systems the tedious and time consuming task of manual logging and trending is replaced by automated data logging, computing the trend, recognition of failure and issuing alarm and/or control of the process. Trend analysis of characteristic frequencies may be performed and limits set indicating the need for component replacement.

However the gas turbines are highly complex rotating machines incorporating a variety of components. In practice a wide variety of faults manifested by symptoms such as unusual pattern can occur. Also a number of factors such as speed variations, intermodulation and side banding can obscure the ain signature and in such instances more sophisticated analysis may be required. Successful implementation of a diagnostic system requires that a unique correlation between the faults and syptoms should be possible. Unfortunately, the symptoms associated with individual faults often overlap, making fault diagnosis confusing. There is also possibility of multiple faults sharing some common symptoms; for example, both unbalance and rotor bow can result in large synchronous vibrations. The situation is further complicated by multi spool engines.

Vibration analysis is basically an energy method and therefore only detects faults that generate significant amounts of or changes in energy. Many faults generate enough energy to trigger an alarm only too late into the failur. It is likely that the sensor placement does not pick up these key components that do not generate enough energy, or the energy generated does not register on sensors. In an example a combustion-chamber fault occured but was not picked up by the thermocouples. The chamber eventually broke up and caused extensive turbine damage [BAINES,1987]. The vibration sensors did not detect the damage until the blade row was stripped by the combustor parts. This highlights the need to economically locate sensors so that two faults could be picked up. The alarm and trip threshold setting could also have been low. In monitoring gross faults to prevent catasrophic failures, the system is effective if it has adequate sensor fit. But to address other objectives, such as minimizing consequential damage, life extension. efficient planning and operation, the strategies may be required to be altered.

In the case of unattended or critical equipment, in which the problems can develop rapidly without obvious symptoms, the measurements are taken with installed sensors and monitored continuously. For less vital equipment the readings are taken periodically and externally with portable instruments.

Acoustic monitoring

Sudden changes of stress by, for example, the formation of cracks, plasicity, and phase transformation, emit elastic waves called acoustic emission. It is beginning to be considered [WADLEY] a potential in-process monitoring technique. Applications of the technique are held back because of complicated nature and because the signals are ontrolled rather subtly by microstructure. However the use of changes in sound waves emitted by the rotating parts of an engine, to monitor engine health, has been made. Sonic trending involves the measurement of sound generated by the engine under normal conditions and an assessment of the significance of differences.

The **Curtiss-Wright sonic analysis** is essentially an acoustic based analysis system, developed primarily for monitoring gas turbine engines. Inputs from a number of microphones are normalised to the level of a predetermined band of noise, characteristic of a given engine, which provides a base for component condition limits and analyser system calibration. In addition to data input, one or more of the microphones monitor engine RPM by sending a discrete signal produced by the engine into a phase-locked filter, the output of which is fed into a frequency reference generator, thereby performing a tracking function and precise control and placement of a filter centre frequency.

When a part or component begins to wear or go through some other physical change, the character of the acoustic signal is altered. By monitoring these characteristics it is possible to detect changes in mechanical condition and to pinpoint the individual component deteriorating.

Bearing Monitoring

Bearings in a powerplant invariably operate under extremely harsh loads viz. severe contact stress, corrosion, lubricant failure, dirt, improper mounting, brinelling and high temperature etc. Under these conditions the bearings develop defects like scratches on the race ways, hairline cracks in the cage assembly or microscopic spalling of the balls or rollers which affect their performance and can lead to premature failures. Monitoring condition of bearing without recourse to extensive and time consuming periodic strip examination hence is very important. The three most important independent indicators for bearing fault diagnosis are the energy level of the signal, the impulsiveness of the signal and the amplitude modulation spectra [BAINES,1987] The techniques for rolling elements bearing monitoring are described by [BANNISTER,1985]. Based on vibration data analysis **detailed analytical** or **discrimenent type** condition monitoring techniques are in use. Analytical methods requires skilled analyst to interpret the data where as deterministic method does not require an expert.

The study of installation dynamics reveals the damage characterised by geometrical changes in rolling elements of the bearing and the raceways. Structural changes associated with fatigue phenomena and cracks in the bearing component can affect the dynamic solution, even though they do not effect the bearing geometry, however, such changes are insignificant. Three types of effects are noticed in damaged bearings with roller elements :-

1 Characteristic changes in vibration spectra at points on the bearing boundaries
2 Transient oscillations at the boundaries of bearing and surrounding structure
3 Pronounced vibration peaks

The microscopic geometric changes of bearing surfaces, caused by damage, give rise to sudden and large variations in the contact pressure. This causes a series of impacts which spread, through bearing components, to the support structure. The wave is elastic, of extremely short duration, and spreads at high velocity. The vibration spectrum of a damaged bearing shows definite changes when compared with spectrum of an undamaged bearing. The changes in the spectrum are largest in the vicinity of the natural frequencies of the installation.

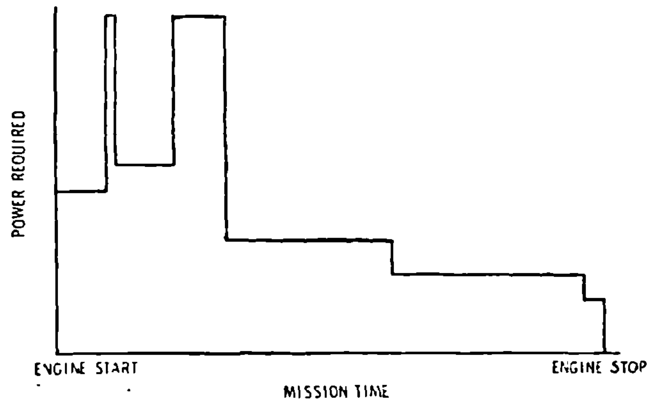
Theoretically the bearing damage can be assessed by studying wave propagation and oscillation phenomena. Because of the bearing installations, the waves are reflected, damped or modified, making it difficult to evaluate the extent of damage in the bearing, but the presence of the wave indicates damaged bearing. When a rolling element passes over the damage, the vibration level at a point on the surface of the bearing will be high, but of very short duration. It may be therefore, very difficult to detect these vibration peaks if the pick-up elements are far removed from the bearing. This requires that the sensors be mounted as near as possible, to the bearing under investigation or an optimal position. Secondary damage can cause several oscillation sequences to be superimposed on each other making identification still more difficult.

The method of vibration monitoring and diagnosis, number and location of transducers, acceptable level of vibration and the action after detection of fault are typical to the manufacturers, type of engine, its use, installation and the logistic support. Since the symptoms associated with individual faults tend to overlap and the possibility that multiple faults may share symptoms, especially in a multi-rotor gas turbine, the diagnosis is often confusing. Initially the analysis involves the manufacturer, who with vibration experience on the type and depending on the installation, draws up a fault tree [AGGARWAL,1986], as shown in Fig 7.6. The logic of the fault tree shows the similarity of analysis using artificial intelligence (expert system) concept described in chapter 7.

ENGINE USAGE MONITORING

Gas turbine rotating components undergo significant excursions in both centrifugal and thermal loads (the latter being time dependent) and inherently experience thermal stresses and metallurgical fatigue to some extent. Hence some major components such as shafts, discs and blades, which are subject to cyclic stresses induced centrifugally and thermally, are lifed. These components are very critical to engine safety and may not be contained after fatigue failure. Life of these components is determined by **creep** and the **Low Cycle Fatigue (LCF)** and they must be replaced after a fixed number of cycles, generally, based on assumption that the parts are subjected to a mission of fixed severity.

Knowledge of the operating load history are very important to determine thermal stresses which change in a complex manner due to transient differential heating and cooling effects. The turbine in reacting to these can accumulate LCF damage and may fracture in critically stressed areas of structural components. During design, component LCF life is calculated based on thermal stresses arising from the assumed load history. However, the actual operating load excursions may be quite different than those assumed. An accurate assessment of the operating characteristics of the engine can help extend hardware inspection intervals, preclude premature removal of parts from service, and prevent excessive conservatism in future design. If the experienced loads are less severe than the design assumptions, extension of inspection intervals and replacement times may be possible [TOLLER,1984]. On the other hand severe loads warrant shorter inspection intervals and limited service life. Engine diagnostics began as a way to extend the time between overhauls and its implementation gave FAA and the manufacturers confidence permitting a safe extension of life.



a — F-14 power required profile

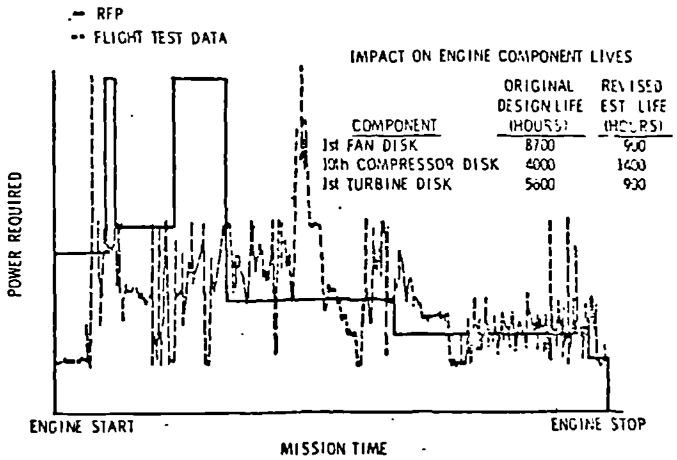


Fig B7 The Sortie Profile of F-14 the Design and Test data.

The requirement of **Engine Usage Monitoring (EUM)** emerged from the need to acquire a better knowledge of LCF in the military aircraft where the load variations and the severity can be high. Theoretical missions, the basis of the LCF life determination, are very simple as compared to actual profiles Fig B7 [WELLS,1987]. Also there is noticeabe difference in actual profiles between aircraft sorties, pilot to pliot, flight configuration and the role. This is highlighted in Fig B8 which shows profiles of two Red Arrow Hawks in same display but at different positions in the formation [HURRY,1983].

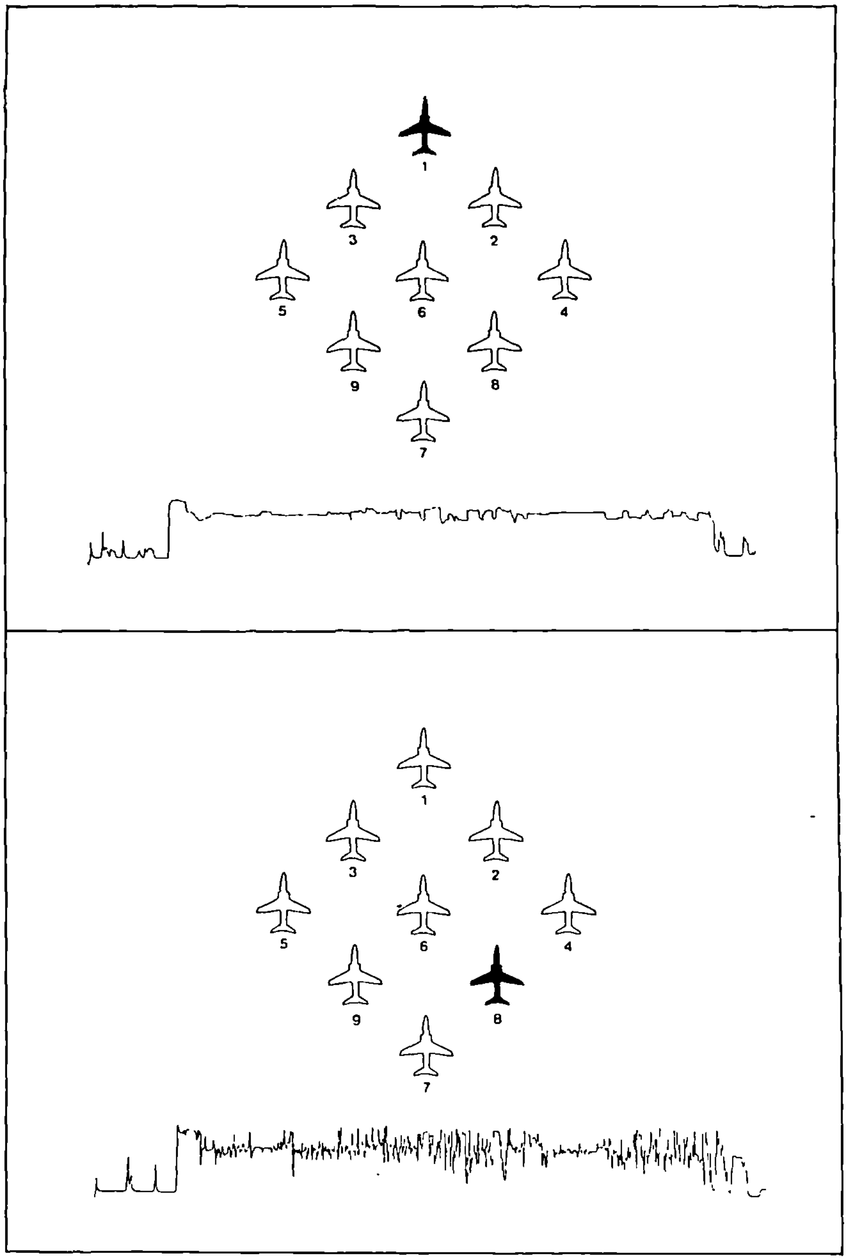


Fig B8 A Comparison of Engine Cycles in Same Sortie But at Different Position in the Formation - Red Arrows

In the industrial field start counters record only start attempt and not other potentially damaging load excursions. The hour meters also do not provide breakdown of operating time at various operating loads. Transient operating conditions can produce significant fatigue damage and are not logged. Therefore whatever be the user, as a minimum, it is necessary to monitor both the rotor speed and operating temperature with time. These two characterize the load history of the major structural components.

Rotor speed is a measure of the centrifugal stress level with in the rotating parts. Early methods were based on centrifugal stresses only, but techniques to calculate the total stresses from separate contributors are now available. There is no simple correlation between the primary operating parameters and the stresses at critical points for components subjected to thermal stresses. This is because the thermal stresses change in a complex manner due to transient differential heating and cooling effects. Thermal stresses are calculated from the gas conditions using expressions which have been previously calibrated against a full detailed analysis of a series of typical acceleration or deceleration transients. Individual on-board calculation of the life consumption for each critical point during the flight is the m st accurate and handiest method.

In the absence of the metal temperature, the thermal load experienced by a component is difficult to quantify. However for a given configuration, the metal temerature excursions can be inferred from the measured gas temperature with reasonable accuracy. With development of High Pressure turbines, importance has been concentrated on thermal stresses and new materials for turbines have been developed for prolonged high temperature operation. Since HP Turbine Inlet temperature are very high and in general not measured, EGT or the second/power turbine inlet temperature could be used. It is necessary to relate excursions in these parameters to the life predictions for various turbine components. Various simplifying assumptions thus minimize the number of monitored parameters without causing big error in fatigue and/or creep damage.

Each component has, based on certain laboratory tests, a **Predicted Safe Cleared Life** in terms of maximum number of a **Reference Stress Cycle (RSC)**. The load profile of Fig B8 can be converted to a number of major and minor cycles. The minor cycles are converted to a portion of the RSC and then major and minor are added to indicate equivalent RSC's. It is not possible to count the RSC's used but a cyclic exchange rate can be agreed between the manufacturer and the user. Thus a component with cyclic life of say 5000 cycles uses 5 cycles (LCF exchange rate) per flying hour, then it is issued with a life of 1000 Hrs. If during, with condition monitoring, usage the LCF life usage rate is found to be 4 cycles per hour, then the component's life on that engine can be extended by 25% to 1250 Hrs.

There is a considerable variation in cycle consumption per flight within a specific sortie code and cyclic usage rate shows non-random base to base and engine to engine variation. Each individual (operator) consumes engine life at different rate, hence the average cycles per hour concept had to give way to on-board LCF counters. LCF assessment and hot section lifing are critical for all gas turbine operators. The transport aircraft operation profiles are quite flat and almost similar in nature for various aircraft and operators. The LCF consumption based on an estimated average exchange rate of fatigue usage per flying hour, is therefore good guess and is still utilised. The airlines frequently use reduced severity mission (for example, takeoff power may be lowered for a partly empty aircraft) and benefit life extension. The refined life cycle counting algorithm is envisioned as a calculation which evaluates from mission profile data and actual severity [DYSON,1984]. Similarly ground based operators follow the logs, start counters and hour meters.

The LCF damage is incurred when cyclic loading produces plastic strain in a component. As mentioned earlier, the n n-random base to base and engine to engine variation in usage rate make exact estimation of the LCF damage a necessity for class A structures. A sample fit can provide data for estimation of LCF life usage on fleet scale like transport aircraft users. For military (fighter/bomber) aircraft LCF counting systems have been developed. This is basically a microprocessor based data processor. Analog data is digitized and processed, together with previous knowledge of LCF life used, to compute and record the LCF life used on a range of engine components.

LCF book keeping thus provides a monitor of life used on each component in every engine and eliminates the need for safety factor to cater for stastical uncertainty of the general application of LCF exchange rates. The LCF calculations are made using the laws relating shaft speed and thermal analysis.

There are two methods currently used wherein :-

1. The LCF consumption is monitored directly on each engine. The technique is particularly applicable to military aircraft where variations are high.

2. The LCF consumed is determined from an estimated average rate of fatigue usage per operating hour or cycle of use. This method is used by transport aircraft and ground based operators.

In gas turbine engines the major engine cycles are associated with starting-running-stopping the machine and minor cycles are associated with vibratory amplitude during operation. For assessing the cumulative effect of fatigue life this is broken down into three stages: 1) cycle counting that is reducing the measured data (gas generator speed, the power turbine speed or time history) into discrete cycles that include the range of each cycle ; 2) assessing damage in individual cycles ; and 3) adding damage produced by individual cycles [EHLERS,1984].

There are a number of cumulative damage laws available eg. Palmgren-Miner's Law or Double Goodman Diagram. The stresses may be calculated by the Range Mean Analysis and Rainflow (Pagoda Roof) Analysis. The most widely used technique is combination of Palmgren-Miner Rule and the Rain flow method and both are well documented. The basis of this law is that if n_i cycles at a stress amplitude of σ_i, for which the average number of cycles to failure is N_i, then the amount of damage which will be caused by this particular stress amplitude will be n_i/N_i.

Another aspect of component life monitoring concerns the deterioration of **hot-end components**, such as turbine blades, nozzle guide vanes etc. which have a significant influence on performance, reliability, maintenance and logistics. These components are in general more damage tolerant than discs and shafts and maintain structural integrity even in presence of cracks and structural removal through corrosion. Degradation in condition of these components however does affect the performance and handling thus requiring monitoring of their condition.

HP turbine blade life distributions are in principle similar to the rotating component life distributions. The life usage rate is also dependent upon the severity of the engine operation. Turbine blade replacement costs are the most significant Life Cycle Cost driver. Hence monitoring the blade usage life, by means other than flying hours, realises significant economic benefits.

Two common modes of failures of blades are **creep and thermal shock**. Creep, plastic deformation from prolonged high temperature operation, is a function of stress, temperature and time while thermal fatigue is related to the temperature gradient within the blade. Since the temperature and stress variations of the turbomachine components are three-dimensional, the computations associated with creep failure are very complex. For aero gas-turbine, creep value is defined as the stress (at the max temperature) to produce 0.1% strain in 100 flying hours. For industrial gas turbines the stress to produce 0.1% strain in 10,000 hours is often used. To evaluate creep data on a lifed component time temperature parametric method is used. The most popular method is Larson and Miller and Manson and Haford method.

Because the thermal stresses have very great influence on the life consumption, they must be calculated with high accurcy. In particular, the determination of the time behaviour of the temperature distribution in the critical components, necessary to achieve this high accuracy, poses a proble. There is no known analytical solution of equations describing rotor temperature time behaviour for the complex geometry. Numerical methods are highly time consuming and require very high computational efforts.

The gas turbine performance is limited through its operating temperature in achievement of a long life. The blades rotating in the combustor exhaust are under the combined effect of thermal and centrifugal stresses. They are often cooled as part of a compromise between performance and ife. The **turbine blade temperature (TBT)** depends on the power setting of the engine, hence is the life of the blade. To determine exact life consumed, monitoring turbine blade temperature is essential. One of the most successfully developed method to read and directly monitor TBT is by the use of radiation pyrometer which can estimate the mean temperature of an array of blades, the mean tempearutre of ndividual blades and the temperature profile across each blade. The use of radiation pyrometer to determine TBT is well documented. The prediction of 'safe life remaining' requires the use of an established algorithm to estimate the development of thermal fatigue and creep. Special equipment is used for this purpose.

Another technique of measuring the temperature of the turbine blades from a stationary position is with an infrared optical pyrometer. The optical device is calibrated relative to a known temperature source, preferably a reserve thermo-couple imbedded in the lower temperatures and lower stress region of the aerofoil to maximise its read out life. This is also used to control over temperature of the blade by suitably integrating it with engine control circuit. Rolls-Royce has developed turbine blade life usage algorithm for estimating HP turbine blade creep and thermal fatigue damage. This is incorporated in Engine Usage Monitoring sysytem (EUMS) Mark II fitted on Harrier aircraft of RAF. Blade instantaneous peak temperatures and temperature differences across the blade sections and therefore the termal strain are worked out by further calculations. Rainflow technique is used to determine strain cycles and their corresponding strain ranges. From these values the fatigue damage accumulated by that section of the blade is calculated.

The rate of damage experienced by the turbine blades is thus dependent upon the engine operation and the environment. Experience on pegasus showed that operating in a hot climate increases this rate of damage. The EMS should have the capability to :-

1. Supply complete flight data to the Ground Replay facility if required, when used in conjunction with the bulk recorder option, together with incident data from the non-volatile memory.

2. Compute all engine life usage algorithm in real time and display the results in one of the several ways to maintainenance personnel immediately on landing.

3. Compute and display specified on board maintenance data such as vibration overspeedx overtemperature overpressure and other engine related incidents

Visual Condition Monitoring (Inspection) Techniques

One of the most effective condition monitoring techniques is visual inspection. Externally visual inspection can detect leaks of gas and fuel, security of pipes, accessories and control linkages. It is the engine internal inspection "endoscope" that yields the best rewards. The presence of nicks, deposits, feathers or blood, fuel, oil, erosion, corrosion, burns, cracks, buckling, distortions and condition of coating etc on the compressor, combustion and turbines of the engine through visual inspection (off-line) provide significant and accurate information.

Although visual inspections, both internal and external, are regarded techniques in their own right, even with the most sophisticated data acquisition and diagnostic systems a visual inspection is carried out before a diagnosis can be confirmed and maintenance action undertaken. The basic methods of internal inspection in current use are :
- Rigid endoscopy (Borescopes or rigid endoprobes)
- Flexible endoscopy (Fibrescopes or flexible endoprobes)

Borescope

These are instruments designed to enable an observer to inspect the inside of a narrow tube, bore or chamber. They are precision built optical systems with arrangements of prisms, achromatic and plain lenses to provide light with the maximum efficiency. The borescope set constists of two units ; chamberscope with a camera attachment for inspecting whole of combustion chamber and its related parts (NGV, fuel nozzles etc) [COLLACOT]; the second, a universal unit for inspecting the compressor and turbine. Source of light is external, with the light transmitted through a fibre optic bundle. It is possible to photograph the observations and the photographs are used for trending. For access to internal parts of the engine, ports are provided, eg. JT9D engine on Boeing 747 has 21 borescope ports to view the gas path from end of the LP compressor to output end of the turbine and additional 8 ports around the circumference of the diffuser case for inspection of the combustion chamber zone. Rigid endscope give exceptionally good views of the object since light is transmitted back to the eye, but the access in straight line only, is a disadvantage.

The effectiveness of borescope inspection on an aircraft engine depends upon the capability of the basic borescope system to extract a useful image from the engine and the access provisions on the engine. The two parameters are related, since the access hole set the maximum diameter of the borescope hence establishing its resolution, illumination, light gathering power and viewing distance. During design, accurate prediction of the problem areas cannot be made, hence the borescope ports are included with previous experience only.

Fibre Optic Scanners

Fibre-optic light pipes solve many viewing problems and coherent (image carrying) devices are used for internal inspection of engine parts. Various types of probes available are : **Cold light rigid probes, Deep probe endoscopes, Pan view fibrescopes and Miniature CCTV/endoscope.** **Flexible endoscopes** enable viewing of cavities and components that do not have straight line access. The information is transmitted back to the eye via fibre bundle, which can reduce the clarity of the view, particularly on photographs. Modern flexible endoscope have excellent optical features.

In some circumstances, the flexible endoscopes need to be guided to position the viewing tip(Fig B9) in the desired position. This is achieved by the use of a guide tube that are specialised and manufactured for particular sites in particular engine types. The image formed at the eye end is a function of the bends in the fibre-optics bundle and care should be excercised against dis-orientation (inversed image).

Fibre optics have also been used for recording flame image, wavelength spectra and frequencies from inside an operating gas turbine combustor [MOREY,1986]. This helps in diagnosis of the combustor especially in determining the level of soot and pollution. This could be a step towards viewing the flame, not only under laboratory conditions, but in the field as well.

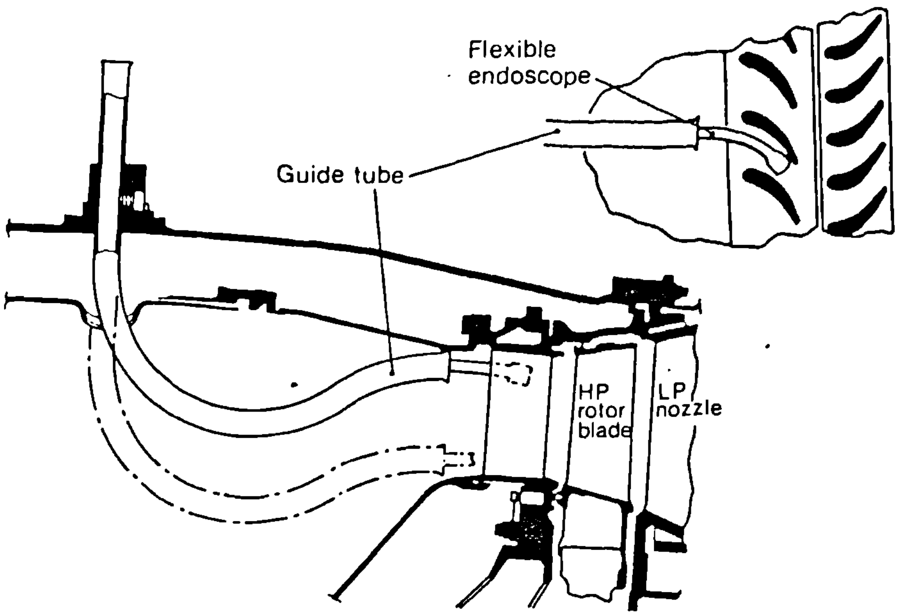


Fig B9 Use of Flexible Endoscope With a Guide Tube

Turbine Exit Spread Monitoring

Turbine Exit Temperature spread monitoring, under steady conditions, is an established technique of condition monitoring the gas generator combustion system and HP turbine gas path components. During commissioning of industrial turbines, it can be used as a tool for making fuel adjustments. A set of equispaced thermocouples, with one thermocouple per burner is necessary for effective spread monitoring. The montioring is carried out continuously (manually or automatically). Typical problems that could be detected by use of T.E.T spread are :-

1. Buckling and cracking of combustion chamber, eventually resulting in pieces becoming detatched and lodging against NGV's.
2. Partially or Fully blocked burner
3. Assymetric distribution of the fuel to the burners.

Fig B10 shows results with a progressively blocked burner when in use with Royal Navy [WALKER,1987].

Limited Transient Monitoring

During start up and shut down limited monitoring of the gas generator transient condition gives useful information not necessarily shown by other methods. During start up the parameters monitored are the Maximum Gas Temperature (MGT) and time to light. MGT is recorded on each engine to monitor hot start occurances and trend analysis which may indicate fuel system drift, starting system shortfall or gas turbine combustion system deterioration [EHLER,1984]. In some cases, in absence of required electric supply, eg. field starting of aircraft etc. the value of MGT might have to be input by the crew.

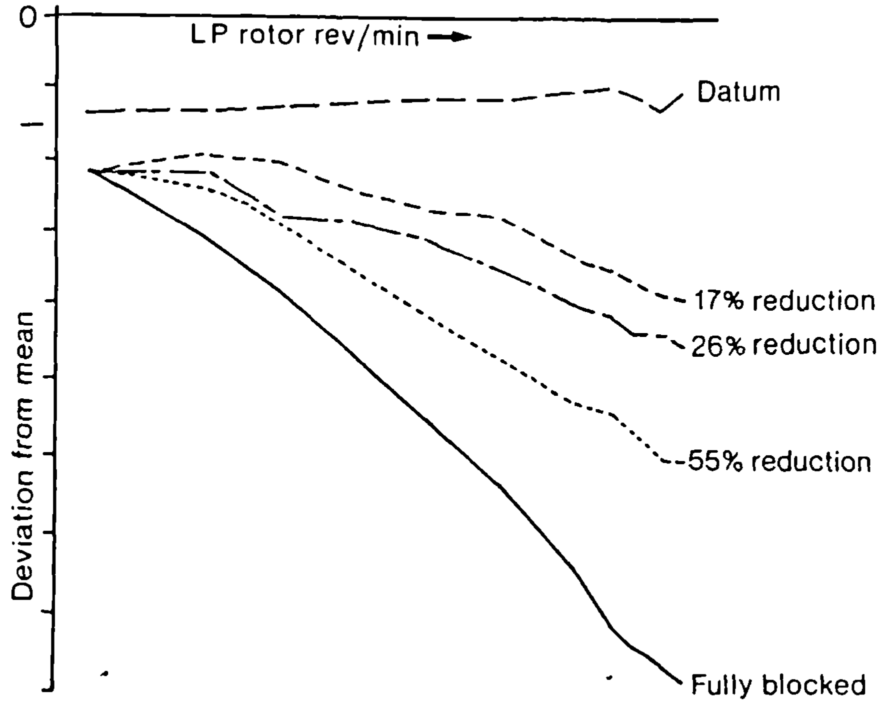


Fig B10 Temperature Spread Indicating Blocked Burner

<u>Gas generator Coast-down Time,</u> time to reach a specified speed for each spool from idle, is also recorded in most of the cases. Trending this time can give useful indications about faults in fuel system, bearings, seals or rotating blade tip rubs. This also generates complete range spectra for vibration analysis. Here again when automatically recording data and in absence of electric supply source, the supply should be run on one engine and the last engine data has to be provided by the crew.

<u>LP cooling air temperature,</u> eg. on Avon, provides an important indication of internal air and oil leakage within gas generator and also provides a check of turbine entry casing which may be deteriorating due to burner malfunctions.

Review

Various techniques of monitoring the mechanical health have been reviewed. These techniques together with gas path analysis form an integrated diagnostic system. Even though a few of the techniques are beginning to appear on-board, most of these techniques are still off-line techniques. No one technique is 100% informative about the complete engine. Hence, each of the fault is normally confirmed by two or more techniques before the engine is taken out of service.

APPENDIX C

MEASUREMENTS

Introduction

Effectiveness of the gas path analysis depends on the effectiveness of the measurement system. Only those faults can be implicitly detected the effects of which can be accurately measured. Accurate observation of judiciously chosen parameters with minimum of disturbance to the engine and its systems, minimum weight and at minimum of the cost is the aim of the measurement system. This Appendix reviews the measurement errors and the effects of the errors in basic measure parameters on deduced values (of interest to GPA).

Measurement Chain

The chain of measurement, whether for display or for recording, is shown in Fig C1 [BENTLEY,1983]. In general the chain consists of four elements or blocks.

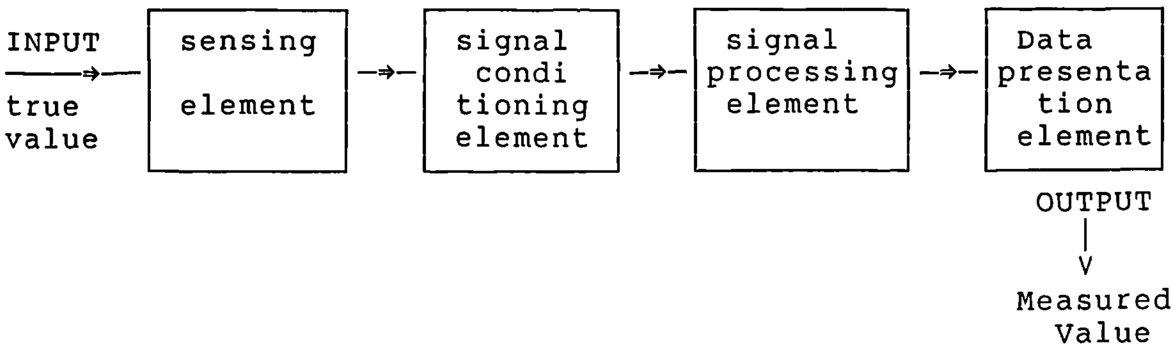


Fig C1 General Structure of a Measurement System

Sensing Elements This is the contact with the process and gives an output which in some way depends on the variable it measures. In the system with more than one sensing elements, the element in contact with the process is called the primary sensing element and the others, secondary.

Signal Conditioning Element converts the sensing element output into a form more suitable for further processing, the output is usually a d.c. voltage, an a.c. voltage, or a frequency signal.

Signal processing element conditions the output of the conditioning element into a form more suitable for presenting or recording. For example an analogue signal may be digitised for manipulation by the computer or for the purpose of storing.

Data presentation element presents the measured value in a recognisable form. This could be conventional display unit or alphanumeric display.

The commonly used word **'transducer'** is a manufactured package which gives an output (usually voltage) corresponding to an input variable such as pressure or temperature. The transducer thus incorporates sensing and signal conditioning elements.

ERRORS

All measurements have measurement errors, defined as difference between the true value and the measured value. Uncertainty is the maximum error which might reasonably be expected and is a measure of the accuracy, i.e., the closeness of the measurement to the true value [ABERNETHY,1975]. There are two types of systems involved and the errors can be classified according to the system.

Measured System Errors

Consider the errors originating in the measured system and the interface of measurement of EGT at a nominal speed and load. There can be an error due to imperfection in modelling the measured system (gas turbine exhaust) which underlies the measurement process. The temperature of the exhaust gases may not be uniform, and a result of measurement that assumes uniform distribution may be in error.

There can be an error that arises due to the changes in the configuration of the measured system produced by the introduction of the sensor [FINKELSTEIN,1983]. The increase of back pressure of the engine, because of the thermocouple in exhaust duct, requires increase in fuel flow and hence an increase in EGT.

The sensor absorbs certain amount of power, however small, thus causing an error. The heat exchange between exhaust gases and the sensor alters the heat content of the gases and hence its temperature.

Measurement System Errors

Whatever be the parameter measured, its measurements incorporate an uncertainty. This uncertainty is due to certain errors depending on the type of system used. For a gas turbine engine system these could be :-

1 **Calibration Hierarchy Errors**

2 **Data Acquisition Errors**

3 **Data Reduction Errors**

Calibration Hierarchy Errors

Error is the difference between the result of a measurement and the true value of the measured quantity. The true value being the quantity under perfect measurement, as defined by the appropriate measurement scale. It is an idealised concept which cannot be empirically determined. Hence a conventional true value, a value approximated to the true value, or statistically determined as most likely value, is normally referred as true value. The error can thus be defined as

Error = measured value - true value

Let us assume that a system of measurement has n elements in series as shown in fig C2. Further we assume that all of these elements are ideal and for each of them the output input relation can be expressed as

$O_i = K_i I_i$ for $i = 1, \ldots\ldots\ldots, n$

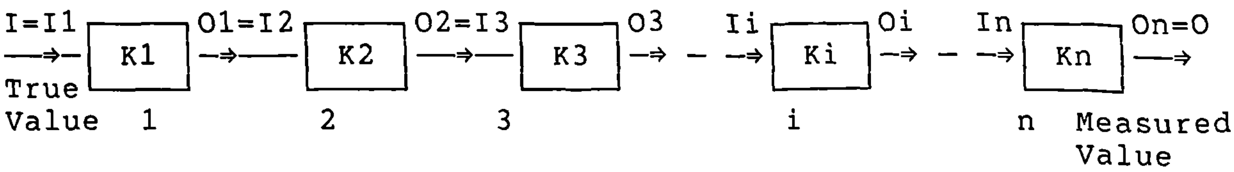


Fig C2 Measurement system of Ideal Elements

Where K_i is the slope. It follows that $O_2 = K_2 I_2 = K_2 K_1 I$ and for the entire system we have

$$O = O_n = K_1 K_2 K_3 \ldots\ldots\ldots K_n I \qquad \ldots \qquad C.1)$$

By definition the error $E = O - I$ which gives

$$E = (K_1 K_2 K_3 \ldots\ldots K_n - 1)I \quad \ldots \quad \ldots (C.2)$$

for $E = 0$ or $K_1 K_2 K_3 \ldots\ldots K_n = 1$ the system is perfectly accurate.

Characteristics of Measurement

Various links of the chain have their individual characteristics which can be divided into two categories :-

- **Static Characteristics**
- **Dynamic Characteristics**

The static characteristics or the steady state characteristics are the relationships which may occur between the input and the output when the input is constant or changes very slowly. These characteristics may further be divided as **Systematic Characteristics** or **Statistical Characteristics.**

Systematic Characteristics are the ones that can be exactly quantified mathematically. These include

Range specifies the minimum and the maximum values of measure. For input it becomes the input range eg. -56 C to 100 C while at the output stage this is the output range which may be 5mV to 51 mV.

Span is the difference of maximum and minimum of the range values. For example in the above case input span is 156 C and output Span is 46mV.

Ideal Straight line is the equation of the line in input output plane that connects lowest value of the range (I_{min}, O_{min}) to the highest value (I_{max}, O_{max}).

Non linearity is the difference or deviation of actual operating characteristics of the link from ideal straight line behaviour. It is normally specified in terms of maximum nonlinearity expressed as a % of output span.

Sensitivity is the rate of change of output with respect to input. Normally it is possible to express output and non linearity as a polynomial of input.

Environmental effects The characteristics of elements of measure can be influenced by the operating conditions such as Pressure, Temperature, Vibrations, Loading, Chemical environment, Ionising radiation and electrical interference.

Two types of changes can take place. In interfering type the zero bias is changed while sensitivity is affected by the modifying type. There is a possibility of existence of both simultaneously.

Hysteresis is the difference in the output for same input value depending upon the previous value. Thus if O_1 output corresponds to the input while increasing the value and O_2 while decreasing from a higher value, then O_1-O_2 is the hysteresis.

Resolution is the largest change in the input that can occur before any change in the output is noted.

Quantisation error is the error which may result from the measurement of a value of a quantity by a process in which response can only change in discrete quantum steps such as in digital measurement.

Wear and ageing As a result of use the physical properties (characteristics) of the system can change. These changes may occur because of structural changes (eg stiffness of springs, recrystalisation, treatment etc.) or damage (crack etc.) due to abuse. The changes may be systematic and gradual with time and may go unnoticed or may be sudden.

Error bands In modern sensors the non-linearity, hysteresis and resolution effects are very small and quantisation of each of these is not worthwhile. In such cases the performance of the element is normally defined in terms of error bands h. This implies that for any input the output will be $\pm h$ of the ideal straight line value. This is however based on the statistical probability density function.

Statistical Characteristics

The effects of small random variations in manufacture of an element can often be represented as a Gaussian or a normal distribution function. These deviations from the mean are the tolerances of manufacture and hence each component will have a different output for same input. This error due to manufacturing tolerances is difficult to quantify and hence is based on the probability distribution function.

The **accuracy** of a measuring instrument is the ability of the instrument to give indications equivalent to the true value of the quantity measured. It is the degree of correspondence of the results of a measurement to the true value of the measured quantity that is free from error. Accuracy should be stated in terms of the systematic and unsystematic uncertainties.

The quantitative characterisation of accuracy should be given in terms of random and systematic uncertainty. Since the uncertainties will be different at different values in the range of the instrument, the uncertainty should be specified as a function of the quantity measured. In practice it is common to specify the maximum uncertainty in the range, as a fraction of the upper limit of the range. The actual accuracy of the instrument in use depends on the magnitude of the influence error effects.

In many cases what is of interest is not the accuracy, but the **repeatability** of an instrument, that is the ability of the instrument to give identical indications or responses, for repeated applications of the same value of the measured quantity under stated conditions of use. It is basically freedom from the random intrinsic error. It is expressed quantitatively by a measure of dispersion of the probability density function p(qi/qm), or generally σ. [FINKELSTEIN, 1983] This is also stated as a function of the measured value.

The repeatability of a measurement is a quantitative expression of the closeness of agreement between successive measurements of the same value of the same quantity carried out by the same method, by similar process at same site and at appropriately short intervals of time. Lack of repeatability is due to random effects in the element and its environment. The most common cause of lack of repeatability in the output are the random environmental input fluctuations. Thus random fluctuations in the ambient temperature cause corresponding time variations in the resistance of an amplifier; which might also be affected by random fluctuations in the supply voltage at the same time.

Repeatability Of a Chain of Measurement

In a measurement system each link of the chain can have the random variations that affect all subsequent components of the chain. Thus by making reasonable assumptions for the probability density functions of input at each level, the elemental probability density function output can be found. The most likely probability density function for input and the environmental effects is the normal or Gaussian distribution function defined as

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[- \frac{(x - \bar{x})^2}{2\sigma^2} \right] \qquad \ldots\ldots \quad (C.3)$$

where

$\bar{x}$ = mean or expected value (specifies centre of distr.)

σ = standard deviation (specifies spread of distr.)

The assumption of a normal distribution is based on the supposition that in a well designed measurement random intrinsic errors will be the result of a large number of uncorrelated component errors each making a small contribution to the resultant error. This results in normal error distribution by the Central Limit Theorem. In many less precise instrument systems however the constituent components of the error are correlated and small in number. But for practical purpose the assumption of normal distribution is adequate.

In general for an element without hysteresis and resolution errors the out put can be expressed in terms of input I, non-linearity effect N(I), ideal straight line intercept a, environmental effects $K_m I_m$ and $K_i I_i$ as

$$\bar{O} = K\bar{I} + a + N(\bar{I}) + K_m\bar{I}_m + K_i\bar{I}_i \qquad \text{.. .. (C.4)}$$

Thus if O is a small deviation in O from mean value, caused by deviations I, Im, Ii from their respective mean values then :

$$p(\bar{O}) = \frac{1}{\sigma_0\sqrt{2\pi}} \exp\left[-\frac{(O - \Theta)^2}{2\sigma^2} \right] \qquad \text{.. (C.5)}$$

If a dependent variable y is a linear combination of independent variables x1,x2,x3 i.e

$$y = a_1x_1 + a_2x_2 + a_3x_3 \qquad \text{.. .. .. (C.6)}$$

and if x_1, x_2, x_3 have Gaussian distribution with standard deviations σ_1, σ_2, σ_3 then the probability distribution of y is also Gaussian with standard deviation given by :

$$= \sqrt{(a_1^2\,\sigma_1^2 + a_2^2\,\sigma_2^2 + a_3^2\sigma_3^2} \qquad \text{. . .(C.7)}$$

Thus the standard deviation of the output is given by

$$\sigma = \sqrt{\left(\frac{\partial O}{\partial I}\right)^2 \sigma^2_I + \left(\frac{\partial O}{\partial I}\right)^2 \sigma^2_{I_M} + \left(\frac{\partial O}{\partial I}\right)^2 \sigma^2_{I_I}} \qquad \text{. . (C.8)}$$

where σ_I, σ_{I_M}, σ_{I_I} are the standard deviations of the input.

Thus the deviation of the output of the complete system of measurement can be determined if the deviations of the elements are known. Alternatively the standard deviation can be determined experimentally (calibration).

The **reproducibility** of a measurement is an expression of the closeness of the agreement between the results of measurements of the same value of the same quantity after correction for certain errors, where the individual measurements are made under different conditions, say by different methods, with different measuring instruments and the like.

<u>Overall Error of the Measurement</u>

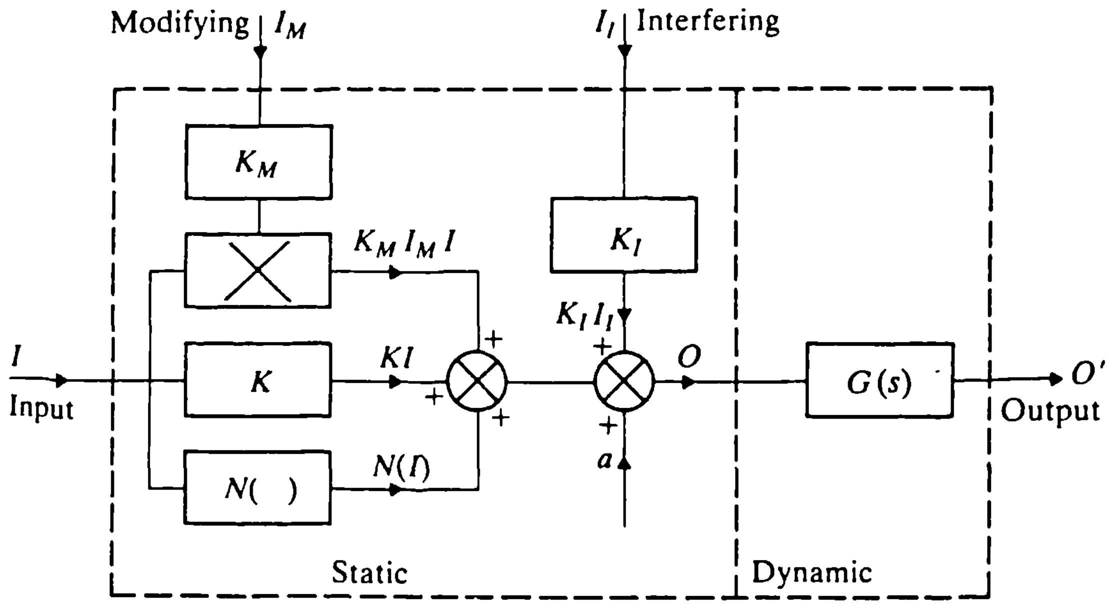


Fig C3 General Model of the Element

In general the errors can thus be quantised as precisely as possible through the use of a general model for an element as shown in Fig C3. This allows us to estimate the mean value of the output of each element as described above. The mean value E of the system error is simply the difference between the mean value of system output and the mean value of system input. Since the probability densities of the output of the individual elements are Gaussian, then the probability density function of the system output O and the system error E is also Gaussian. If we consider the standard deviation of input as zero, the standard deviation of the system and that of the error are identical. The reason for the assumption of zero mean error is that an intrinsic random error with a mean different from zero can be taken to be an uncertain systematic error.

Similarly for small non linearity, hysteresis and environmental effects, the errors grouped under error band can be expressed in Gaussian probability density function. For error bands with rectangular probability density function the overall effects are quantised to a standard deviation of $h/\sqrt{3}$.

It is hence possible to represent the error distribution as Gaussian probability density function that would consider the systematic as well as statistical characteristics. Further with input deviation as zero this becomes the standard deviation of the output of the measurement system. In this sense the measurement error can be said to have two components viz. **Fixed error (Bias)** and the **Random error (Precision)**. The random error is seen in repeated measurements which is in general a Gaussian distribution where standard deviation (σ) is used as a measure of precision. Precision index for N measurements X_i giving X as the average is worked statistically as

$$s = \sqrt{\frac{\sum_{i=1}^{N} (Xi - \bar{X})^2}{N - 1}} \quad \ldots\ldots \quad (C.9)$$

Fixed Errors

The second component, **bias**, is the constant or systematic error. In repeated measurements, each measurement has the same bias. The bias cannot be determined unless the measurements are compared with the true value of quantity measured.

Four classes of bias viz. **large known bias, small known bias, large unknown bias** and **small unknown bias** exist. The known biases are eliminated by comparing the instrument with a standard instrument and obtaining a correction. This process is called calibration. However sometimes small known biases may be difficult to correct and the magnitude of the bias may not warrant expensive calibration.

Unknown biases are not correctable since they may exist, but their magnitude or the sign may not be known. Every effort must be made to eliminate all large unknown biases since these errors convert the controlled measurement process into an uncontrolled worthless effort. Sources of large unknown bias errors are numerous eg. human error in data processing, incorrect data handling and installation of instrumentation, and unexpected environmental disturbances such as shock and bad flow profiles. Normally there are no large unknown bias errors in a well-controlled measurement process. To ensure existence of a controlled measurement process, all measurements should be statistically monitored. This would identify drifts, trends and movements of bias to out-of-control situation using histories of data.

It is both difficult and frustrating to estimate the limit of unknown bias. Exact bias can be determined only with the knowledge of the true value and the measured value, which is almost impossible. An effort must be made to obtain special tests or data that will provide bias information. A few examples are :-

1. Interlab, interfacility, intercompany tests on measurement devices, test rigs and full scale engines.

2. Flight test data verses altitude test chamber data verses ground test data.

3. Special comparison of standards with instruments in the actual test environment.

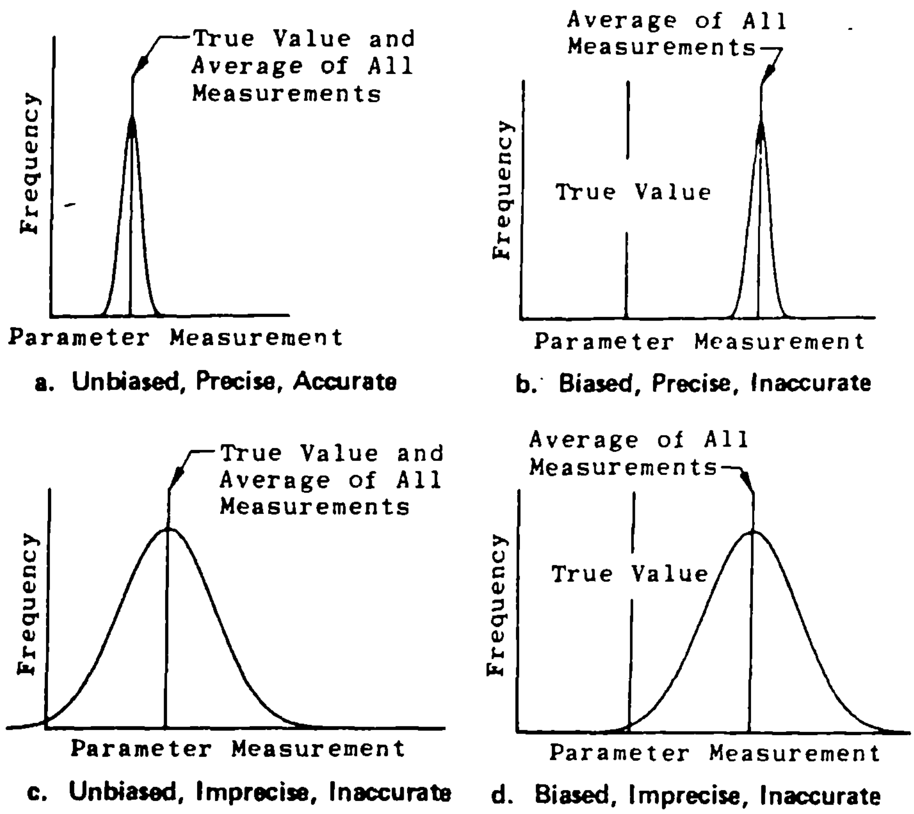


Fig C4 Measurement Errors (Precision Bias and Accuracy)

4. Ancillary or concomitant functions that provide the same performance parameter thus confirming the value e.g. in a test cell mass flow determination can be by numerous methods and a comparison made.

5. Special calibrations may be performed when it is known that a bias results from a particular cause, allowing the cause to perturbate through its complete range to determine the range of bias.

If there is no source of data for bias, the judgement of the most knowledgeable instrumentation expert on the measurement has to be used. Here again without data the upper limit on the largest possible bias error reflects the lack of knowledge. Fig C4 shows bias and precision errors.

Bias of a Chain of Measurement

In the present context most the independent parameters are derived from measurands. Thus the individual measurement bias inaccuracies will have cumulative effect on the derived parameter. This effect is quantized as follow.

Let us have a parameter Q which is funcion of n varibles M_1 ,M_2 ,M_3 . . . .M_n which can be independently measured. We can state the relation in equation form as

$$Q = f(M_1, M_2, M_3, \ldots M_n) \quad . \quad .. \qquad (C.10)$$

Let ΔQ_i be the increment in Q, when a measurement M_i has an increment ΔM_i. For i = 1 to n if ΔQ denotes the sum $\Sigma \Delta Q_i$ then we can write

$$Q \pm \Delta Q = f(M_1 \pm \Delta M_1, M_2 \pm \Delta M_2, M_3 \pm \Delta M_3, \ldots\ldots M_n \pm \Delta M_n)$$

$$= f(M_1, M_2, M_3, \ldots M_n) \pm \Delta M_1 \frac{\partial f}{\partial M_1} \pm \Delta M_2 \frac{\partial f}{\partial M_2} \quad . \quad (C.11)$$

$$\pm \Delta M_n \frac{\partial f}{\partial M_n} \pm \frac{1}{2} \left[(\Delta M_1)^2 \frac{\partial^2 f}{\partial M_1{}^2} \pm \ldots . \right] \quad \pm \quad \ldots . \quad (C.12)$$

$$= Q \pm \quad \Delta M_1 \frac{\partial f}{\partial M_1} \pm \Delta M_2 \frac{\partial f}{\partial M_2} \ldots \pm \Delta M_n \frac{\partial f}{\partial M_n} \quad . \; . \; .(C.13)$$

$$\pm \frac{1}{2}\left[(\Delta M_1)^2 \frac{\partial^2 f}{\partial {M_1}^2} \pm \ldots\right] \pm \ldots \quad . \qquad (C.14)$$

Assuming the ΔM's to be very small ($\Delta\Delta$ 1% error) the higher order terms can be neglected. This the simplifies to

$$\Delta Q = \Delta M_1 \frac{\partial f}{\partial M_1} \pm \Delta M_2 \frac{\partial f}{\partial M_2} \ldots \pm \Delta M_n \frac{\partial f}{\partial M_n} \quad . . \; (C.15)$$

The absolute error then can be written as

$$\Delta Q_{abs} = \left|\Delta M_1 \frac{\partial f}{\partial M_1}\right| + \left|\Delta M_2 \frac{\partial f}{\partial M_2}\right| \ldots + \left|\Delta M_n \frac{\partial f}{\partial M_n}\right| \quad .. \; (C.16)$$

In order to eliminate the effects of opposite signs the root mean square (RMS) value can be written as

$$\Delta Q_{abs} = \sqrt{\left(\Delta M_1 \frac{\partial f}{\partial M_1}\right)^2 + \left(\Delta M_2 \frac{\partial f}{\partial M_2}\right)^2 \ldots + \left(\Delta M_n \frac{\partial f}{\partial M_n}\right)^2} \quad ..(C.17)$$

The cumulative effect of the errors is thus a weighted root mean square of the individual component errors.

Dynamic Characteristics

In addition to the static characteristics, discussed above for the system of measurement and its elements, there exist the dynamic characteristics. These characteristics are representative of the behaviour of the output when the input suddenly undergoes a change. In addition to the component characteristics the output is also dependent on the magnitude, nature, rate and frequency of the change.

Dynamic error The error in the operation of an instrument used in the dynamic mode in which instantaneous value of the instrument indication is required to be a function of the instantaneous value of the measured, varying quantity. Practical instruments have lag and hence the value output (measured) depends not only on the instantaneous quantity measured but also on the previous value. The difference between the instantaneous indication or measurement and the instantaneous measured value is the dynamic error. These are not considered for steady state diagnostics and hence are not discussed.

Data Acquisition errors Since data are acquired by measuring the electrical output resulting from a measurement system, the acquisition errors set in. These comprise of signal conditioning and recording elements. The best method to determine these errors is to perform end-to-end calibration.

Data reduction errors Computers operate on raw data to produce output in engineering units. The errors in this process stem from calibration curve fits and computer resolution.

Error reduction techniques

The errors in a measurement system because of non ideal characteristics of the constituent elements can be identified through calibration of the system. Once the element with most non-ideal behaviour has been identified, compensation strategies to eliminate or minimize such errors can be devised. This would produce significant reduction in the error of the overall system. Various methods of error reduction are :-

- Compensating non-linear element
- Zero environmental sensitivity
- Opposing environmental inputs
- High gain negative feed back
- Computer estimation of measured value

UNCERTAINTY

As mentioned earlier for performance diagnostics, the values of interest are deduced from measurable quantities. This evaluation is made by direct known relationships. The errors in the measured quantities are hence likely to affect those determined from them through the function. The effect of the propagation may be approximated with the Taylor's series method.

Uncertainty of Deduced Parameters

Let Q_m denote deduced quantity from measured quantities Q_1, Q_2, Q_3... by use of relation

$$Q_m = f(Q_1, Q_2, Q_3, \ldots) \quad . \quad . \qquad (C.18)$$

Then the estimate of Q_m is taken as

Then the estimate of Q_m is taken as

$$q_m = f(q_1, q_2, q_3 \ldots) \quad . \quad . \quad (C.19)$$

where q_1, q_2, q_3 .... are the estimates of the mean of Q_1, Q_2, Q_3 ..

Then if for random uncertainties the estimated variances of Q_1,Q_2,Q_3.. are $\sigma^2(Q_1)$, $\sigma^2(Q2)$, $\sigma^2(Q3)$ ..... we have :

$$\sigma^2(Q_m) = \left(\frac{\partial Q_m}{\partial Q_1}\right)\sigma^2(Q_1) + \left(\frac{\partial Q_m}{\partial Q_2}\right)\sigma^2(Q_2) + \left(\frac{\partial Q_m}{\partial Q_1}\right)\sigma^2(Q_3) \qquad \ldots(C.20)$$

The variance of the mean is given by :

$$\bar{\sigma}^2(Q_m) = \left(\frac{\partial Q_m}{\partial Q_1}\right)\bar{\sigma}^2(Q_1) + \left(\frac{\partial Q_m}{\partial Q_2}\right)\bar{\sigma}^2(Q_2) + \left(\frac{\partial Q_m}{\partial Q_1}\right)\bar{\sigma}^2(Q_3) \qquad ..(C.21)$$

The above equations neglect higher order terms and also assume that all components are independent of each other.

In the case of systematic uncertainties, $\Delta(Q_m)_1$ is the component of systematic uncertainty of Q_m due to the systematic uncertainty ΔQ_1, in Q_1 etc. then :

$$\Delta(Q_m)_1 = \left|\frac{\partial Q_m}{\partial Q_1}\right|\Delta Q_1 \qquad . \;.. \;. \; (C.22)$$

There is no rigorous way of combining the systematic uncertainty components to give the overall systematic uncertainty $\Delta(Q_m)$.

Two relations are used in practice. One adds the components :

$$\Delta(Q_m) = \left|\frac{\partial Q_m}{\partial Q_1}\right|\Delta Q_1 + \left|\frac{\partial Q_m}{\partial Q_2}\right|\Delta Q_2 + \ldots.. \qquad (C.23)$$

This is likely to be overestimate and represents the estimate of the maximum of uncertainty. The second method combines the systematic uncertainties in quadrature :

$$\Delta(Q_m) = \left[\left(\frac{\partial Q_m}{\partial Q_1}\right)^2 (\Delta Q_1)^2 + \left(\frac{\partial Q_m}{\partial Q_2}\right)^2 [\Delta Q_2]^2 + \ldots\ldots\right]^{0.5} \qquad (C.24)$$

This method tends to under estimate the uncertainty. The uncertainties of the relation can be dealt with by introducing them as an uncertain parameter in the above equations.

Example: Thus for a gas turbine engine the sensitivity of non dimensional performance parameters for the whole engine can be represented in term of sensitivity of its component measures [ABERNETHY,1973] eg.

From relation TSFC = W_f/F_N we get

$$\Delta TSFC = \frac{\partial TSFC}{\partial W_f} + \frac{\partial TSFC}{\partial F_N} \Delta F_N \qquad .. \qquad (C.25)$$

$$= \frac{1}{F_N} \Delta F_N - \frac{Wf}{F_N^{\,2}} \Delta F_N$$

where $\dfrac{\partial TSFC}{\partial W_f}$ and $\dfrac{\partial TSFC}{\partial F_N}$ are the partial derivatives of thrust specific fuel consumption with respect to fuel flow and net thrust. The precision index is approximated by

$$S_{TSFC} = \sqrt{\left(\frac{\partial TSFC}{\partial W_f} S_{W_f}\right)^2 + \left(\frac{\partial TSFC}{\partial F_N} S_{F_N}\right)^2} \qquad ..(C.26)$$

$$= \sqrt{\left(\frac{1}{F} S_{W_f}\right)^2 + \left(\frac{-W_f}{F2} S_F\right)^2} \qquad .. \qquad (C.27)$$

The effect of measurement accuracies on deduced parameters can cumulative. Consider for example a Fan efficiency derived by the relation

$$\eta = \frac{(P_o/P_i)^{\kappa} - 1}{(T_o/T_i - 1)} \quad .. \quad .. \quad .. \quad (C.29)$$

where :

η = Isentropic efficiency
P_o = Outlet pressure
P_i = Inlet pressure
T_o = Outlet temperature
T_i = Inlet temperature
κ = coeff $(C_p/C_v - 1)\,(C_p/C_v)$
C_p, C_v = Specific heats at constant pressure and volume

Expanding this in Taylor's series we have

$$d\eta = \left\{ \left[\frac{\kappa(P_o/P_i)^{\kappa}}{To/Ti - 1}\right]^2 \left[\left(\frac{dP_o}{P_o}\right)^2 + \left(\frac{dP_i}{P_i}\right)^2 \right] + \left[\frac{\eta(T_o/T_i)}{To/Ti - 1}\right]^2 \left[\left(\frac{dT_o}{T_o}\right)^2 + \left(\frac{dT_i}{T_i}\right)^2 \right] \right\}^{0.5}$$

.... (C.30)

Using typical values for a fan, a ±0.1% error in pressure measurement produces a 0.34% error in efficiency. Similarly a ± 3/8% error in temperature alone gives 1.4% error in the fan efficiency. The combined effect of the two errors is approx 1.44 % error.

Review Various errors of the measurement systems have been analysed and the effects of these errors on the parameters that are deduced studied. The instrument errors in general can be classified as stationary error or the bias, and a noise of the measure which is random. The noise can, for simplicity of analysis be assumed to be a Gaussian with a mean value of zero. The effects of the error in measurement of a parameter are transferred to the deduced parameter through their relationship equation.

LEVEL	2	3	4	5	6
DETEM	CPU	ENGINE	INTAKE	AFROMV	CONTRO
	MENU		COMPRE	VFROMA	RECORD
	IFOUL		BURNER	DELT12	PUDRIV
	DESIGN		TURBIN	TPRHO	AITKEN
	OFF DESIGN		DUCTER	AMEP	WATINJ
	TRANSIENT	RECORD	MIXEES	A1TOA2	SHAFOF
		THROT	NOZCON	MAPBAC	CDCAL
			NOZDIV	MATRIX	RECOGI
	ANALYZER	MATRIX	ARITHY	ABCNOZ	DIRECT
	TREND	SERIEGEN	MIXFUL	COMBUS	PARABO
		G05CCF	HETCOL	RESET	AFQUIR
		G05EGF	HETHOT	BOUNDM	SINTE2
	PERTURB	TIMER		SHOCKN	SEARCH
		TIME		SONNOZ	BRIK_MATCH
		LIB$WAIT		SBSNOZ	RKWORD
	GENERATOR			SVBNOZ	SINTER
		G05CCF		RESET	SONICC
		G05CBF		NOZCO	QUADR
	COEFF_LOOP	FOUL_RESET			DIRECT
	DIAGNOSTIC	DIAGNOSTIC_WRITE			
	IFOUL	DISPLAY2			
		DISPLAY6		DISPLAY4	
			OUTPUT	COEFF_WRITE	
				SENSOR_COEFF_WRITE	
					DISPLAY8
					DISPLAY7
					DISPLAY5
	GRAF_LOOP	GRAPHIC	DESIGN_VAL_WRITE		
			GRAF_OUT		
	INPUT			INTITLE	
				BRIK_MATCH	COMP
				UPPER_CASE	UNPACK
				RKWORD	UNPACK2
				DISPLAY1	
				BKSPS	
DATA BLOCK					

TABLE D1 - DETEM PROGRAM/SUBROUTINE HIERARCHY

Thrust Generating Engines

Gross Thrust	vs	RPM
Net Trust	vs	RPM
Fuel Flow	vs	RPM
Mass Flow	vs	RPM
EPR	vs	RPM
Specific Thrust	vs	RPM
Nozzle Area	vs	RPM
s.f.c	vs	RPM

Shaft Power Generating Engines

Shaft Power	vs	RPM
Fuel Flow	vs	RPM
sfc	vs	RPM
Eq fu Con	vs	RPM
EPR	vs	RPM
Mass Flow	vs	RPM
Torque	vs	RPM
Sp Th Effcy	vs	RPM

TABLE D2 LIST OF GRAPHS (All parameters are standardised to ISA conditons)

```
-+-----------+-----------+-----------+-----------+-----------+-----------+----------
 |+---+      |+---+      |+---+      |+---+      |+---+      |+---+      |+---+
 I|1  |      C|2  |      B|3  |      T|4  |      T|5  |      D|6  |      N|7  |
 N+---+      M+---+      R+---+      R+---+      R+---+      C+---+      O+---+
 T Stn       P Stn       N Stn       B Stn       B Stn       T Stn       Z Stn
 K           1           1           1           2           1           1
 |           |           |           |           |           |           |
-+-----------+-----------+-----------+-----------+-----------+-----------+----------
```

```
                                                      +-------------------------+
 TWO SPOOL TURBO SHAFT                                | Do you want to change   |
       ENGINE                                         | default stations?       |
                                                      | Type Y or y for yes     |
                                                      |      N or n for no      |
                                                      +-------------------------+
```

```
-+-------+-------+--------+
 |+---+  |+---+  |+---+   ++-------+-------+-------+-------+-------+-------+------
 I|1  |  F|2  |  P|3  |   C+---+   C+---+   B+---+   T+---+   T+---+   D+---+   N+---+
 N+---+  A+---+  R+---+   M|4  |   M|5  |   R|6  |   R|7  |   R|8  |   C|9  |   O|10 |
 T Stn   N Stn   E Stn    P+---+   P+---+   N+---+   B+---+   B+---+   T+---+   Z+---+
 K       1       1        1 Stn    2 Stn    1 Stn    1 Stn    2 Stn    1 Stn    1 Stn
 |       |       |        ++-------+-------+-------+-------+-------+-------+------
-+-------+-------+--------+
                           21
```

```
                                                      +-------------------------+
 TWO SPOOL NON MIXING                                 | Do you want to change   |
 TURBO FAN ENGINE                                     | default stations?       |
                                                      | Type Y or y for yes     |
                                                      |      N or n for no      |
                                                      +-------------------------+
```

```
-+-------+-------+-------+-------------------------------------+
 |+---+  |+---+  |+---+  +-------+-------+-------+-------+------+-+-------+------
 I|1  |  F|2  |  P|3  |  C+---+  C+---+  B+---+  T+---+  T+---+  D+---+  N+---+
 N+---+  A+---+  R+---+  M|4  |  M|5  |  R|6  |  R|7  |  R|8  |  C|9  |  O|10 |
 T Stn   N Stn   E Stn   P+---+  P+---+  N+---+  B+---+  B+---+  T+---+  Z+---+
 K       1       1       1 Stn   2 Stn   1 Stn   1 Stn   2 Stn   1 Stn   1 Stn
 |       |       |       +-------+-------+-------+-------+------+-+-------+------
-+-------+-------+-------+--------------BY PASS ---------------+
                          21                                      22
```

```
    TWO SPOOL MIXING                                  +-------------------------+
    TURBO FAN ENGINE                                  | Do you want to change   |
                                                      | default stations?       |
                                                      | Type Y or y for yes     |
                                                      |      N or n for no      |
                                                      +-------------------------+
```

```
-+---------+---------+---------+---------+---------+---------+---------+-------
 |+---+    |+---+    |+---+    |+---+    |+---+    |+---+    |+---+    |+---+
 I|1  |    C|2  |    C|3  |    B|4  |    T|5  |    T|6  |    D|7  |    N|8  |
 N+---+    M+---+    M+---+    R+---+    R+---+    R+---+    C+---+    O+---+
 T Stn     P Stn     P Stn     N Stn     B Stn     B Stn     T Stn     Z Stn
 K         1         2         1         1         2         1         1
 |         |         |         |         |         |         |         |
-+---------+---------+---------+---------+---------+---------+---------+-------
```

```
                                                      +-------------------------+
TWO SPOOL TURBOJET                                    | Do you want to change   |
   ENGINE                                             | default stations?       |
                                                      | Type Y or y for yes     |
                                                      |      N or n for no      |
                                                      +-------------------------+
```

TABLE D3 THE SCREEN DISPLAY OF THE ENGINE LAYOUT DURING INPUT OF THE ENGINE DATA ONLY ONE DISPLAY IS SHOWN

```
+---------------------------------------------------------------------------+
|Type the TITLE for engine modelling. Press <RET>.                          |
|                                                                           |
|  It should not have more than 3 continuous spaces or slashes(/).          |
|                                                                           |
|                                                                           |
+--------------SIMULATION OF DEGRADED ENGINE--------------------------------+

|+-----------------++-----------------++-----------------++-----------------+|
|| Design Point    || Off Design      ||Diagnostic       ||Engine_run       ||
|+-----------------++-----------------++-----------------++-----------------+|
|+-----------------++-----------------++-----------------++-----------------+|
|| Trending        || Analysis        ||Evaluate matrix  ||transient        ||
|+-----------------++-----------------++-----------------++-----------------+|
+---------------------------------------------------------------------------+


|+-----------------++-----------------++-----------------++-----------------+|
||  S I Units      ||Imperial Units   ||                 ||                 ||
|+-----------------++-----------------++-----------------++-----------------+|
|                                                                           |
|                                                                           |
+      SIMULATION OF DEGRADED ENGINE                                        +

 Select choice using left and right arrow keys. Press <RET>

+---------------------------------------------------------------------------+
|+-----------------++-----------------++-----------------++-----------------+|
||Kerosine         ||Hydrogen         ||                 ||                 ||
|+-----------------++-----------------++-----------------++-----------------+|
|                                                                           |
|                                                                           |
+      SIMULATION OF DEGRADED ENGINE                                        +

 Select choice using left and right arrow keys. Press <RET>

+---------------------------------------------------------------------------+
|+-----------------++-----------------++-----------------++-----------------+|
||Built in  maps   ||supplied  maps   ||                 ||                 ||
|+-----------------++-----------------++-----------------++-----------------+|
|                                                                           |
|                                                                           |
+      SIMULATION OF DEGRADED ENGINE                                        +

 Select choice using left and right arrow keys. Press <RET>
```

TABLE D4 DISPLAYS FOR ESSENTIAL INFORMATION INPUT TO BUILD THE INPUT FILE.
PROMPTS APPEAR WHEN AND WHERE REQUIRED

TURBIN

```
+------------------------------------------------------------+-------------------------+
| IN STATION    6                   VARIABLES              | help is available       |
| OUT STATION   7               Non Dim mass flow          |type "help" or "HELP"    |
|                               Turbine rpm  or power      | and press <RET>         |
|                                                          +-------------------------+
| +------+-----+-----------------------------+-+--------+    +-------------------------+
| |BD No| D No| BRICK  DATA  DESCRIPTION|S| VALUE  |      | RESULTS CALCULATED      |
| +------+-----+-----------------------------+-+--------+    |In order of call         |
| | 56  |D(1) |Auxiliary work or Power   |+|  25000      | ------------            |
| | 57  |D(2) |Rel.Non-dimensional flow  |+|  -1         |  COMP    R101           |
| | 58  |D(3) |Rel.Non-dimensional Speed|+|  -1          |  COMP    R102           |
| | 59  |D(4) |Isentropic Efficiency     |+|  .87        |  BURN    R103           |
| | 60  |D(5) |Power Turbine Rel. Speed |+|  -1          |  NOZC    R104           |
| | 61  |D(6) |Driven Compressor Number |+|  3           |  BURN    R105           |
| | 62  |D(7) |Turbine Map Number        |+|  2          |  COMP    R107           |
| | 63  |D(8) |Power Law Index           |+|  0          |                         |
| | 64  |D(9) |Compressor work           |+|  R107       |                         |
| |     |D(10)|Associated Lumped Volume |+|              |                         |
| |     |D(12)|Rotor Design Speed (RPM) |+|              |                         |
+------------------------------------------------------------+                         |
                                                             +-------------------------+
```

Result calculated for compressor D(6) above ; for power turbine = -1

Note: The PROMPT above changes for every input. Only R and h (or H) characters are acceptable. For the second, the help display shown below is superimposed.

```
+---------------------------------------------------------------------------------+
|              HELP                                                               |
| This Brick calculates the outlet conditions from a turbine (compressor          |
|  or power), given the inlet conditions, design-point values of TF and           |
| CN (see below), isentropic efficiency and compressor power (compressor          |
| turbine) or power output (power turbine).                                       |
| D(1) = Auxiliary Power (compressor-) or Power Output (power-turbine)            |
| D(2) = relative inlet non-dimensional Mass Flow TF (in range 0.to 1.)           |
| or default value -1. (which sets TF = 0.8)                                      |
| D(3) = relative non-dimensional rotational speed CN (in range 0. to 1.)         |
| or default value -1. (which sets CN = ).6)                                      |
| D(4) = Design-Point Isentropic Efficiency (in range 0. to 1.)                   |
| D(5) = Design-Point relative Rotational Speed (free power turbine) or -1.       |
| D(6) = Serial Number of driven Compressor (compressor turbine) or 0.            |
| D(7) = Turbine Map Number                                                       |
| D(8) = Power Law Index n in the relation D(1) varies as (rev/min)**n, or        |
| 0. if D(1) is constant                                                          |
| D(9) = Compressor Power Input (compressor turbine) or -1.                       |
| D(10) = Lumped Volume                  ) (at present all these values           |
| D(11)= Moment of Inertia of Rotor      )  MUST be entered as 0.)                |
| D(12) = Design Rotational Speed of Rotor )          PRESS <RET> to Cont         |
+---------------------------------------------------------------------------------+
```

TABLE D5 TURBINE MODULE DATA INPUT DISPLAY AND HELP DISPLAY FOR THE SAME MODULE.

```
+-------------------------------------------------------------------------+
|                                 +------------------+------------------+ |
|                                 |OFF_DESIGN_RUN    |TREND The Data    | |
|                                 +------------------+------------------+ |
| +--------------------------+    |DIAGNOSTIC_RUN    |PLOT The GRAPHS   | |
| | CONTINUE (No Change)     |    +------------------+------------------+ |
| +--------------------------+    |ENGINE_RUN simul  |Calculate COVAR.  | |
| | STOP The Program_run     |    +------------------+------------------+ |
| +--------------------------+    |ANALYZE the Data  |TRANSIENT ANALYS. | |
|                                 +------------------+------------------+ |
|                                 |EXIT .. screen mode and read file.   | |
|                                 +-------------------------------------+ |
|                                                                         |
| +---------------------------------------------------------------+       |
| |  Select bricks using the ARROW keys. To accept (inv_vid)      |       |
| |   PRESS <RET>. To terminate select STOP or EXIT.              |       |
| +---------------------------------------------------------------+       |
+-------------------------------------------------------------------------+
```

TABLE D6(a) SCREEN DISPLAY FOR CHANGING THE ENGINE RUN MODE

Fouling Of	PRESS	MASS	EFFIC
COMP No 1	3.2	2.8	1.75
COMP No 2	1	1.03	1.8
COMP No 3	0.95	1	3.5
&	EFFIC	AREA	
TURB No 1			
TURB No 2	.87	1.4	
TURB No 3	1	.56	
EXIT			

TABLE D6(b) SCREEN DISPLAY FOR INPUT OF DEGRADATIONS OF THE ENGINE

```
+RPM --+Pin --+Tin --+Pout-+Tout-+-mas---+---++RPM --+Pin --+Tin --+Pout-+Tout-+-mas---+
|      |1.000|288.1|1.000|288.1|672.50|IN||      |1.000|288.1|1.000|288.1|672.50|
+-----+-----+-----+-----+-----+-s m--+--++-----+-----+-----+-----+-----+-s m--+
|100.0|1.000|288.1|1.490|328.1|.85000|CO||100.0|1.000|288.1|1.490|328.1|.85000|
+-----+-----+-----+-----+-----+-s m--+--++-----+-----+-----+-----+-----+-s m--+
|100.0|1.490|328.1|2.160|371.9|.85000|CO||100.0|1.490|328.1|2.160|371.9|.85000|
+-----+-----+-----+-----+-----+-s m--+--++-----+-----+-----+-----+-----+-s m--+
|100.0|2.160|371.9|19.74|761.1|.85000|CO||100.0|2.160|371.9|19.74|761.1|.85000|
+-----+-----+-----+-----+-----+-mf ---+--++-----+-----+-----+-----+-----+-mf ---+
|      |19.74|761.1|18.50|1506.|1.8365|BU||      |19.74|761.1|18.50|1550.|1.9580|
+-----+-----+-----+-----+-----+------+--++-----+-----+-----+-----+-----+------+
|100.0|18.50|1364.|5.068|1033.|      |TU||100.0|18.50|1400.|5.283|1072.|      |
+-----+-----+-----+-----+-----+------+--++-----+-----+-----+-----+-----+------+
|100.0|5.068|1033.|1.346|775.5|      |TU||100.0|5.283|1072.|1.491|817.3|      |
+-----+-----+-----+-----+-----+------+--++-----+-----+-----+-----+-----+------+
|      |1.490|328.1|1.460|328.1|      |DU||      |1.490|328.1|1.460|328.1|      |
+-----+-----+-----+-----+-----+-XN ---+--++-----+-----+-----+-----+-----+-XN ---+
|      |1.460|328.1|1.460|328.1|180.54|NZ||      |1.460|328.1|1.460|328.1|187.65|
+-----+-----+-----+-----+-----+------+--++-----+-----+-----+-----+-----+------+
| DESIGN POINT PERFOMANCE               |  | NEW DESIGN POINT PERFOMANCE           |
+---------------------------------------+  +---------------------------------------+
```

TABLE D7 SCREEN DISPLAY OF THE DESIGN POINT PERFORMANCE CALCULATED FROM THE INPUT FILE DATA AND CHANGED WITH INPUT FROM SCREEN FOR TIT OF 1550 K

```
+RPM --+Pin --+Tin --+Pout-+Tout-+-mas---+---+RPM --+Pin --+Tin --+Pout-+Tout-+-mas---+
|      |1.000|288.1|1.000|288.1|672.50|IN|      |1.000|288.1|1.000|288.1|633.57|
+-----+-----+-----+-----+-----+-s m--+--+-----+-----+-----+-----+-----+-s m--+
|100.0|1.000|288.1|1.490|328.1|.85000|CO|95.00|1.000|288.1|1.439|324.1|.83159|
+-----+-----+-----+-----+-----+-s m--+--+-----+-----+-----+-----+-----+-s m--+
|100.0|1.490|328.1|2.160|371.9|.85000|CO|95.00|1.439|324.1|2.100|369.1|.93661|
+-----+-----+-----+-----+-----+-s m--+--+-----+-----+-----+-----+-----+-s m--+
|100.0|2.160|371.9|19.74|761.1|.85000|CO|98.00|2.100|369.1|19.30|755.4|.87913|
+-----+-----+-----+-----+-----+-mf ---+--+-----+-----+-----+-----+-----+-mf ---+
|      |19.74|761.1|18.50|1550.|1.9580|BU|      |19.30|755.4|18.16|1550.|1.8695|
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
|100.0|18.50|1400.|5.283|1072.|      |TU|98.00|18.16|1399.|5.270|1074.|      |
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
|100.0|5.283|1072.|1.491|817.3|      |TU|95.00|5.270|1074.|1.712|844.4|      |
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
|      |1.490|328.1|1.460|328.1|      |DU|      |1.439|324.1|1.412|324.1|      |
+-----+-----+-----+-----+-----+-XN ---+--+-----+-----+-----+-----+-----+-XN ---+
|      |1.460|328.1|1.460|328.1|187.65|NZ|      |1.412|324.1|1.412|324.1|168.39|
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
| DESIGN POINT PERFOMANCE               |  | OFF DESIGN PERFOMANCE                 |
+---------------------------------------+  +---------------------------------------+

                                                +--------------------+
                                                |WAITING PRESS <RET> |
                                                +--------------------+
```

TABLE D8 SCREEN DISPLAY OF THE ACCAEPTED DESIGN POINT PERFORMANCE UNDER OFF DESIGN CONDITIONS (95% N1) A FOR TWO SPOOL BYPASS TURBOFAN

Fouling Of	PRESS	MASS	EFFIC
COMP No 1	0	2.5	1.8
COMP No 2	0	1.1	0.9
COMP No 3	0	0.75	1.03
&	EFFIC	AREA	
TURB No 1	0.34	0.26	
TURB No 2	0.56	0.15	
EXIT			

Values of the degradations Input from the screen to simulate diagnostic engine

RPM	Pin	Tin	Pout	Tout	mas		RPM	Pin	Tin	Pout	Tout	mas
	1.000	288.1	1.000	288.1	634.60	IN		1.000	288.1	1.000	288.1	626.68
					s m							s m
95.00	1.000	288.1	1.436	323.9	.82620	CO	95.00	1.000	288.1	1.426	323.7	.85214
					s m							s m
95.00	1.436	323.9	2.045	364.6	.86405	CO	95.00	1.426	323.7	2.041	365.8	.92612
					s m							s m
96.38	2.045	364.6	18.76	745.6	.89296	CO	95.66	2.041	365.8	17.93	747.4	.92185
					mf							mf
	18.76	745.6	17.69	1550.	1.8196	BU		17.93	747.4	16.87	1550.	1.7688
96.38	17.69	1397.	5.242	1077.		TU	95.66	16.87	1398.	4.938	1077.	
95.00	5.242	1077.	1.656	842.2		TU	95.00	4.938	1077.	1.526	839.4	
	1.436	323.9	1.409	323.9		DU		1.426	323.7	1.399	323.7	
					XN							XN
	1.409	323.9	1.409	323.9	167.23	NZ		1.399	323.7	1.399	323.7	162.76
CLEAN ENGINE PERFOMANCE							FOULED ENGINE PERFOMANCE					

WAITING PRESS <RET>

TABLE D9 DISPLAY OF BASE LINE ENGINE PERFORMANCE AND THE DEGRADED ENGINE PERFORMANCE SIDE BY SIDE TO STUDY THE EFFECTS OF DEGRADATIONS (SHOWN ABOVE) FOR FAULT TREE GENERATION AND AS A TEACHING AID

TWO SPOOL BY-PASS TURBO FAN ENGINE

```
+RPM -+Pin -+Tin -+Pout-+Tout-+-mas--+--+RPM -+Pin -+Tin -+Pout-+Tout-+-mas--+
|     |     |     |     |     |      |IN|     |1.000|288.1|.9800|288.1|88.850|
+-----+-----+-----+-----+-----+-s m--+--+-----+-----+-----+-----+-----+-s m--+
|     |     |     |4.346|465.7|      |CO|100.0|.9800|288.1|4.352|465.9|.89774|
+-----+-----+-----+-----+-----+-s m--+--+-----+-----+-----+-----+-----+-s m--+
|100.6|     |     |19.45|749.4|      |CO|100.5|4.352|465.9|19.43|748.9|.89732|
+-----+-----+-----+-----+-----+-mf --+--+-----+-----+-----+-----+-----+-mf --+
|     |     |     |     |     |1.6791|BU|     |19.43|748.9|18.46|1446.|1.6761|
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
|     |     |     |     |     |      |TU|100.5|18.46|1446.|6.992|1189.|      |
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
|     |6.990|1165.|     |     |      |TU|100.0|6.992|1164.|3.599|1013.|      |
+-----+-----+-----+-----+-----+-pow--+--+-----+-----+-----+-----+-----+-pow--+
|     |3.602|1009.|     |     |      |TU|100.0|3.599|1008.|1.034|771.1|2478.6|
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
|     |     |     |     |     |      |DU|     |1.034|771.1|1.003|771.1|      |
+-----+-----+-----+-----+-----+-XN --+--+-----+-----+-----+-----+-----+-XN --+
|     |     |     |     |     |      |NZ|     |1.003|771.1|1.003|771.1|2.6555|
+-----+-----+-----+-----+-----+------+--+-----+-----+-----+-----+-----+------+
| OBSERVED PERFOMANCE                |  | SIMULATED PERFOMANCE               |
+------------------------------------+  +------------------------------------+
```

VALUES OF THE FAULTS IMPOSED FOR DATA
****

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1
-1.2	-1.4	-0.86	-0.93	0.0000

EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
0.000	0.3700	-0.5600	0.52	0.65

***** DEGRADED ENGINE CALCULATIONS. Converged after 7 Loops

values of the variables :

var(1)	var(2)	var(3)	var(4)	var(5)
98.8194	98.6009	99.1198	99.0629	100.0066

var(6)	var(7)	var(8)	var(9)	var(10)
99.9874	100.2608	99.4420	100.4626	100.3269

Values of the faults detected :
****

GAMcomp1	EFFcomp1	GAMcomp2	EFFcomp2	AREAtur1
-1.1806	-1.3991	-0.8802	-0.9371	0.0066

EFFtur1	AREAtur2	EFFtur2	AREAtur3	EFFtur3
-0.0126	0.2608	-0.5580	0.4626	0.3269

TABLE D10 SCREEN DISPLAY IN THE ANALYZER MODE DISPLAYING THE OBSERVED VALUES SIMULATED ENGINE PARAMETERS . FAULTS ANALYSED BY ITERATION WHEN A HP TURBINE IS REPLACED IN A DEGRADED THREE SPOOL TURBO-SHAFT ENG

```
THREE SPOOL TURBO SHAFT DIAGNOSTIC SIMULATION ////
DI SI KE FP
-1
-1
INTAKE S1,2 D1-4 R101
COMPRE S2,3 D5-10 R102      V1,2,5
COMPRE S3,4 D11-16 R103     V2,2,11  W3,2,12   M,2,12 N,1,3,4
& X,1,3,6 Y,1,4,4 Z,1,4,6
PREMAS S4,14,5  D17-20
PREMAS S14,15,16  D21-24
BURNER S5,6 D25-27 R104     V4,1,6,6  M,2,104
TURBIN S6,7 D28-35,103      V5,2,29
MIXEES S7,15,8
TURBIN S8,9 D36-43,102      V6,2,37  W7,2,38  M,1,8,4 N,1,8,6
MIXEES S9,16,10
TURBIN S10,11 D44-52        V8,2,45  W9,2,44  M,1,10,6
DUCTER S11,12 D53-55 R105
NOZCON S12,13,1  D56-56 R106
PERFOR S1,0,0  D57-60,106,101,104,61-62,74,63
CODEND
engine data////
   1  0.0          ! Altitude [ ft or m ]
   2  0.0          ! I.S.A Deviation deg C
   3  0.0          ! Flight Mach Number
   4  0.98         ! Pressure  Recovery
   !  COMPRE   Data Follows
   5  -1           ! Z-Parameter(See Help)
   6  -1           ! Speed Rel. to design
   7  4.472        ! Design Pressure Ratio
   8  0.87         ! Isentropic Efficiency
   9  0            ! Error Selection
  10  4            ! Compressor Map Number
   !   COMPRE   Data Follows
  11  -1           ! Z-Parameter(See Help)
  12  -1           ! Speed Rel. to design
  13  4.472        ! Design Pressure Ratio
  14  0.87         ! Isentropic Efficiency
  15  1            ! Error Selection
  16  4            ! Compressor Map Number
   !  PREMAS   Data Follows
  17  .08          ! 1st Outlet Rel. Mass Flow
  18  .03          ! 1st Outlet Mass Flow Loss
  19  1.0          ! 1st Outlet Rel. Total Pr
  20  0            ! 1st Outlet Total Pr Loss
   !  PREMAS   Data Follows
  21  .92          ! 1st Outlet Rel. Mass Flow
  22  0            ! 1st Outlet Mass Flow Loss
  23  1            ! 1st Outlet Rel. Total Pr
  24  0            ! 1st Outlet Total Pr Loss
   !  BURNER   Data Follows
  25  .05          ! Pressure Drop Ratio
  26  1.0          ! Combustion Efficiency
  27  -1           ! Fuel  Flow
   !  TURBIN   Data Follows
  28  0            ! Auxiliary work or Power
  29  -1           ! Rel.Non-dimensional flow
```

TABLE D11 INPUT DATA FILE CREATED BY THE PROGRAM

```
30  -1          ! Rel.Non-dimensional Speed
31  .88         ! Isentropic Efficiency
32  -1          ! Power Turbine Rel. Speed
33  2           ! Driven Compressor Number
34  2           ! Turbine Map Number
35  -1          ! Power Law Index
! Compressor work
!   MIXEES   Data Follows
!   TURBIN   Data Follows
36  0           ! Auxiliary work or Power
37  -1          ! Rel.Non-dimensional flow
38  -1          ! Rel.Non-dimensional Speed
39  0.88        ! Isentropic Efficiency
40  -1          ! Power Turbine Rel. Speed
41  1           ! Driven Compressor Number
42  2           ! Turbine Map Number
43  -1          ! Power Law Index
! Compressor work
!   MIXEES   Data Follows
!   TURBIN   Data Follows
44  25000000    ! Auxiliary work or Power
45  -1          ! Rel.Non-dimensional flow
46  -1          ! Rel.Non-dimensional Speed
47  .88         ! Isentropic Efficiency
48  1.0         ! Power Turbine Rel. Speed
49  0           ! Driven Compressor Number
50  2           ! Turbine Map Number
51  -1          ! Power Law Index
52  -1          ! Compressor work
!   DUCTER   Data Follows
53  0           ! Switch for reheat
54  0.03        ! Tot Pr loss/Inl Tot Pr
55  100000      ! Combustion Efficiency
!   NOZCON   Data Follows
56  -1          ! Exit Area Switch(-1 if fixed)
!   PERFOR   Data Follows
57  25000000    ! Power(if Power Turbine)
58  1           ! Propeller Efficiency(or 1.)
59  1           ! Scaling Index if req.(or 0)
60  25000000    ! Req.Dsgn Net Thrst or Power
! Gross Thrust for Nozzle 1
! Momentum Drag for Intake 1
! Fuel Flow to Comb.1 or Duct
61  0           ! Gross Thrust for Nozzle 2
62  0           ! Momentum Drag for Intake 2
! Fuel Flow to Comb.2 or Duct
63  -11         ! End of  data for PERFOR
-1
! Staion input
1  2  90
6  6  1434
13 7  30
-1             !End of station input
6  0.95             ! off design data
-1                  !end of off-design brick data
-1                  !end of off-design station data
-3
```

TABLE D11 INPUT DATA FILE CREATED BY THE PROGRAM

APPENDIX E

ANALYTIC DETERMINATION OF COEFFICIENTS

1. Introduction

This appendix details the method of determination of the coefficients of the influence matrix by the analytic technique. Detailed description of the method can be found in reference URBAN,1969. Equations relating various components are first written for the engine. The derivation of equations is also described by CONNOLY,1985 and DUPLAIN,1986. In the appendix these equations for a three spool turbo-shaft engine are detailed. The coefficients values for gas turbines in general are then detailed in Table E1. Coefficients, based on similar tables calculated for a two spool turbo-fan engine using a computer program are listed in Table E2.

Similarly the coefficients worked from the aero-thermodynamic relationships for a two spool industrial gas turbine engine are given in Table E3. The coefficients derived based on Table E1 are given in Table E4. The computer program for determining the coefficients is typical depending on the component relationships. Thus whereas it is comparatively easy to compute coefficients analytically for a specified engine, determination of the coefficients as a general program is not straight forward.

2. Flow Continuity Requirements

$$Wa_3 = Wa_2$$

$$Wa_4 = Wa_3 - Wa_4h - Wa_4\ell$$

$$Wgth = Wa_4 + Wf$$

$$Wgt\ell = Wgth + W_4h$$

$$Wgpt = Wgt\ell + W_4\ell$$

3. Compound Symbols

3.1 Applicable to the Compressors

3.1.1 Compressor maps (see figure A2)

$$\mu_\ell = \left.\frac{\partial\Gamma_2/\Gamma_2}{\dfrac{\partial N_1/\sqrt{\theta_2}}{N_1/\sqrt{\theta_2}}}\right|_{P_3/P_2 \,=\, Cte} \quad ; \quad \mu_h = \left.\frac{\partial\Gamma_3/\Gamma_3}{\dfrac{\partial N_2/\sqrt{\theta_3}}{N_2/\sqrt{\theta_3}}}\right|_{P_4/P_3 \,=\, Cte}$$

$$S_\ell = \left.\frac{\partial\Gamma_2/\Gamma_2}{\dfrac{\partial P_3/P_2}{P_3/P_2}}\right|_{N_1/\sqrt{\theta_2} \,=\, Cte} \quad ; \quad S_h = \left.\frac{\partial\Gamma_3/\Gamma_3}{\dfrac{\partial P_4/P_3}{P_4/P_3}}\right|_{N_2/\sqrt{\theta_3} \,=\, Cte}$$

$\left.\frac{\partial\Gamma}{\Gamma}\right|_D =$ Change in Pumping Capacity at Constant $N/\sqrt{\theta}$ and P_h/P_ℓ Caused by Deterioration.

<u>Note</u>: in this particular application, μ_h (for HP Compressor) is equal to μ_ℓ (for LP Compressor).

3.1.2 Compressor Efficiency Maps (see figure A3)

$$ELN1 = \left.\frac{\partial ETACL/ETACL}{\dfrac{\partial N_1/\sqrt{\theta_2}}{N_1/\sqrt{\theta_2}}}\right|_{P_3/P_2 \,=\, Cte} \quad ;$$

$$ELP1 = \left.\frac{\partial ETACL/ETACL}{\dfrac{\partial P_3/P_2}{P_3/P_2}}\right|_{N_1/\sqrt{\theta_2} \,=\, Cte} \quad ;$$

$$EHN2 = \left.\frac{\partial ETACH/ETACH}{\dfrac{\partial N_2/\sqrt{\theta_3}}{N_2/\sqrt{\theta_3}}}\right|_{P_4/P_3 \,=\, Cte} \quad ; \text{ and}$$

$$EHP2 = \left. \frac{\partial ETACH/ETACH}{\frac{\partial P_4/P_3}{P_4/P_3}} \right|_{N_2/\sqrt{\theta_3} = Cte}$$

Note: In this case, EHN2 = ELN1 and EHP2 = ELP1.

3.1.3 Compressor Work

$$\alpha_\ell = \frac{C_{p3}'T_3'}{ETACL\ \Delta hc\ell} \left\{\frac{\gamma-1}{\gamma}\right\}; \quad \alpha_h = \frac{C_{p4}'T_4'}{ETACH\ \Delta hch} \left\{\frac{\gamma-1}{\gamma}\right\}$$

$$\beta_{\ell 3} = \frac{C_{p3}T_3}{\Delta hc\ell}\ ; \quad \beta_{h4} = \frac{C_{p4}T_4}{\Delta hch}$$

$$\beta_{\ell 2} = \frac{C_{p2}(T_3'-T_2)}{ETACL\ \Delta hc\ell} + \frac{C_{p2}T_2}{\Delta hc\ell}; \quad \beta_{h3} = \frac{C_{p3}(T_4'-T_3)}{ETACH\ \Delta hch} + \frac{C_{p3}\dot{T}_3}{\Delta hch}$$

3.2 Applicable to the Turbines

3.2.1 Turbine Maps (see figure A4)

$$EHN = \left. \frac{\partial \Gamma_5/\Gamma_5}{\frac{\partial N_2/\sqrt{\theta_5}}{N_2/\sqrt{\theta_5}}} \right|_{P_5/P_6 = Cte} ; \quad ELN = \left. \frac{\partial \Gamma_6/\Gamma_6}{\frac{\partial N_1/\sqrt{\theta_6}}{N_1/\sqrt{\theta_6}}} \right|_{P_6/P_7 = Cte} ;$$

$$EPTN = \left. \frac{\partial \Gamma_7/\Gamma_7}{\frac{\partial N/\sqrt{\theta_7}}{N/\sqrt{\theta_7}}} \right|_{P_7/P_8 = Cte} ; \quad EHP = \left. \frac{\partial \Gamma_5/\Gamma_5}{\frac{\partial P_5/P_6}{P_5/P_6}} \right|_{N_2/\sqrt{\theta_5} = Cte} ;$$

$$ELP = \left. \frac{\partial \Gamma_6/\Gamma_6}{\frac{\partial P_6/P_7}{P_6/\Gamma_7}} \right|_{N_1/\sqrt{\theta_6} = Cte} ; \quad EPTP = \left. \frac{\partial \Gamma_7/\Gamma_7}{\frac{\partial P_7/P_8}{P_7/P_8}} \right|_{N_{pt}/\sqrt{\theta_7} = Cte}$$

3.2.2 Turbine Efficiency Maps (see figure A5)

$$ETNH = \left. \frac{\partial ETATH/ETATH}{\dfrac{\partial N_2/\sqrt{h_{5-6}}}{N_2/\sqrt{h_{5-6}}}} \right|_{P_5/P_6 = Cte} ;$$

$$ETNL = \left. \frac{\partial ETATL/ETATL}{\dfrac{\partial N_1/\sqrt{h_{6-7}}}{N_1/\sqrt{h_{6-7}}}} \right|_{P_7/P_6 = Cte} ;$$

$$ETNPT = \left. \frac{\partial ETAPT/ETAPT}{\dfrac{\partial N_{pt}/\sqrt{h_{7-8}}}{N_{pt}/\sqrt{h_{7-8}}}} \right|_{P_7/P_8 = Cte} ;$$

$$ETPH = \left. \frac{\partial ETATH/ETATH}{\dfrac{\partial P_5/P_6}{P_5/P_6}} \right|_{N_2/\sqrt{\theta_5} = Cte} ;$$

$$ETPL = \left. \frac{\partial ETATL/ETATL}{\dfrac{\partial P_6/P_7}{P_6/P_7}} \right|_{N_1/\sqrt{\theta_6} = Cte} ; \text{ and}$$

$$ETPPT = \left. \frac{\partial ETAPT/ETAPT}{\dfrac{\partial P_7/P_8}{P_7/P_8}} \right|_{N_{pt}/\sqrt{\theta_7} = Cte}$$

3.2.3 Turbine Work

$$A_h = \frac{Wgth}{\Delta H_{th}} \left\{ h_5 - h_6 - ETATH(h_5 - h_6') + ETATH \frac{T_6'}{T_5a}(h_5 - h_5a) \right\}$$

$$A_\ell = \frac{Wgtl}{H_{t\ell}} \left\{ h_6 - h_7 - ETATL(h_6 - h_7') + ETATL \frac{T_7'}{T_6a}(h_6 - h_6a) \right\}$$

$$A_{pt} = \frac{Wgpt}{\Delta H_{pt}} \left\{ h_7 - h_8 - ETAPT(h_7 - h_8') + ETAPT \frac{T_8'}{T_7a}(h_7 - h_7a) \right\}$$

$$B_h = \frac{Wa_3}{\Delta H_{th}} \left\{ h_4 - h_6 - ETATH\ R_{4h}(h_4 - h_6') + ETATH \frac{T_6'}{T_5a} R_{4h}(h_4 - h_5a) \right\}$$

$$B_\ell = \frac{Wa_3}{\Delta H_{t\ell}} \left\{ h_4 - h_7 - ETATL\ R_{4\ell}(h_4 - h_7') + ETATL \frac{T_7'}{T_6a} R_{4\ell}(h_4 - h_6a) \right\}$$

$$D_h = \frac{W_4h\ Cp_4T_4}{\Delta H_{th}} \left\{ 1 - ETATH\ R_{4h} \left\{ 1 - \frac{T_6'}{T_5a} \right\} \right\}$$

$$D_\ell = \frac{W_{4\ell}\ Cp_4T_4}{\Delta H_{t\ell}} \left\{ 1 - ETATL\ R_{4\ell} \left\{ 1 - \frac{T_7'}{T_6a} \right\} \right\}$$

$$\Omega_{h5} = \frac{Wgth\ Cp_5T_5}{\Delta H_{th}} \left\{ 1 - ETATH \left\{ 1 - \frac{T_6'}{T_5a} \right\} \right\}$$

$$\Omega_{\ell 6} = \frac{Wgt\ell\ C_{p6}T_6}{\Delta H_{t\ell}} \left\{ 1 - ETATL \left\{ 1 - \frac{T_7'}{T_6a} \right\} \right\}$$

$$\Omega_{pt7} = \frac{Wgpt\ Cp_7T_7}{\Delta H_{pt}} \left\{ 1 - ETAPT \left\{ \frac{1-T_8'}{T_{7a}} \right\} \right\}$$

$$\Omega_{h6} = \frac{Wgt\ell\ Cp_6T_6}{\Delta H_{th}}$$

$$\Omega_{\ell 7} = \frac{Wgpt\ Cp_7T_7}{\Delta H_{t\ell}}$$

$$\Omega_{pt8} = \frac{Wgpt\ Cp_8T_8}{\Delta H_{pt}}$$

$$\theta_h = \frac{ETATH\ T_6'\ R(Wgth + R_{4h}\ W_{4h})}{\Delta H_{th}}$$

$$\theta_\ell = \frac{ETATL\ T_7'\ R(Wgt\ell + R_{4\ell}\ W_{4\ell})}{\Delta H_{t\ell}}$$

$$\theta_{pt} = \frac{ETAPT\ T_8'\ R(Wgpt)}{\Delta H_{pt}}$$

4. Component Equations

4.1 Inlet Duct Loss

$$\frac{P_1-P_2}{P_1} = \frac{\Delta P}{P_1} = f(\Gamma_2{}^2,\ \text{Design Level})$$

$$\left.\frac{\partial \Delta P}{P_1}\right|_D = \left\{1-\frac{\Delta P}{P_1}\right\}\frac{\partial P_1}{P_1} - \left\{1-\frac{\Delta P}{P_1}\right\}\frac{\partial P_2}{P_2} - \frac{2\Delta P}{P_1}\frac{\partial \Gamma_2}{\Gamma_2}$$

4.2 Engine Inlet RAM Pressure

$P_{amb} = P_1$

4.3 Engine Inlet RAM Temperature

$T_{amb} = T_1$

4.4 LP Compressor Airflow - Speed Relationship

$\Gamma_2 = f(N_1/\sqrt{\theta_2},\ P_3/P_2,\ \text{Pumping Capacity})$

$$\left.\frac{\partial \Gamma_2}{\Gamma_2}\right|_D = \frac{\partial \Gamma_2}{\Gamma_2} - \mu_\ell \frac{\partial N_1/\sqrt{\theta_2}}{N_1/\sqrt{\theta_2}} + S_\ell \frac{\partial P_3}{P_3} - S_\ell \frac{\partial P_2}{P_2}$$

4.5 HP Compressor Airflow - Speed Relationship

$\Gamma_3 = f(N_2/\sqrt{\theta_3},\ P_4/P_3,\ \text{Pumping Capacity})$

$$\left.\frac{\partial \Gamma_3}{\Gamma_3}\right|_D = \frac{\partial \Gamma_3}{\Gamma_3} - \mu_h \frac{\partial N_2/\sqrt{\theta_2}}{N_2/\sqrt{\theta_2}} + \frac{\mu_h}{2}\left\{\frac{\partial T_3}{T_3} - \frac{\partial T_2}{T_2}\right\} + S_h \left\{\frac{\partial P_4}{P_4} - \frac{\partial P_3}{P_3}\right\}$$

4.6 LP Compressor Efficiency

$$ETACL = \frac{(h_3' - h_2)}{(h_3 - h_2)}$$

$$\alpha_\ell \cdot \left\{\frac{\partial P_3}{P_3} - \frac{\partial P_2}{P_2}\right\} - \beta_{\ell 3} \frac{\partial T_3}{T_3} + \beta_{\ell 2} \frac{\partial T_2}{T_2} - \frac{\partial ETACL}{ETACL} = 0$$

4.7 LP Compressor Efficiency Variation

$$ETACL = f(N_1/\sqrt{\theta_2},\ P_3/P_2,\ \text{Design Level})$$

$$\left.\frac{\partial ETACL}{ETACL}\right|_D = \frac{\partial ETACL}{ETACL} - ELN1 \frac{\partial N_1/\sqrt{\theta_2}}{N_1/\sqrt{\theta_2}} - ELP1 \left\{\frac{\partial P_3}{P_3} - \frac{\partial P_2}{P_2}\right\}$$

4.8 HP Compressor Efficiency

$$ETACH = \frac{(h_4' - h_3)}{(h_4 - h_3)}$$

$$\alpha_h \left\{\frac{\partial P_4}{P_4} - \frac{\partial P_3}{P_3}\right\} - \beta_{h4} \frac{\partial T_4}{T_4} + \beta_{h3} \frac{\partial T_3}{T_3} - \frac{\partial ETACH}{ETACH} = 0$$

4.9 HP Compressor Efficiency Variation

$$ETACH = f(N_2/\sqrt{\theta_3},\ P_4/P_3,\ \text{Design Level})$$

$$\left.\frac{\partial ETACH}{ETACH}\right|_D = \frac{\partial ETACH}{ETACH} - EHN2 \frac{\partial N_2/\sqrt{\theta_2}}{N_2/\sqrt{\theta_2}} + \frac{EHN_2}{2} \left\{\frac{\partial T_3}{T_3} - \frac{\partial T_2}{T_2}\right\} - EHP \left\{\frac{\partial P_4}{P_4} - \frac{\partial P_3}{P_3}\right\}$$

4.10 Main Burner Pressure Loss

$$\frac{\Delta P_b}{P_4} = f\left(M_4^{\,2},\ \frac{\Delta T_b}{T_4},\ \text{Design Level}\right)$$

$$\left.\frac{\partial \Delta P_b}{P_4}\right|_D = \left\{1 + \frac{\Delta P_b}{P_4}\right\}\frac{\partial P_4}{P_4} - \left\{1 - \frac{\Delta P_b}{P_4}\right\}\frac{\partial P_5}{P_5} + \frac{T_4}{\Delta T_b}\,\frac{\Delta P_b}{P_4}\,\frac{\partial T_4}{T_4}$$

$$- \frac{T_5 \Delta P_b}{\Delta T_b P_4}\,\frac{\partial T_5}{T_5} - \frac{2\Delta P_b}{P_4}\,\frac{\partial W_{a4}}{W_{a4}}$$

4.11 Main Burner Heat Release

$$W_f\ \text{ETAB}\ q_f = [\text{Wgth}\ h_5 - W_{a4} h_4] - W_f h_4$$

$$\frac{\partial \text{ETAB}}{\text{ETAB}} = \frac{\partial \text{Wgth}}{\text{Wgth}} + \frac{C_{p5} T_5}{\Delta h_b}\,\frac{\partial T_5}{T_5} - \frac{C_{p4} T_4}{\Delta h_b}\,\frac{\partial T_4}{T_4} - \frac{\partial W_f}{W_f}$$

4.12 HP Turbine Efficiency

$$\text{ETATH} = \frac{\Delta H_{th}}{\Delta H_{th}'} = \frac{\text{Wgth}(h_5 - h_6) + W_4 h(h_4 - h_6)}{\text{Wgth}(h_5 - h_6') + R_4 h W_4 h(h_4 - h_6')}$$

$$A_h\,\frac{\partial \text{Wgth}}{\text{Wgth}} + \frac{B_h W_4 h}{W_{a3}}\,\frac{\partial W_4 h}{W_4 h} + D_h\,\frac{\partial T_4}{T_4} + \Omega_{h5}\,\frac{\partial T_5}{T_5} + \Omega_{h6}\,\frac{\partial T_6}{T_6}$$

$$- \frac{\Theta_h\,\partial P_5}{P_5} + \frac{\Theta_h\,\partial P_6}{P_6} - \frac{\partial \text{ETATH}}{\text{ETATH}} = 0$$

4.13 HP Turbine Efficiency Variation

$$ETATH = f(N_2/\sqrt{h_5 - h_6},\ P_5/P_6,\ \text{Design Level})$$

$$\left.\frac{\partial ETATH}{ETATH}\right|_D = \frac{\partial ETATH}{ETATH} - ETNH \left\{\frac{\partial N_2/\sqrt{\theta_2}}{N_2/\sqrt{\theta_2}} + \frac{1}{2}\frac{\partial T_2}{T_2}\right\} + \frac{ETNH}{2}\left\{\left\{\frac{C_{p5}T_5}{h_5 - h_6}\frac{\partial T_5}{T_5}\right\}\right.$$

$$\left. - \left\{\frac{C_{p6}T_6}{h_5 - h_6}\frac{\partial T_6}{T_6}\right\}\right\} - ETPH\left\{\frac{\partial P_5}{P_5} - \frac{\partial P_6}{P_6}\right\}$$

4.14 LP Turbine Efficiency

$$ETATL = \frac{\Delta H_{t\ell}}{\Delta H_{t\ell}'} = \frac{Wgt\ell\ (h_6 - h_7) + W_{4\ell}\ (h_4 - h_7)}{Wgt\ell\ (h_6 - h_7') + R_{4\ell}W_{4\ell}\ (h_4 - h_7')}$$

$$A_\ell \frac{\partial Wgt\ell}{Wgt\ell} + \frac{B_\ell W_{4\ell}}{W_{a3}}\frac{\partial W_{4\ell}}{W_{4\ell}} + D_\ell \frac{\partial T_4}{T_4} + \Omega_{\ell 6}\frac{\partial T_6}{T_6} - \Omega_{\ell 7}\frac{\partial T_7}{T_7}$$

$$- \theta_\ell \frac{\partial P_6}{P_6} + \theta_\ell\left\{\frac{\partial P_7/P_2}{P_7/P_2} + \frac{\partial P_2}{P_2}\right\} - \frac{\partial ETATL}{ETATL} = 0$$

4.15 LP Turbine Efficiency Variation

$$ETATL = f(N_1/\sqrt{h_6 - h_7},\ P_6/P_7,\ \text{Design Level})$$

$$\left.\frac{\partial ETATL}{ETATL}\right|_D = \frac{\partial ETATL}{ETATL} - ETNL\frac{\partial N_1/\sqrt{\theta_2}}{N_1/\sqrt{\theta_2}} + \frac{ETNL}{2}\left\{\left\{\frac{C_{p6}T_6}{h_6 - h_7}\frac{\partial T_6}{T_6}\right\}\right.$$

$$\left. - \left\{\frac{C_{p7}T_7}{h_6 - h_7}\frac{\partial T_7}{T_7}\right\} - \frac{\partial T_2}{T_2}\right\} - ETPL\frac{\partial P_6}{P_6} + ETPL\left\{\frac{\partial P_7/P_2}{P_7/P_2} + \frac{\partial P_2}{P_2}\right\}$$

4.16 Power Turbine Efficiency

$$ETAPT = \frac{\Delta H_{pt}}{\Delta H_{pt}'} = \frac{Wgpt\ (h_7 - h_8)}{Wgpt\ (h_7 - h_8')}$$

$$A_{pt} \frac{\partial Wgpt}{Wgpt} + \Omega_{pt7} \frac{\partial T_7}{T_7} - \Omega_{pt8} \frac{\partial T_8}{T_8} - \Theta_{pt} \frac{\partial P_7/P_2}{P_7/P_2}$$

$$+ \Theta_{pt} \left\{ \frac{\partial P_8}{P_8} + \frac{\partial P_2}{P_2} \right\} - \frac{\partial ETAPT}{ETAPT} = 0$$

4.17 Power Turbine Efficiency Variation

$$ETAPT = f(N_{pt}/\sqrt{h_7 - h_8},\ P_7/P_8,\ \text{Design Level})$$

$$\left.\frac{\partial ETAPT}{ETAPT}\right|_D = \frac{\partial ETAPT}{ETAPT} - ETNPT \frac{\partial N_{pt}/\sqrt{\theta_2}}{N_{pt}/\sqrt{\theta_2}} - \frac{ETNPT}{2} \frac{\partial T_2}{T_2} + \frac{ETNPT}{2} \left\{ \right.$$

$$\left. \left\{ \frac{C_{p7}\ T_7}{h_7 - h_8} \frac{\partial T_7}{T_7} \right\} - \left\{ \frac{C_{p8}\ T_8}{h_7 - h_8} \frac{\partial T_8}{T_8} \right\} \right\} - ETPPT \left\{ \right.$$

$$\left. \frac{\partial P_7/P_2}{P_7/P_2} - \frac{\partial P_8}{P_8} - \frac{\partial P_2}{P_2} \right\}$$

4.18 High Pressure Spool Power Balance

$$SHP_x + W_{a3}\ (h_4 - h_3) = Wgth\ (h_5 - h_6) + W_{4h}\ (h_4 - h_6)$$

$$\frac{SHP_x}{\Delta H_{th}} \frac{\partial SHP_x}{SHP_x} = \frac{Wgth\ (h_5-h_6)}{\Delta H_{th}} \frac{\partial Wgth}{Wgth} - \frac{W_{a3}\ (h_4-h_3)}{\Delta H_{th}} \frac{\partial W_{a3}}{W_{a3}}$$

$$+ \frac{W_{4h}\ (h_4-h_6)}{\Delta H_{th}} \frac{\partial W_{4h}}{W_{4h}} + \frac{W_{a3}\ Cp_3 T_3}{\Delta H_{th}} \frac{\partial T_3}{T_3}$$

$$+ \frac{W_{4h}\ Cp_4 T_4}{\Delta H_{th}} \frac{\partial T_4}{T_4} + \frac{Wgth\ Cp_5 T_5}{\Delta H_{th}} \frac{\partial T_5}{T_5} - \Omega_{h6} \frac{\partial T_6}{T_6}$$

4.19 Low Pressure Spool Power Balance

$$W_{a2}\ (h_3-h_2) = Wgt\ell\ (h_6-h_7) + W_{4\ell}\ (h_4-h_7)$$

$$\frac{Wgt\ell\ (h_6-h_7)}{\Delta H_{t\ell}} \frac{\partial Wgt\ell}{Wgt\ell} - \frac{W_{4\ell}\ (h_4-h_7)}{\Delta H_{t\ell}} \frac{\partial W_{4\ell}}{W_{4\ell}} - \frac{W_{a3}\ Cp_3 T_3}{\Delta H_{t\ell}} \frac{\partial T_3}{T_3}$$

$$+ \frac{W_{a2}\ Cp_2 T_2}{\Delta H_{t\ell}} \frac{\partial T_2}{T_2} + \frac{W_{4\ell}\ Cp_4 T_4}{\Delta H_{t\ell}} \frac{\partial T_4}{T_4} + \frac{Wgt\ell\ Cp_6 T_6}{\Delta H_{t\ell}} \frac{\partial T_6}{T_6}$$

$$- \Omega_{\ell 7} \frac{\partial T_7}{T_7} - \frac{W_{a2}(h_3-h_2)}{\Delta H_{t\ell}} \frac{\partial W_{a2}}{W_{a2}} = 0$$

4.20 Shaft Power (SHP)

$$SHP_{pt} = Wgpt\ (h_7-h_8)$$

$$\frac{Wgpt\ (h_7-h_8)}{\Delta H_{pt}} \frac{\partial Wgpt}{Wgpt} + \frac{Wgpt\ C_{p7} T_7}{\Delta H_{pt}} \frac{\partial T_7}{T_7} - \Omega_{pt8} \frac{\partial T_8}{T_8} - \frac{SHP_{pt}}{\Delta H_{pt}} \frac{\partial SHP}{SHP_{pt}} = 0$$

4.21 HP Turbine Inlet Nozzle Flow

$$\frac{\Gamma_5}{A_5} = \frac{Wgth\ \sqrt{\theta_5}}{A_5\ \delta_5} = f(P_5/P_6,\ N_2/\sqrt{\theta_5})$$

$$\frac{\partial A_5}{A_5} = \frac{\partial Wgth}{Wgth} + \frac{1}{2}(1+EHN)\frac{\partial T_5}{T_5} - EHN\frac{\partial N_2/\sqrt{\theta_2}}{N_2/\sqrt{\theta_2}} - \frac{EHN}{2}\frac{\partial T_2}{T_2}$$

$$- (1+EHP)\frac{\partial P_5}{P_5} + EHP\frac{\partial P_6}{P_6}$$

4.22 LP Turbine Inlet Nozzle Flow

$$\frac{\Gamma_6}{A_6} = \frac{Wgt\ell\ \sqrt{\theta_6}}{A_6\ \delta_6} = f(P_6/P_7,\ N_1/\sqrt{\theta_6})$$

$$\frac{\partial A_6}{A_6} = \frac{\partial Wgt\ell}{Wgt\ell} + \frac{1}{2}(1+ELN)\frac{\partial T_6}{T_6} - ELN\frac{\partial N_1/\sqrt{\theta_2}}{N_1/\sqrt{\theta_2}} - \frac{ELN}{2}\frac{\partial T_2}{T_2}$$

$$- (1+ELP)\frac{\partial P_6}{P_6} + ELP\left\{\frac{\partial P_7/P_2}{P_7/P_2} + \frac{\partial P_2}{P_2}\right\}$$

4.23 Power Turbine Inlet Nozzle Flow

$$\frac{\Gamma_7}{A_7} = \frac{Wgpt\ \sqrt{\theta_7}}{A_7\ \delta_7} = f(P_7/P_8,\ N_{pt}/\sqrt{\theta_7})$$

$$\frac{\partial A_7}{A_7} = \frac{\partial Wgpt}{Wgpt} + \frac{1}{2}(1+EPTN)\frac{\partial T_7}{T_7} - EPTN\frac{\partial N_{pt}/\sqrt{\theta_2}}{N_{pt}/\sqrt{\theta_2}} - (1+EPTP)\left\{\right.$$

$$\left.\frac{\partial P_8}{P_8}\right\} + EPTP\left\{\left\{\frac{\partial P_7/P_2}{P_7/P_2}\right\} + \frac{\partial P_2}{P_2}\right\} - \frac{EPTN}{2}\frac{\partial T_2}{T_2}$$

4.24 HP Compressor Discharge - HP Turbine Cooling Flow

$$\frac{\Gamma}{A} = \frac{W_{4h}\sqrt{\theta_4}}{A_{d4h}\,\delta_{s4}} \approx \text{Cte (constant duct pressure drop)}$$

$$\left.\frac{\partial W_{4h}}{W_{a3}}\right|_D = \frac{W_{4h}}{W_{a3}}\frac{\partial W_{4h}}{W_{4h}} + \frac{W_{4h}}{W_{a3}}\left\{\frac{1}{2}\frac{\partial T_4}{T_4} - \frac{\partial P_{s4}}{P_{s4}}\right\}$$

4.25 LP Compressor Discharge - LP Turbine Cooling Flow

$$\frac{\Gamma}{A} = \frac{W_{4\ell}\sqrt{\theta_4}}{A_{d4\ell}\,\delta_{s4}} \approx \text{Cte (due to constant duct pressure drop)}$$

$$\left.\frac{\partial W_{4\ell}}{W_{a3}}\right|_D = \frac{W_{4\ell}}{W_{a3}}\frac{\partial W_{4\ell}}{W_{4\ell}} + \frac{W_{4\ell}}{W_{a3}}\left\{\frac{1}{2}\frac{\partial T_4}{T_4} - \frac{\partial P_{s4}}{P_{s4}}\right\}$$

4.26 LP Compressor Discharge Static Pressure

$$\frac{\partial P_t/P_s}{P_t/P_s} = \frac{\gamma M_3^2}{1-M_3^2}\frac{\partial \Gamma_3}{\Gamma_3}$$

$$\frac{\partial P_3}{P_3} - \frac{\partial P_{s3}}{P_{s3}} - \frac{\gamma M_3^2}{1-M_3^2}\frac{\partial \Gamma_3}{\Gamma_3} = 0$$

4.27 HP Compressor Discharge Static Pressure

$$\frac{\partial P_t/P_s}{P_t/P_s} = \frac{\gamma M_4^2}{1-M_4^2}\frac{\partial \Gamma_4}{\Gamma_4}$$

$$\frac{\partial P_4}{P_4} - \frac{\partial P_{s4}}{P_{s4}} - \frac{\gamma M_4^2}{1-M_4^2}\frac{\partial \Gamma_4}{\Gamma_4} = 0 \qquad \text{or}$$

$$\left\{1 + \frac{\gamma M_4^2}{1-M_4^2}\right\}\frac{\partial P_4}{P_4} - \frac{\partial P_{s4}}{P_{s4}} - \left\{\frac{\gamma M_4^2}{1-M_4^2}\right\}\frac{\partial W_{a4}}{W_{a4}} - \left\{\frac{1}{2}\frac{\gamma M_4^2}{1-M_4^2}\frac{\partial T_4}{T_4}\right\} = 0$$

4.28 LP Compressor Inlet Flow

$$W_{a2} = \frac{\Gamma_2 \delta_2}{\sqrt{\theta_2}}$$

$$\frac{\partial W_{a2}}{W_{a2}} - \frac{\partial \Gamma_2}{\Gamma_2} - \frac{\partial P_2}{P_2} + \frac{1}{2}\frac{\partial T_2}{T_2} = 0$$

4.29 HP Compressor Inlet Flow

$$W_{a3} = \frac{\Gamma_3 \delta_3}{\sqrt{\theta_3}}$$

$$\frac{\partial W_{a3}}{W_{a3}} - \frac{\partial \Gamma_2}{\Gamma_2} - \frac{\partial P_3}{P_3} + \frac{1}{2}\frac{\partial T_3}{T_3} = 0$$

4.30 HP Compressor Discharge Flow

$$W_{a4} = W_{a3} - W_{4h} - W_{4\ell}$$

$$\frac{\partial W_{a4}}{W_{a4}} - \frac{W_{a3}}{W_{a4}}\frac{\partial W_{a3}}{W_{a3}} + \frac{W_{4h}}{W_{a4}}\frac{\partial W_{4h}}{W_{4h}} + \frac{W_{4\ell}}{W_{a4}}\frac{\partial W_{4\ell}}{W_{4\ell}} = 0$$

4.31 HP Turbine Inlet Flow

$$Wgth = Wa_4 + Wf$$

$$\frac{\partial Wgth}{Wgth} - \frac{Wa_4}{Wgth}\frac{\partial Wa_4}{Wa_4} - \frac{Wf}{Wgth}\frac{\partial Wf}{Wf} = 0$$

4.32 LP Turbine Inlet Flow

$$Wgt\ell = Wgth + W_4h$$

$$\frac{\partial Wgt\ell}{Wgt\ell} - \frac{Wgth}{Wgt\ell}\frac{\partial Wgth}{Wgth} - \frac{W_4h}{Wgt\ell}\frac{\partial W_4h}{W_4h} = 0$$

4.33 Power Turbine Inlet Flow

$$Wgpt = Wgt\ell + W_{4\ell}$$

$$\frac{\partial Wgpt}{Wgpt} - \frac{Wgt\ell}{Wgpt}\frac{\partial Wgt\ell}{Wgt\ell} - \frac{W_{4\ell}}{Wgpt}\frac{\partial W_{4\ell}}{W_{4\ell}} = 0$$

4.34 Exhaust Duct Pressure Loss

$$\frac{P_8 - P_{amb}}{P_8} = \frac{\Delta P}{P_8} = f(\Gamma_8{}^2, \text{Design Level})$$

$$\frac{\Delta P}{P_8}\,\frac{\partial \Delta P}{\Delta P}\bigg|_D = \left\{1+\frac{\Delta P}{P_8}\right\}\left\{\frac{\partial P_8}{P_8}+\frac{\partial P_2}{P_2}\right\} - \left\{1-\frac{\Delta P}{P_8}\right\}\frac{\partial P_{amb}}{P_{amb}}$$

$$- \frac{2\Delta P}{P_8}\,\frac{\partial W_{gpt}}{W_{gpt}} - \frac{\Delta P}{P_8}\,\frac{\partial T_8}{T_8}$$

4.35 <u>Engine Pressure Ratio Continuity</u>

$$\frac{P_7}{P_2}\bigg|_D = \frac{P_1(1-\Delta P/P_1)\ P_3/P_2\ P_4/P_3\ (1-\Delta P_b)}{P_5/P_6\ (P_6/P_7)\ P_2}$$

$$\frac{\partial P_7/P_2}{P_7/P_2}\bigg|_D = \left\{1-\frac{1}{1-\Delta P/P_1}\right\}\frac{\partial P_1}{P_1} - \frac{\partial P_2}{P_2} + \frac{\partial P_4}{P_4} - \left\{\frac{1}{1-\Delta P_b/P_4}\right\}$$

$$\frac{\partial \Delta P_b}{P_4} - \frac{\partial P_5}{P_5} + \frac{\partial P_7/P_2}{P_7/P_2}$$

4.36 <u>Specific Fuel Consumption</u>

$$SFC = \frac{W_f}{SHP}$$

$$\frac{\partial SFC}{SFC} + \frac{\partial SHP}{SHP} - \frac{\partial W_f}{W_f} = 0$$

	TURBINE INLET TEMP. VARIATION $\frac{\partial T_{t4}}{T_{t4}}$	ENGINE SPEED VARIATION $\frac{\partial N}{N}$	SHAFT POWER EXTRACTION $\partial \frac{SHP}{w_a}$	ENGINE INLET TEMP. VARIATION $\frac{\partial T_{t2}}{T_{t2}}$	ENG. IN. PRESS. VAR. $\frac{\partial P_{t2}}{P_{t2}}$	AMB. PRESS. VAR. $\frac{\partial P_{am}}{P_{am}}$	COMP. DISCHARGE AIR BLEED (For 1% Bleed, $\frac{\partial w_b}{w_a} = -.01$) $\frac{\partial w_b}{w_a}$	COMP. INLET AIRFLOW VAR. $\frac{\partial w_a}{w_a}$	COMPRESSOR EFFICIENCY VARIATION $\frac{\partial \eta_c}{\eta_c}$	BURNER PRESS. LOSS VARIATION $\partial \frac{\Delta P_b}{P_{t3}}$	BURNER EFF. VAR. $\frac{\partial \eta_b}{\eta_b}$	TURBINE AREA VARIATION $\frac{\partial A_4}{A_4}$	TURBINE EFF. VAR. $\frac{\partial \eta_t}{\eta_t}$	GAS GEN. EXH. PRESS. VAR. $\frac{\partial P_{t5}}{P_{t5}}$	EXH. NOZ. OR POWER TURB EFF. VAR. $\frac{\partial \eta}{\eta}$
$\partial T_{t4}/T_{t4}$	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\partial N/N$	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
$\partial w_a/w_a$ INLET	0	μ	0	$-\frac{1+\mu}{2}$	1	1	0	1	0	0	0	0	0	0	0
$\partial T_{t3}/T_{t3}$	$\frac{k-1}{2k\eta_c}$	$\mu\frac{k-1}{k\eta_c}$	0	$\frac{k+1}{2k}-\frac{k-1}{k\eta_c}\frac{\mu}{2}$	0	0	$\frac{k-1}{k\eta_c}$	$\frac{k-1}{k\eta_c}$	$-\frac{k-1}{k\eta_c}\frac{1}{\alpha}$	$\frac{k-1}{k\eta_c}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	0	$-\frac{k-1}{k\eta_c}$	0	0	0
$\partial P_{t3}/P_{t3}$	$\frac{1}{2}$	μ	0	$-\frac{1+\mu}{2}$	1	1	1	1	0	$\frac{1}{1-\Delta P_b/P_{t3}}$	0	-1	0	0	0
$\frac{\partial w_f}{w_f}$	$\frac{T_{t4}}{\Delta T_b}-\frac{k-1}{2k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$\mu\left(1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\right)$	0	$-\left[\frac{1}{2}+\frac{k+1}{2k}\frac{T_{t3}}{\Delta T_b}\right]-\frac{\mu}{2}\left[1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\right]$	1	1	$1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\frac{1}{\alpha}$	$-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	-1	$\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	0	0	0
$\frac{\partial w_f P_{t3}}{w_f P_{t3}}$	$\frac{T_{t4}}{\Delta T_b}-\frac{k-1}{2k\eta_c}\frac{T_{t3}}{\Delta T_b}-\frac{1}{2}$	$-\mu\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	0	$-\frac{T_{t3}}{\Delta T_b}\left(\frac{k+1}{2k}-\frac{k-1}{k\eta_c}\frac{\mu}{2}\right)$	0	0	$-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\frac{1}{\alpha}$	$\frac{-1}{1-\frac{\Delta P_b}{P_{t3}}}\left(1+\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\right)$	-1	$1+\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	0	0	0
$\partial Z_2/Z_2$	1	μ	0	$-\frac{1+\mu}{2}$	0	0	1	1	0	0	-1	0	0	0	0
$\partial Z_3/Z_3$	$\frac{1}{2}$	0	0	0	0	0	0	0	0	$\frac{-1}{1-\Delta P_b/P_{t3}}$	-1	1	0	0	0
$\partial w_g/w_g$	0	μ	0	$-\frac{1+\mu}{2}$	1	1	1	1	0	0	0	0	0	0	0
$\frac{\partial T_{t5}}{T_{t5}}$	$1+\frac{k-1}{k}\left(\frac{2-\alpha}{2\phi_t}\right)$	$-\mu\frac{k-1}{k}\frac{\alpha}{\phi_t}$	$\frac{-550}{Jc_p T_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]$	$\frac{k-1}{k}\left[\frac{1+\mu}{2}\frac{\alpha}{\phi_t}-\frac{1}{\phi_t}\right]$	0	0	$\frac{k-1}{k}\left(\frac{1-\alpha}{\phi_t}\right)$	$-\frac{k-1}{k}\frac{\alpha}{\phi_t}$	$\frac{k-1}{k}\frac{1}{\phi_t}$	$-\frac{k-1}{k}\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	0	$\frac{k-1}{k}\frac{\alpha}{\phi_t}$	0	0	0
$\frac{\partial P_{t5}}{P_{t5}}$	$\frac{2+\phi_t-\alpha}{2\phi_t}$	$\mu\frac{\phi_t-\alpha}{\phi_t}$	$\frac{-550}{RT_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]$	$-\left(\frac{1+\mu}{2}\right)\left(\frac{\phi_t-\alpha}{\phi_t}\right)-\frac{1}{\phi_t}$	1	1	$\frac{1+\phi_t-\alpha}{\phi_t}$	$\frac{\phi_t-\alpha}{\phi_t}$	$\frac{1}{\phi_t}$	$-\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	0	$-\frac{\phi_t-\alpha}{\phi_t}$	$\frac{1}{\phi_t}$	1	0
$\frac{\partial A_n}{A_n}$	$-\frac{k+1}{2k}\left(\frac{2-\alpha}{2\phi_t}\right)-\epsilon_n\left(\frac{2+\phi_t-\alpha}{2\phi_t}\right)$	$\mu\left[\frac{k+1}{2k}\frac{\alpha}{\phi_t}-\epsilon_n\left(\frac{\phi_t-\alpha}{\phi_t}\right)\right]$	$\frac{550}{RT_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\cdot\left[\frac{k+1}{2k}+\epsilon_n\right]$	$\frac{k+1}{2k}\left(\frac{1}{\phi_t}-\frac{1+\mu}{2}\frac{\alpha}{\phi_t}\right)+\epsilon_n\left[\frac{1+\mu}{2}\left(\frac{\phi_t-\alpha}{\phi_t}\right)+\frac{1}{\phi_t}\right]$	$-\epsilon_n$	0	$-\frac{k+1}{2k}\left(\frac{1-\alpha}{\phi_t}\right)-\epsilon_n\left(\frac{1+\phi_t-\alpha}{\phi_t}\right)$	$\frac{k+1}{2k}\frac{\alpha}{\phi_t}-\epsilon_n\left(\frac{\phi_t-\alpha}{\phi_t}\right)$	$-\frac{1}{\phi_t}\left[\frac{k+1}{2k}+\epsilon_n\right]$	$\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)\left[\frac{k+1}{2k}+\epsilon_n\right]$	0	$\frac{k-1}{2k}\frac{\alpha}{\phi_t}+(1+\epsilon_n)\left(\frac{\phi_t-\alpha}{\phi_t}\right)$	$\frac{-1}{\phi_t}(1+\epsilon_n)$	$-(1+\epsilon_n)$	0
$\frac{\partial F_n}{F_n}$	$\frac{F_g}{F_n}\left[\frac{k-1}{2k}\left(\frac{2-\alpha}{2\phi_t}\right)+\frac{\phi_n}{2}\left(\frac{2+\phi_t-\alpha}{2\phi_t}\right)+\frac{1}{2}\right]$	$\mu\left\{1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2}-\frac{\alpha}{\phi_t}\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]\right\}$	$-\frac{550}{RT_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\cdot\frac{F_g}{F_n}\left[\frac{k-1}{2k}+\frac{\phi_n}{2}\right]$	$-\left(\frac{1+\mu}{2}\right)\left\{1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2}+\frac{1}{\phi_t}\left(\frac{2}{1+\mu}-\alpha\right)\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]\right\}$	$1+\frac{F_g}{F_n}\frac{\phi_n}{2}$	1	$1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2}+\left(\frac{1-\alpha}{\phi_t}\right)\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]$	$1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2}-\frac{\alpha}{\phi_t}\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]$	$\frac{F_g}{F_n}\frac{1}{\phi_t}\left[\frac{k-1}{2k}+\frac{\phi_n}{2}\right]$	$-\frac{F_g}{F_n}\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)$	0	$\frac{F_g}{F_n}\left[-\frac{\phi_n}{2}+\frac{\alpha}{\phi_t}\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]$	$\frac{F_g}{F_n}\frac{\phi_n}{2\phi_t}$	$\frac{F_g}{F_n}\frac{\phi_n}{2}$	$\frac{1}{2}\frac{F_g}{F_n}$
$\frac{\partial HP_{pt}}{HP_{pt}}$	$1+\frac{\phi_{pt}}{2}+\left(\frac{2-\alpha}{2\phi_t}\right)\left[\frac{k-1}{k}+\phi_{pt}\right]$	$\mu\left[1+\phi_{pt}-\frac{\alpha}{\phi_t}\left(\frac{k-1}{k}+\phi_{pt}\right)\right]$	$\frac{-550}{RT_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\cdot\left[\frac{k-1}{k}+\phi_{pt}\right]$	$-\left(\frac{1+\mu}{2}\right)\left[1+\phi_{pt}+\frac{1}{\phi_t}\left(\frac{2}{1+\mu}-\alpha\right)\left(\frac{k-1}{k}+\phi_{pt}\right)\right]$	$1+\phi_{pt}$	1	$1+\phi_{pt}+\left(\frac{1-\alpha}{\phi_t}\right)\left(\frac{k-1}{k}+\phi_{pt}\right)$	$1+\phi_{pt}-\frac{\alpha}{\phi_t}\left(\frac{k-1}{k}+\phi_{pt}\right)$	$\frac{1}{\phi_t}\left[\frac{k-1}{k}+\phi_{pt}\right]$	$-\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)\left(\frac{k-1}{k}+\phi_{pt}\right)$	0	$\frac{\alpha}{\phi_t}\left(\frac{k-1}{k}+\phi_{pt}\right)-\phi_{pt}$	$\frac{\phi_{pt}}{\phi_t}$	ϕ_{pt}	1
$\frac{\partial T_{t6}}{T_{t6}}$	$1-\eta_{pt}\frac{k-1}{2k}$	$-\mu\eta_{pt}\frac{k-1}{k}$	0	$\left(\frac{1+\mu}{2}\right)\eta_{pt}\frac{k-1}{k}$	$-\eta_{pt}\frac{k-1}{k}$	0	$-\eta_{pt}\frac{k-1}{k}$	$-\eta_{pt}\frac{k-1}{k}$	0	0	0	$\eta_{pt}\frac{k-1}{k}$	$-\eta_{pt}\frac{k-1}{k}\frac{1}{\phi_t}$	$-\eta_{pt}\frac{k-1}{k}$	$-\frac{k-1}{k}\frac{1}{\phi_{pt}}$
$\partial T_{t2}/T_{t2}$	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
$\partial P_{t2}/P_{t2}$	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
$\partial P_{am}/P_{am}$	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
$\partial \eta_c/\eta_c$	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
$\frac{\partial \Delta P_b/P_{t3}}{\Delta P_b/P_{t3}}$	0	0	0	0	0	0	0	0	0	$\frac{1}{\Delta P_b/P_{t3}}$	0	0	0	0	0
$\partial \eta_b/\eta_b$	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
$\partial A_4/A_4$	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
$\partial \eta_t/\eta_t$	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
$\partial \eta/\eta$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$$Z=\frac{w_f}{P\left(1-\frac{T_{t2}}{T_{t4}}\right)} \qquad \mu=\left.\frac{\partial w_a/w_a}{\partial N/N}\right|_{T_{t4}=\text{¢}} \qquad \alpha=\frac{\frac{k-1}{k}\left(\frac{P_{t3}}{P_{t2}}\right)^{\frac{k-1}{k}}}{\left(\frac{P_{t3}}{P_{t2}}\right)^{\frac{k-1}{k}}-1} \qquad \phi_t=\frac{\frac{k-1}{k}}{\left(\frac{P_{t4}}{P_{t5}}\right)^{\frac{k-1}{k}}-1}$$

$$\phi_n=\phi_{pt}=\frac{\frac{k-1}{k}}{\left(\frac{P_{t5}}{P_{am}}\right)^{\frac{k-1}{k}}-1} \qquad \epsilon_n=\frac{\frac{k+1}{2}-\left(\frac{P_{t5}}{P_{am}}\right)^{\frac{k-1}{k}}}{k\left[\left(\frac{P_{t5}}{P_{am}}\right)^{\frac{k-1}{k}}-1\right]}=0 \text{ Beyond Choking}$$

$$\frac{F_g}{F_n}=\frac{1}{1-M_0\sqrt{\frac{kT_{am}}{2\eta_n T_{t4}}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\left[\frac{k-1}{k}+\phi_n\right]}}$$

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TURBINE INLET TEMP. VARIATION $\frac{\partial T_{t4}}{T_{t4}}$	ENGINE SPEED VARIATION $\frac{\partial N}{N}$	SHAFT POWER EXTRACTION $\partial \frac{SHP}{w_a}$	ENGINE INLET TEMP. VARIATION $\frac{\partial T_{t2}}{T_{t2}}$	ENG. IN. PRESS. VAR. $\frac{\partial P_{t2}}{P_{t2}}$	AMB. PRESS. VAR. $\frac{\partial P_{am}}{P_{am}}$	COMP. DISCHARGE AIR BLEED (For 1% Bleed, $\frac{\partial w_a}{w_a} = -.01$) $\frac{\partial w_a}{w_a}$	COMP. INLET AIRFLOW VAR. $\frac{\partial w_a}{w_a}$	COMPRESSOR EFFICIENCY VARIATION $\frac{\partial \eta_c}{\eta_c}$	BURNER PRESS. LOSS VARIATION $\partial \frac{\Delta P_b}{P_{t3}}$	BURNER EFF. VAR. $\frac{\partial \eta_b}{\eta_b}$	TURBINE AREA VARIATION $\frac{\partial A_4}{A_4}$	TURBINE EFF. VAR. $\frac{\partial \eta_t}{\eta_t}$	GAS GEN. EXH. PRESS. VAR. $\frac{\partial P_{t5}}{P_{t5}}$	EXH. NOZ. OR POWER TURB EFF. VAR. $\frac{\partial \eta}{\eta}$
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	μ	0	$-\frac{1+\mu}{2}$	1	1	0	1	0	0	0	0	0	0	0
$\frac{k-1}{2k\eta_c}$	$\mu\frac{k-1}{k\eta_c}$	0	$\frac{k+1}{2k}-\frac{k-1}{k\eta_c}\frac{\mu}{2}$	0	0	$\frac{k-1}{k\eta_c}$	$\frac{k-1}{k\eta_c}$	$-\frac{k-1}{k\eta_c}\frac{1}{\alpha}$	$\frac{k-1}{k\eta_c}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	0	$-\frac{k-1}{k\eta_c}$	0	0	0
$\frac{1}{2}$	μ	0	$-\frac{1+\mu}{2}$	1	1	1	1	0	$\frac{1}{1-\Delta P_b/P_{t3}}$	0	-1	0	0	0
$\frac{T_{t4}}{\Delta T_b}-\frac{k-1}{2k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$\mu\left(1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\right)$	0	$-\left[\frac{1}{2}+\frac{k+1}{2k}\frac{T_{t3}}{\Delta T_b}\right] + \frac{\mu}{2}\left[1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\right]$	1	1	$1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$1-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\frac{1}{\alpha}$	$-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	-1	$\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	0	0	0
$\frac{T_{t4}}{\Delta T_b}-\frac{k-1}{2k\eta_c}\frac{T_{t3}}{\Delta T_b}-\frac{1}{2}$	$-\mu\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	0	$-\frac{T_{t3}}{\Delta T_b}\left(\frac{k+1}{2k}-\frac{k-1}{k\eta_c}\frac{\mu}{2}\right)$	0	0	$-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$-\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	$\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\frac{1}{\alpha}$	$\frac{-1}{1-\frac{\Delta P_b}{P_{t3}}}\left(1+\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}\right)$	-1	$1+\frac{k-1}{k\eta_c}\frac{T_{t3}}{\Delta T_b}$	0	0	0
1	μ	0	$-\frac{1+\mu}{2}$	0	0	1	1	0	0	-1	0	0	0	0
$\frac{1}{2}$	0	0	0	0	0	0	0	0	$\frac{-1}{1-\Delta P_b/P_{t3}}$	-1	1	0	0	0
0	μ	0	$-\frac{1+\mu}{2}$	1	1	1	1	0	0	0	0	0	0	0
$1+\frac{k-1}{k}\left(\frac{2-\alpha}{2\phi_t}\right)$	$-\mu\frac{k-1}{k}\frac{\alpha}{\phi_t}$	$\frac{-550}{Jc_p T_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]$	$\frac{k-1}{k}\left[\frac{1+\mu}{2}\frac{\alpha}{\phi_t}-\frac{1}{\phi_t}\right]$	0	0	$\frac{k-1}{k}\left(\frac{1-\alpha}{\phi_t}\right)$	$-\frac{k-1}{k}\frac{\alpha}{\phi_t}$	$\frac{k-1}{k}\frac{1}{\phi_t}$	$-\frac{k-1}{k}\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	0	$\frac{k-1}{k}\frac{\alpha}{\phi_t}$	0	0	0
$\frac{2+\phi_t-\alpha}{2\phi_t}$	$\mu\frac{\phi_t-\alpha}{\phi_t}$	$\frac{-550}{R T_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]$	$-\left(\frac{1+\mu}{2}\right)\left(\frac{\phi_t-\alpha}{\phi_t}\right)-\frac{1}{\phi_t}$	1	1	$\frac{1+\phi_t-\alpha}{\phi_t}$	$\frac{\phi_t-\alpha}{\phi_t}$	$\frac{1}{\phi_t}$	$-\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)$	0	$-\frac{\phi_t-\alpha}{\phi_t}$	$\frac{1}{\phi_t}$	1	0
$-\frac{k+1}{2k}\left(\frac{2-\alpha}{2\phi_t}\right) - \epsilon_n\left(\frac{2+\phi_t-\alpha}{2\phi_t}\right)$	$\mu\left[\frac{k+1}{2k}\frac{\alpha}{\phi_t}-\epsilon_n\left(\frac{\phi_t-\alpha}{\phi_t}\right)\right]$	$\frac{550}{R T_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\cdot\left[\frac{k+1}{2k}+\epsilon_n\right]$	$\frac{k+1}{2k}\left(\frac{1}{\phi_t}-\frac{1+\mu}{2}\frac{\alpha}{\phi_t}\right) + \epsilon_n\left[\frac{1+\mu}{2}\left(\frac{\phi_t-\alpha}{\phi_t}\right)+\frac{1}{\phi_t}\right]$	$-\epsilon_n$	0	$-\frac{k+1}{2k}\left(\frac{1-\alpha}{\phi_t}\right) - \epsilon_n\left(\frac{1+\phi_t-\alpha}{\phi_t}\right)$	$\frac{k+1}{2k}\frac{\alpha}{\phi_t}-\epsilon_n\left(\frac{\phi_t-\alpha}{\phi_t}\right)$	$-\frac{1}{\phi_t}\left[\frac{k+1}{2k}+\epsilon_n\right]$	$\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)\left[\frac{k+1}{2k}+\epsilon_n\right]$	0	$\frac{k-1}{2k}\frac{\alpha}{\phi_t} + (1+\epsilon_n)\left(\frac{\phi_t-\alpha}{\phi_t}\right)$	$\frac{-1}{\phi_t}(1+\epsilon_n)$	$-(1+\epsilon_n)$	0
$\frac{F_g}{F_n}\left[\frac{k-1}{2k}\left(\frac{2-\alpha}{2\phi_t}\right) + \frac{\phi_n}{2}\left(\frac{2+\phi_t-\alpha}{2\phi_t}\right)+\frac{1}{2}\right]$	$\mu\left\{1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2} - \frac{\alpha}{\phi_t}\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]\right\}$	$-\frac{550}{R T_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\cdot\frac{F_g}{F_n}\left[\frac{k-1}{2k}+\frac{\phi_n}{2}\right]$	$-\left(\frac{1+\mu}{2}\right)\left\{1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2} + \frac{1}{\phi_t}\left(\frac{2}{1+\mu}-\alpha\right)\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]\right\}$	$1+\frac{F_g}{F_n}\frac{\phi_n}{2}$	1	$1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2} + \left(\frac{1-\alpha}{\phi_t}\right)\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]$	$1+\frac{F_g}{F_n}\left[\frac{\phi_n}{2} - \frac{\alpha}{\phi_t}\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]$	$\frac{F_g}{F_n}\frac{1}{\phi_t}\left[\frac{k-1}{2k}+\frac{\phi_n}{2}\right]$	$-\frac{F_g}{F_n}\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)$	0	$\frac{F_g}{F_n}\left[-\frac{\phi_n}{2} + \frac{\alpha}{\phi_t}\left(\frac{k-1}{2k}+\frac{\phi_n}{2}\right)\right]$	$\frac{F_g}{F_n}\frac{\phi_n}{2\phi_t}$	$\frac{F_g}{F_n}\frac{\phi_n}{2}$	$\frac{1}{2}\frac{F_g}{F_n}$
$1+\frac{\phi_{pt}}{2} + \left(\frac{2-\alpha}{2\phi_t}\right)\left[\frac{k-1}{k}+\phi_{pt}\right]$	$\mu\left[1+\phi_{pt} - \frac{\alpha}{\phi_t}\left(\frac{k-1}{k}+\phi_{pt}\right)\right]$	$\frac{-550}{R T_{t4}\eta_t}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\cdot\left[\frac{k-1}{k}+\phi_{pt}\right]$	$-\left(\frac{1+\mu}{2}\right)\left[1+\phi_{pt} + \frac{1}{\phi_t}\left(\frac{2}{1+\mu}-\alpha\right)\left(\frac{k-1}{k}+\phi_{pt}\right)\right]$	$1+\phi_{pt}$	1	$1+\phi_{pt} + \left(\frac{1-\alpha}{\phi_t}\right)\left(\frac{k-1}{k}+\phi_{pt}\right)$	$1+\phi_{pt} - \frac{\alpha}{\phi_t}\left(\frac{k-1}{k}+\phi_{pt}\right)$	$\frac{1}{\phi_t}\left[\frac{k-1}{k}+\phi_{pt}\right]$	$-\frac{\alpha}{\phi_t}\left(\frac{1}{1-\frac{\Delta P_b}{P_{t3}}}\right)\left(\frac{k-1}{k}+\phi_{pt}\right)$	0	$\frac{\alpha}{\phi_t}\left(\frac{k-1}{k}+\phi_{pt}\right)-\phi_{pt}$	$\frac{\phi_{pt}}{\phi_t}$	ϕ_{pt}	1
$1-\eta_{pt}\frac{k-1}{2k}$	$-\mu\eta_{pt}\frac{k-1}{k}$	0	$\left(\frac{1+\mu}{2}\right)\eta_{pt}\frac{k-1}{k}$	$-\eta_{pt}\frac{k-1}{k}$	0	$-\eta_{pt}\frac{k-1}{k}$	$-\eta_{pt}\frac{k-1}{k}$	0	0	0	$\eta_{pt}\frac{k-1}{k}$	$-\eta_{pt}\frac{k-1}{k}\frac{1}{\phi_t}$	$-\eta_{pt}\frac{k-1}{k}$	$-\frac{k-1}{k}\frac{1}{\phi_{pt}}$
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	$\frac{1}{\Delta P_b/P_{t3}}$	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$$Z = \frac{w_f}{P\left(1-\frac{T_{t3}}{T_{t4}}\right)} \qquad \mu = \left.\frac{\partial w_a/w_a}{\partial N/N}\right|_{T_{t4}=c} \qquad \alpha = \frac{\frac{k-1}{k}\left(\frac{P_{t3}}{P_{t2}}\right)^{\frac{k-1}{k}}}{\left(\frac{P_{t3}}{P_{t2}}\right)^{\frac{k-1}{k}}-1} \qquad \phi_t = \frac{\frac{k-1}{k}}{\left(\frac{P_{t4}}{P_{t5}}\right)^{\frac{k-1}{k}}-1} \qquad \phi_n = \phi_{pt} = \frac{\frac{k-1}{k}}{\left(\frac{P_{t5}}{P_{am}}\right)^{\frac{k-1}{k}}-1}$$

$$\epsilon_n = \frac{\frac{k+1}{2}-\left(\frac{P_{t5}}{P_{am}}\right)^{\frac{k-1}{k}}}{k\left[\left(\frac{P_{t5}}{P_{am}}\right)^{\frac{k-1}{k}}-1\right]} = 0 \text{ Beyond Choking}$$

$$\frac{F_g}{F_n} = \frac{1}{1-M_o\sqrt{\frac{kT_{am}}{2\eta_n T_{t4}}\left[\frac{\frac{k-1}{k}+\phi_t}{\phi_t}\right]\left[\frac{k-1}{k}+\phi_n\right]}}$$

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	DELN1C2	DELP25	DELP2	DELP3	DELBPR	DELT3	DELT2	DELP4	DELN2C2	DELBETA	DELWA3	DELT25
GAMT2PC	-2.6000	-1.3500	1.3500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2PC	-3.0500	-1.1000	-0.1000	1.2000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAMT2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
GAM3DES	0.0000	0.0000	0.0000	-0.1700	-1.4700	0.0000	1.4700	0.0000	0.0000	0.0000	0.0000	0.1700
WA3	0.0000	0.0000	0.0000	-1.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAF	0.0000	-2.6543	2.6543	0.0000	8.5869	-8.6041	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAFD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACL	0.0000	-2.8355	0.0000	2.8355	4.4287	0.0000	-8.1318	0.0000	0.0000	0.0000	0.0000	0.0000
ETACLD	0.5500	0.5500	0.0000	-0.5500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACH	0.0000	0.0000	0.0000	-0.6030	0.0000	0.0000	1.9341	0.0000	0.0000	0.0000	0.0000	0.6030
ETCHD	0.0000	0.0000	0.0000	0.0900	0.5500	0.0000	-0.5500	0.0000	0.0000	0.0000	0.0000	-0.0900
WA4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0958
DELPB	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0631
ETAB	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATHD	0.0000	0.0000	0.0000	0.0000	-0.0250	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATL	0.0000	0.6575	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATLD	-0.1200	0.0300	0.0000	0.0000	-0.0600	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
T5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6376	0.0000	0.0000	0.0000	-0.0073	0.0000
WGTL	0.0000	0.0000	0.0000	0.0000	6.3026	-7.1471	-1.2855	0.0000	0.0000	0.0000	0.0146	0.0000
A5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A6	0.1500	0.0900	0.0000	0.0000	0.0750	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELJD	0.0000	0.0000	1.0009	0.0000	0.0000	-0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELP/P7	0.0000	1.0010	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AJN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELP/P1	0.0000	-0.9966	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELM	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pam	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELXN	0.0000	0.0000	0.0000	0.0000	0.0000	0.1867	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W4H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W35L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0081	0.0040	0.0000
WB3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM3	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000	0.0000	0.0000
Pst35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	-2.0000	0.0000	0.0000
T35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	-2.0000	0.0000
W4L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W35H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0061	0.0000	0.0000
WAT	0.0000	-1.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2	0.0000	-1.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGTH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WG4H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGJN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TAM	0.0000	0.0000	0.0000	0.0000	-1.1034	0.0000	0.0000	0.0000	1.1027	0.0000	0.0000	0.0000
SFC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE E2 COMPUTED VALUES OF THE FAULT COEFFICIENT MATRIX FOR A TWO SPOOL HIGH BY-PASS RATIO NON MIXING HYPOTHETICAL TURBO-FAN ENGINE SHEET 1 of 4

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	DELT4	DELPs4	DELWA4	DELP5	DELT5	DELWGTH	DELWf	DELW4H	DELW35	DELT35	DELT6	DELP6
GAMT2PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAMT2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM3DES	0.0000	0.0000	-2.9400	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA3	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAF	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAFD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACLD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACH	-2.0729	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETCHD	0.0000	0.0000	1.1000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA4	-0.0479	-1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0958	0.0000
DELPB	0.0620	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.1262	0.0000
ETAB	-0.4786	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATHD	0.0000	0.0000	-0.0500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATLD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
T5	0.2774	0.0000	0.0000	0.0000	0.0000	-0.2496	0.0000	0.0000	1.8924	0.0000	0.0000	-1.0103
WGTL	0.0138	0.0000	0.0000	0.0000	-0.2885	0.0000	0.0000	-1.0158	0.0000	2.7802	0.0000	0.0000
A5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELP/P7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AJN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELP/P1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pam	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELXN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W4H	0.1008	-0.2016	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
W35L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
WB3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pst35	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
T35	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W4L	0.1008	-0.0050	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
W35H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
WAT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAD	0.0000	0.0000	0.0000	0.0000	0.1571	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAG	0.0000	0.0000	0.0000	0.0000	-1.0081	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB35	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	-1.0000	0.0000	0.0000	0.0000	-1.0000
WB4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.0000	-1.0000	0.0000	0.0000
WGTH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WG4H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.9752	0.0000	0.0000	0.9752
WGJN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9752	0.0000	0.9752	0.0000	0.0000
TAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SFC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE E2 COMPUTED VALUES OF THE FAULT COEFFICIENT MATRIX FOR A TWO SPOOL HIGH BY PASS RATIO NON MIXING HYPOTHETICAL TURBO FAN ENGINE SHEET 2 of 4
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	DELW4L	DELW35L	DELT7	DELP7/P2	DELWGTL	DELW35H	DELWA2	DELWAD	DELPD	DELWAJD	DELPam	DELWGJN
GAMT2PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAMT2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM3DES	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAF	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAFD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACLD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETCHD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELPB	0.0000	-0.1251	-0.9369	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAB	-1.0000	1.1237	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATH	0.0000	2.9561	-0.6482	0.0000	-3.1826	0.6482	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATHD	0.0000	0.0822	-0.0600	0.0000	-0.0531	0.0600	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATL	0.0000	0.0000	0.0000	0.0000	3.1708	-0.6575	0.0000	-3.0448	0.6575	0.0000	0.0000	0.0000
ETATLD	0.0000	0.0000	0.0000	0.0000	0.2495	-0.0300	0.0000	-0.1787	0.0300	0.0000	0.0000	0.0000
T5	0.0000	3.2872	0.0000	1.0000	-3.1826	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGTL	0.0000	0.0000	0.0000	0.0000	4.2858	0.0000	1.0305	-3.0448	0.0000	0.0000	0.0000	0.0000
A5	0.0000	0.5000	-1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A6	0.0000	0.0000	0.0000	0.0000	0.4250	-1.0900	1.0000	0.0000	0.0900	0.0000	0.0000	0.0000
DELJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.9991	-0.0018	0.0000
AJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.4700	1.0000	0.0000
DELP/P7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0010	1.0010	0.0000	0.0000	-0.9990
AJN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	-1.8500
DELP/P1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pam	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELXN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0874	0.0000	0.0994	0.7944	0.3438
W4H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W35L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pst35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
T35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W4L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W35H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
WAG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGTH	-0.0171	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WG4H	0.0000	0.0000	0.0000	-0.9921	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGJN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SFC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE E2 COMPUTED VALUES OF THE FAULT COEFFICIENT MATRIX FOR A TWO SPOOL HIGH BY-PASS RATIO NON MIXING HYPOTHETICAL TURBO-FAN ENGINE SHEET 3 of 4

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	DELP8	DELP1	DELTam	DELWAT	DELXN	DELPs35	DELWb3	DELPs3
GAMT2PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAMT2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM3DES	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAF	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAFD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACLD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETCHD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELPB	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAB	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATHD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATLD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
T5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGTL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.8306
A5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DELJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
AJD	0.0000	0.0000	0.0000	0.0000	0.4700	0.0000	0.0000	0.0000
DELP/P7	-0.0020	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000
AJN	1.0000	0.0000	0.0000	0.0000	0.8500	0.0000	0.0000	0.0000
DELP/P1	0.0000	0.0000	0.0000	0.9966	0.0000	0.0000	0.0000	0.0000
DELM	0.0000	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000	0.0000
Pam	0.0000	0.0000	0.0000	1.0000	-1.0000	0.0000	0.0000	0.0000
DELXN	0.2056	0.0000	-1.0000	0.0000	-0.4432	0.0000	0.0000	0.0000
W4H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W35L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
GAM3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pst35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
T35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W4L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W35H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAT	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAD	0.0000	-1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
WAJD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.1558	-1.0000
WAG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
WB35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WB4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGTH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WG4H	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGJN	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SFC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE E2 COMPUTED VALUES OF THE FAULT COEFFICIENT MATRIX FOR A TWO SPOOL HIGH BY-PASS RATIO NON MIXING HYPOTHETICAL TURBO-FAN ENGINE SHEET 4 OF 4

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TWO SPOOL INDUSTRIAL GAS TURBINE COEFFICIENTS MATRIX

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-- DESIGN POINT OPERATION --

	GAMT2	N1c2	P3	P2	WA2	T3	T2	PS3	WA3	P4	T4	WGTH	WF	WH3/WA2
GAMT2-PC	1.0000	-1.6244	0.0473	-0.0473	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2-PC	1.0000	0.0000	0.0000	1.0000	-1.0000	0.0000	-0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2-D	0.0000	0.0000	0.5004	-0.5004	0.0000	-1.7833	1.6700	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACH-D	0.0000	-0.1858	0.1439	-0.1439	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
M3	0.0000	0.0000	1.1238	0.0000	0.0000	0.0619	0.0000	-1.0000	-0.1238	0.0000	0.0000	0.0000	0.0000	0.0000
DPB/P3	0.0000	0.0000	1.0500	0.0000	0.0000	0.0440	0.0000	0.0000	-0.1000	-0.9500	-0.0940	0.0000	0.0000	0.0000
ETAB-D	0.0000	0.0000	0.0000	0.0000	0.0000	-0.6602	0.0000	0.0000	0.0000	0.0000	1.6602	1.0000	-1.0000	0.0000
ETATH	0.0000	0.0000	0.0000	0.4098	0.0000	0.1455	0.0000	0.0000	0.0000	-0.4098	2.0430	0.2520	0.0000	-1.3169
ETATH-D	0.0000	0.1485	0.0000	0.0721	0.0000	0.0000	0.0743	0.0000	0.0000	-0.0721	-0.1970	0.0000	0.0000	0.0000
ETAPT	0.0000	0.0000	0.0000	-0.6575	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAPT-D	0.0000	0.0000	0.0000	-0.1045	0.0000	0.0000	0.0743	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SHPX/WA3	0.0000	0.0000	0.0000	0.0000	-0.9309	-1.2430	0.5880	0.0000	0.0000	0.0000	3.0993	1.1680	0.0000	-0.8414
WAPT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A4	0.0000	0.0445	0.0000	0.0280	0.0000	0.0000	0.0223	0.0000	0.0000	-1.0230	0.4778	1.0000	0.0000	0.0000
A5	0.0000	0.0000	0.0000	-1.0353	0.0000	0.0000	0.0223	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DP/P1	-0.1000	0.0000	0.0000	-0.9500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
W3H/WA2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0700	0.0000	-0.1400	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
WA3L/WA2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0300	0.0000	-0.0600	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGTH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.9777	0.0000	0.0000	1.0000	-0.0223	0.0000
WA3	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	-0.8000	0.0000	0.0000	0.0000	0.0000	-0.1400
DP/P1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.8035	0.0000	-0.1375
DP/P6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
P5/P2	0.0000	0.0000	1.0000	-1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000	0.0000	0.0000	0.0000
SFC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000

TABLE E3   FAULT COEFFICIENT MATRIX OF AN INDUSTRIAL GAS TURBINE ENGINE   (1 of 2)

TWO SPOOL INDUSTRIAL GAS TURBINE COEFFICIENTS MATRIX

-- DESIGN POINT OPERATION --

	T5	ETATH	P5/P2	WGTL	T6	P6	ETAPT	NPTc2	P1	SHP	SFC
GAMT2-PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2-PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
GAM2-D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETACH-D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
M3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DPB/P3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAB-D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATH	-2.0884	-1.0000	0.4098	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETATH-D	0.1219	1.0000	0.0721	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ETAPT	0.1302	0.0000	-0.6575	-0.0082	-3.1500	0.6575	-1.0000	0.0000	0.0000	0.0000	0.0000
ETAPT-D	-0.2902	0.0000	-0.1045	0.0000	0.2159	0.1045	1.0000	0.1485	0.0000	0.0000	0.0000
SHPX/WA3	-2.2995	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WAPT	4.1426	0.0000	0.0000	1.0000	-3.1501	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000
A4	0.0000	0.0000	0.0230	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A5	0.4778	0.0000	-1.0353	1.0000	0.0000	0.0353	0.0000	0.0445	0.0000	0.0000	0.0000
DP/P1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9500	0.0000	0.0000
TAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
W3H/WA2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA3L/WA2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WGTH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WA3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DP/P1	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DP/P6	0.0000	0.0000	0.0000	-0.0600	-0.0300	0.9700	0.0000	0.0000	0.0000	0.0000	0.0000
P5/P2	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
SFC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000

TABLE E3 FAULT COEFFICIENT MATRIX OF AN INDUSTRIAL GAS TURBINE ENGINE (2 of 2)

	WA	T5	T2	P2	N1	T3	P3	Wf T	6	P6/P2	T7	P7/P2	NPt	SHP
GAM1	1.0		0.5	-1.682	-1.8		0.682							
ETAC			1.67	-0.6443	-0.1858	-1.7833	0.6433							
ETAB	1.2221	1.7466				-0.7466		-0.9777						
T5	-0.125					0.0445	0.1							
ETAT	-0.9705	3.7167	-0.089	0.6683	0.1485	0	-0.481	-0.1777	-1.96	0.481				
ETAPT	-0.8117		-0.089	-0.856	2			-0.015	2.94	-0.742	-2.94	0.762	-0.178	
DELWA								-0.018	-4.207		3.073		1	1

TABLE E4 INFLUENCE COEFICIENT FOR A TWO SPOOL GAS TURBINE ENGINE DETERMINED BY THE USE OF TABLE E1

APPENDIX F

Consider a system where M measurements ($Z_1, Z_2 . . . Z_M$) are taken and we expect N variables ($X_1, X_2, X_3 . . . . . X_N$)

The relation between the variables and the dependent parameters can be written as:

$$Z_1 = A_{11}X_1 + A_{12}X_2 + A_{13}X_3 + \ldots + A_{1N}X_N \qquad (F.5)$$

$$Z_2 = A_{21}X_1 + A_{22}X_2 + A_{23}X_3 + \ldots + A_{2N}X_N \qquad (F.6)$$

$$Z_3 = A_{31}X_1 + A_{32}X_2 + A_{33}X_3 + \ldots + A_{3N}X_N \qquad (F.7)$$

$$Z_4 = A_{41}X_1 + A_{42}X_2 + A_{43}X_3 + \ldots + A_{4NN} \qquad (F.8)$$

$$\vdots$$

$$Z_M = A_{M1}X_1 + A_{M2}X_2 + A_{M3}X_3 + \ldots + A_{MN}X_N \qquad (F.9)$$

This can be represented in the matrix notations as

[Z] = [H][X] which is equation (F.1)

Now in order to determine the matrix [H] we make all independent variables zero except X1 (say). Then the equations can be written as

$$Z_1 = A_{11}X_1 = A_{11} \quad \text{(when X1=1)}$$

$$Z_2 = A_{12}X_1 = A_{12} \quad \text{(when X1=1)}$$

$$Z_3 = A_{13}X_1 = A_{13} \quad \text{(when X1=1)}$$

$$\vdots$$

$$Z_M = A_{1M}X_1 = AM \quad \text{(when X1=1)}$$

thus values of the first column of the matrix H are determined as equal to the measurements when only X1 is non-zero and is unity. Similarly when $X_2=1$ and others are zero the second column can be determined. As the result we have the matrix

$$\begin{bmatrix} H \end{bmatrix} = \begin{bmatrix} A11 & A12 & A13 & .. & A1N \\ A21 & A22 & A23 & .. & A2N \\ A31 & A32 & A33 & .. & A3N \\ A41 & A42 & A43 & .. & A4N \\ \vdots & \vdots & \vdots & & \vdots \\ AM1 & AM2 & AM3 & .. & AMN \end{bmatrix}$$