CRANFIELD UNIVERSITY

WANG JIAN

AIRCRAFT HYDRAULIC POWER SYSTEM DIAGNOSTICS, PROGNOSTICS AND HEALTH MANAGEMENT

SCHOOL OF ENGINEERING

MSc by Research

MSc

Academic Year: 2011 - 2012

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

This Individual Research Project (IRP) is the extension research to the group design project (GDP) work which the author has participated in his Msc programme. The GDP objective is to complete the conceptual design of a 200-seat, flying wing civil airliner—FW-11. The next generation aircraft design demands higher reliability, safety and maintainability.

With the development of the vehicle hydraulic system technology, the equipment and systems become more and more complex, their reliability and maintenance become more difficult for designers, manufacturers and customers. To improve the mission reliability and reduce life cycle cost, there is strong demand for the application of health management technology into airframe system design.

In this research, the author introduced diagnostic, prognostic and health management (DPHM) concept into the aircraft hydraulic power system development. As a brand new technology, it is a challenge to apply the DPHM techniques to on-board system. Firstly, an assumed hydraulic power system was designed for FW-11 by the author and used as the case in his IRP research. Then the crucial components and key parameters needed to be monitored were obtained based on Function Hazard Analysis and Failure Modes Effects Analysis of this system. The writer compared a few diagnostic and prognostic methods in detail, and then selected suitable ones for a hydraulic power system. A diagnostic process was applied to the hydraulic power system using a Case-based reasoning (CBR) approach, whilst a hybrid prognostic method was suggested for the system. After that, a diagnostic, prognostic and health management (DPHM) architecture of the hydraulic power system was designed at system level based on the diagnostic and prognostic research. The whole research work provided a general and practical instruction for hydraulic system design by means of DPHM application.

Keywords: Hydraulic, FMEA, CBR, DPHM, diagnostic, prognostic

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LIST OF ABBREVIATIONS

ACMP	Alternating current motor pumps
ADP	Air Driven Pump
ANN	Artificial neural network
CAAC	Civil Aviation Administration of China
CBM	Condition-based maintenance
CBR	Case-based reasoning
DoD	Department of Defense
DPHM	Diagnostics, prognostics and health management
EASA	European Aviation Safety Agency
EDP	Engine Driven Pump
EHA	Electrical-Hydrostatic Actuator
EMA	Electromechanical Actuator
EMP	Electronic Electric Motor Pump
EPS	Electrical Power System
FAA	Federal Aviation Administration
FHA	Functional hazard Assessment
FMECA	Failure modes effect and criticality analysis
FTA	Fault Tree Analysis
HSMU	Hydraulic System Management Unit
IRP	Individual Research Project
IVHM	Integrated Vehicle Health Management
LRU	Line Replaceable Unit
MBR	Model-based reasoning
OMS	On-board Maintenance Systems
PDFs	Probability density functions
PHM	Prognostic and health management
RAT	Ram Air Turbine
RUL	Remaining useful life
SOV	Shut-off Valve

1 Introduction

1.1 Introduction

This thesis consists of the Individual Research Project (IRP) and a Group Design Project (GDP) in which the author has participated during the current academic year. The GDP is to design a Flying wing civil aircraft—FW-11 which, in its conceptual phase, is a long range, 250-seat, next generation airliner. The IRP is an extension research of the GDP, which aims to incorporate diagnostics, prognostics and health management (DPHM) concepts into the FW-11 hydraulic power system. The research also contributes to the design target of the GDP work.

In this chapter, the background and problem statement are presented first to demonstrate the purpose of this project. It is followed by the research objectives and methodology of this thesis.

1.2 Background

An aircraft's hydraulic power system is one of the essential secondary power systems which transfer mechanical energy from engines to actuators by pressurised fluid. Hydraulic power for aircraft first appeared in the 1930s and has remained an effective solution for over seventy years. With the development of hydraulic system technologies, the equipment and systems have become increasingly complex. This means in turn that system fault detecting and failure predicting is complex. At the same time, new investment in research and development has resulted in the intensification of competition in the civil aviation market. To gain a competitive advantage, future aircraft design aims for improved reliability and safety. The DPHM technology is a new philosophy in airframe systems design which aims to scientifically improve system reliability and maintainability. It can also enhance economic efficiency in the product life-cycle.

The Health Management concept is the capability to make appropriate decisions about maintenance actions based on real-time monitoring, diagnosis and prognosis information, available resources, and operational demand [1]. The main functions of PHM technique incorporate three aspects: Real-time monitoring, Diagnostics and

Prognostics. The first primarily aims to acquire system or components status by advanced sensor technologies and related software in real time. Diagnostic is a fault identification and failure detection process based on the monitoring parameters and historgraphic data. The Prognosis process predicts the state of health and remaining life or the appropriate operating time span of systems and components. From the "Engine monitoring system" of the A-7 in the 1970s to the JSF PHM application in recent years, prognostics and health management (PHM) techniques have gradually developed into a complete concept. Figure 1-1 shows a typical DPHM functional flow.

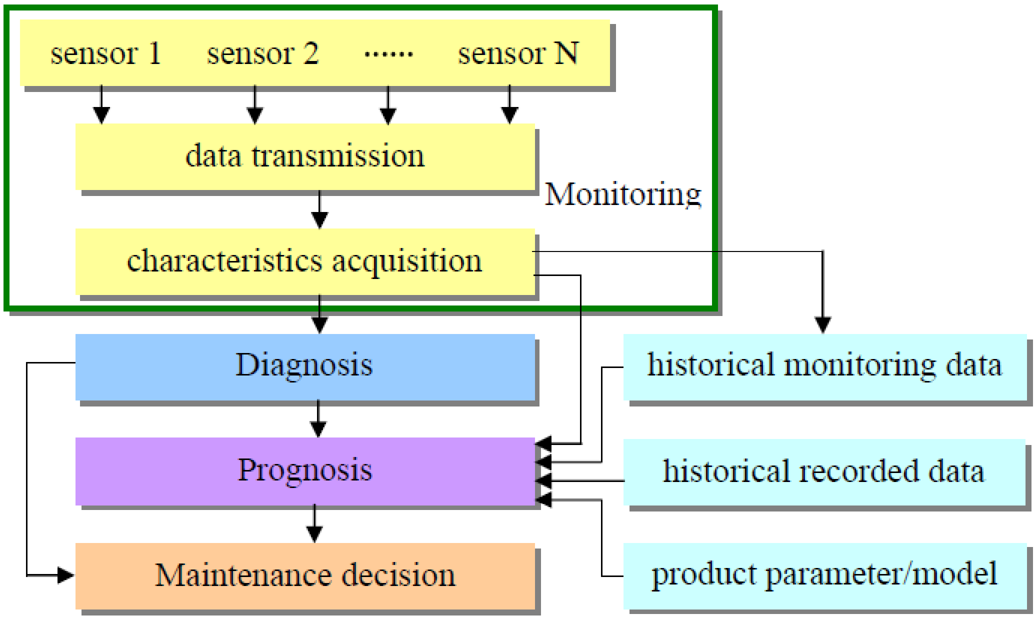


Figure 1-1: A typical functional flow of a DPHM system [2]

1.3 Status and Questions

With new technologies such as Fly-by-Wire, Electric Air Conditioning and Electromechanical Actuator (EMA) applied to aircraft systems, traditional energy systems, including hydraulic power, faced greater challenges. It can be seen from more and more publications and sci-tech articles that aircraft will incorporate more-electric systems and even all-electric system instead of hydraulically powered systems. This will undoubtedly simplify the system architecture and reduce system failure modes. Currently, neither the Airbus A380 nor Boeing B787, those new generation airplanes, can operate without a hydraulic power system. [3][4]In current technical conditions, hydraulic power has significant advantages because of its higher power to weight ratio, especially in large power actuation mechanisms. [25] However, how is the position of hydraulic power in aircraft system to be maintained? How can we reduce the hydraulic power system failure rate to improve aircraft safety and reliability? How can we detect potential hydraulic hardware faults and failures and avoid catastrophic accidents? How can the maintenance workload be simplified to reduce life cycle costs?

There is, therefore, a strong demand for the incorporation of prognostic and health management technology into aircraft hydraulic power systems.

1.4 Research Objectives and Scope

This research aims to develop a prognostic and health management approach to a flying wing aircraft hydraulic power system as an extension of the Group Design Project (GDP). Aircraft systems with PHM technology will make the new airliner designed in the GDP more competitive in a future aviation market.

The GDP design process was divided into three phases. For the each phase, the task and objective were as follow:

- Phase-I: Data collection and market analysis to establish specific design requirements
- Phase-II: Utilize existing aircraft design methods to complete a conventional aircraft conceptual design as a baseline
- Phase-III: Develop a flying wing aircraft for comparison with the baseline to see the benefits and challenges of the new concept

By means of individual research as part of this thesis, the appropriate PHM methods for the hydraulic system had to be studied in depth. The following objectives will be achieved through this research:

- Understanding development, status and the main function of PHM.
- Familiarisation with the characteristics and operational principles of different diagnostics and prognostic methods.
- To design a hydraulic power system for the FW-11 aircraft.
- To establish the main failure modes of the hydraulic power system through

safety analysis.

- Use of appropriate diagnostic and prognostic methods in hydraulic power system design.
- To design a suitable DPHM architecture for the hydraulic power system based on its features and the above approaches.

Therefore, this research first focuses on designing a hydraulic power system for the FW-11 aircraft. Then the studies concentrate on the main functions of DPHM——diagnostic and prognostic approaches and the concept of DPHM framework building. Nevertheless, the signal detection and measurement techniques, such as sensors and probes, are less involved in this thesis due to limited time. The whole research work aims to improve the hydraulic power system design by means of DPHM application.

1.5 Methodology

In Group Design Project, 22 students work as a team to finish the conceptual design of FW-11aricraft. In this phase, the author mainly contributed to the mass estimations and landing gear design of the aircraft. A summary of the GDP work and the author's contributions are presented in Appendix A.

In the IRP research, the author attempts to develop a generic DPHM methodology for aircraft hydraulic power systems.

A literature review of PHM technologies will be given at first, which includes the histories and status of PHM, PHM functions and PHM methods classification.

Then the author will establish an hydraulic power system architecture for the FW-11 aircraft as a case study .The system function will then be briefly described.

Prior to the application work of DPHM, a set of safety analysis methods are employed to determine which components and system parameters are essential. Functional hazard Assessment (FHA) is conducted for the whole system to identify hazardous function failure conditions and associated hazard levels. The failure modes effect and criticality analysis (FMECA) will be performed for each component of the hydraulic power system to identify the critical components and their potential failure modes. Fault Tree Analysis (FTA) for the selected failure modes which have higher hazard levels is carried out in order to determine the possible cause and the probabilities of failure. All of these analyses are the fundamentals of the following work.

Based on the analyses results, suitable diagnosis and prognosis methods are chosen for the appropriate components of the hydraulic power system. The diagnostic and prognostic applications are then the subject of research and in-depth discussion

The hydraulic power system DPHM architecture is included in the next chapter. It is the integration of the above diagnostics and prognostics research and the interface between the hydraulic power system and the aircraft level IVHM system.

Finally, the conclusions of all research work and future work are discussed.

2 Literature review

2.1 PHM Technology History and Status

PHM technology, such as Built-in test (BIT), diagnostics, condition-based maintenance and prognostic, has been incorporated in industrial applications since the 1970s. As a typical milestone of early PHM technology, the Engine Monitoring System was applied to the A-7 in the mid 1970's. "Recently, stringent advanced diagnostic, prognostics, and health management capability requirements have begun to be placed on some of the more sophisticated new applications." [6]

The evolution of aircraft system health management technology developed by the Department of Defense (DoD) and NASA is shown below.

Table 2-1 Evolution of Health Management Technologies [7]

	DoD	NASA
1950s	• Reliability analysis • System Test and Evaluation • Quality Methods	• Reliability Analysis • System Test and Evaluation
1960s	• Modelling • Failure Analysis	• Modelling and Simulation • Failure Analysis • Telemetry of Data • Systems Engineering
1970s	• System monitoring • Reliability Centred Maintenance • Systems Engineering • Built In Test (BIT)	• System Monitoring • On-board fault protection • Redundancy management • Byzantine fault theory
1980s	• Expanded BIT • Data buses and digital processing • Engine Health Monitoring • Total Quality Management	• Expanded BIT • Data buses and digital processing
1990s	• Integrated Diagnostics • Flight Data Recording	• Diagnostics • Vehicle Health Monitoring • Vehicle Health Management • System Health Management
2000s	• Prognostics • Integrated Vehicle Health Monitoring • Integrated Vehicle Health Management	• Integrated System Health Management • Integrated System Health Engineering and Management

The table shows health management developed from system test and monitoring technologies. In the early stages, aircraft fault diagnosis relied mainly on ground testing.

However, faults could not be precisely detected due to the limitations of measurement instrumentation and methods. Some failure mode will not recur during ground operation. Modeling and simulation were applied in fault analysis from the 1960s, but aircraft testing was still carried out externally.

When BIT was employed in avionic systems in the 1970s, system monitoring and fault diagnosis was brought to an on-board stage. In the next decade, BIT techniques were incorporated into different aircraft systems. At the same time, testability, reliability and maintainability were put onto the same level as system design. Testability was considered as a separate discipline which can be seen in MLT -STD-2165 issued by United States Department of Defense in 1985.

Over the last twenty years, sensing techniques, diagnostic and prognostic methods have made significant progress. In 1993 ARINC first introduced the guidance of on-board Maintenance Systems (OMS) design. Subsequently the application of Condition-based maintenance (CBM) and PHM brought a revolution in aircraft maintenance, which was adopted in the Boeing 747-400 airplanes and F-35 respectively.

Currently, the PHM system adopted on the F-35 is a comprehensive set of diagnostics, prognostic and health management capabilities. From the architecture shown in the following figure, we can see that the PHM on the F-35 includes two parts: on-board PHM and off-board PHM. [8] The on-board PHM system provides air vehicle information monitoring and management for airframe, mission system etc. It also provides logistics support for the end-user and makes the JSF fleet communicate with the joint distribution information system (JDIS) off-board, which helps the maintainers to make decisions and plan on-ground maintenance [9].

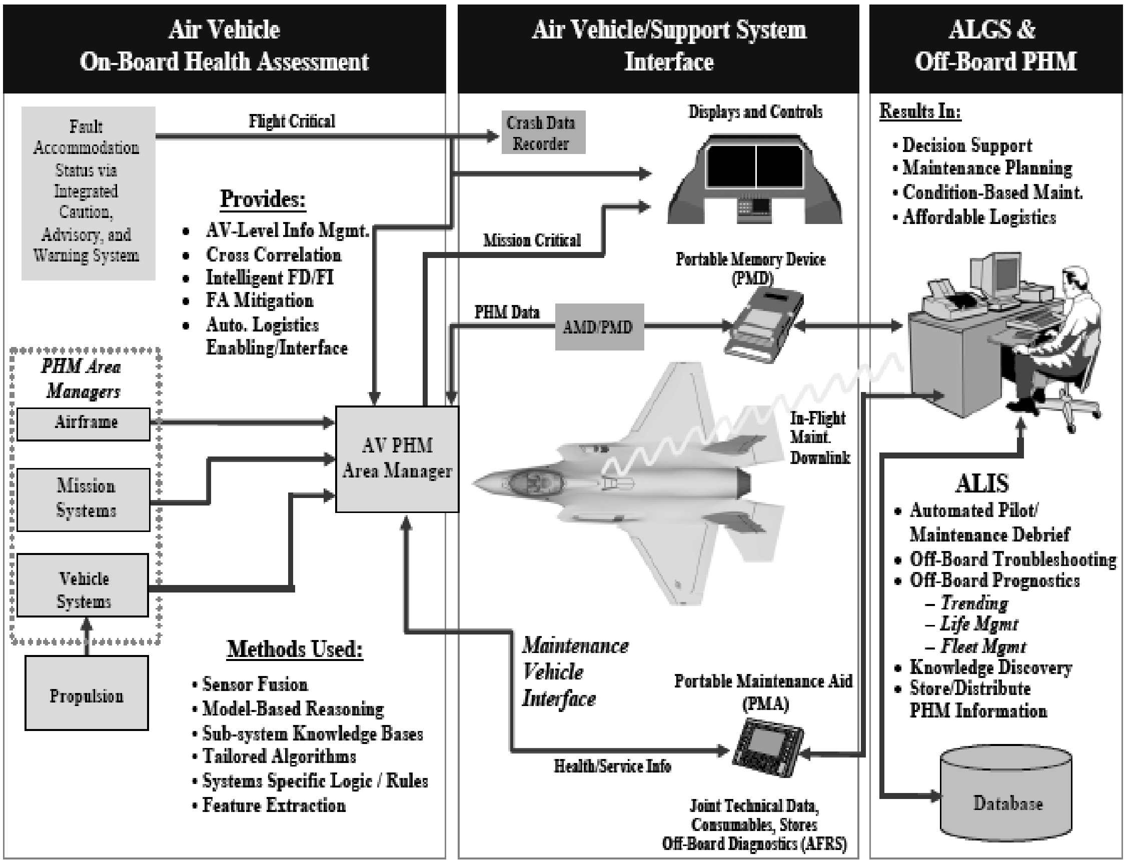


Figure 2-1: F-35 PHM Architecture [8]

2.2 PHM Function and Benefits

Generally, PHM systems incorporate functions of condition monitoring, state assessment, fault or failure diagnostics, failure progression analysis, prognostics, and maintenance support [10]. As Figure 2-2 shows, the diagnostics and prognostics are the main component of a PHM application.

Diagnosis is the process of detecting or inferring the cause of any abnormal or unexpected behaviour of a component, or a system, or the failure of an aircraft to perform its function(s) .Generally, it is based on automated detection and judgment logic. The sources of any failure or fault related to the Line Replaceable Unit (LRU) can be found by diagnosis. Diagnostic applications make use of system information from the design phase, such as FHA, FMECA, FTA and testability analysis [10].

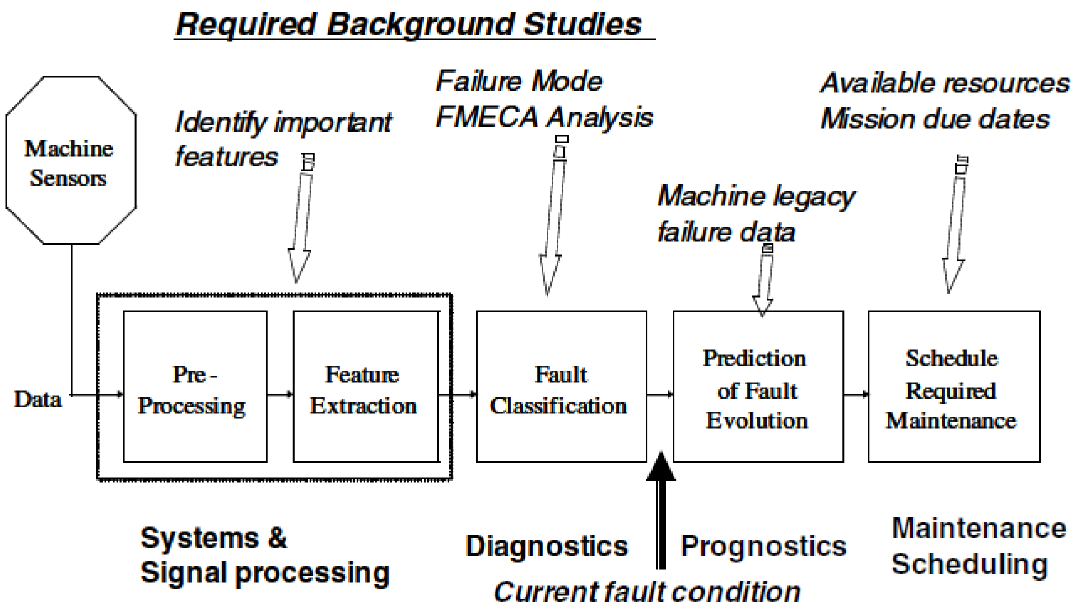


Figure 2-2 A typical PHM cycle [6]

Prognosis is the ability to predict accurately and precisely the remaining useful life of a failing component or subsystem [6]. Aircraft prognostic systems incorporate an evolution capability of on-board prediction. Compared to a ground station, data processing with on-board prognostic will eliminate the potential for data dropout or incorrect processing.

A modern and comprehensive PHM system for aircraft will greatly increase mission reliability and safety. Meanwhile, aircraft downtime will be reduced significantly due to improved maintainability. It can also be of benefit for both operational and support and life-cycle cost reduction as well as safety improvement [6].

The following lists the benefits of PHM applications:[6][11]

- Provide advance warning of system failure
- Less interruption of mission schedule
- Time saving for inspections
- Improve fault detection ability
- Make the change of maintenance philosophy: from the “On failure or per schedule” to “on condition”.
- Reduce testing equipment and ground support

- Simplify the maintainer training program
- Life-cycle cost reduction

2.3 Classification of diagnostics technologies

A typical diagnostics process can be described as in the following diagram. Firstly the system or components operational information is obtained through observation. Then the observational data is processed by comparison to the expected behavior. Finally the diagnosis result is given by the diagnostic reasoning engine.

Currently widely-used diagnostic technologies will be described individually in the following section. And there will be a comparison to discuss their particular advantages and drawbacks.

According to Ann Patterson-Hine [12], rule-based expert systems, case-based reasoning (CBR), model-based reasoning (MBR), learning systems and probabilistic reasoning are described as representative of diagnostic approaches.

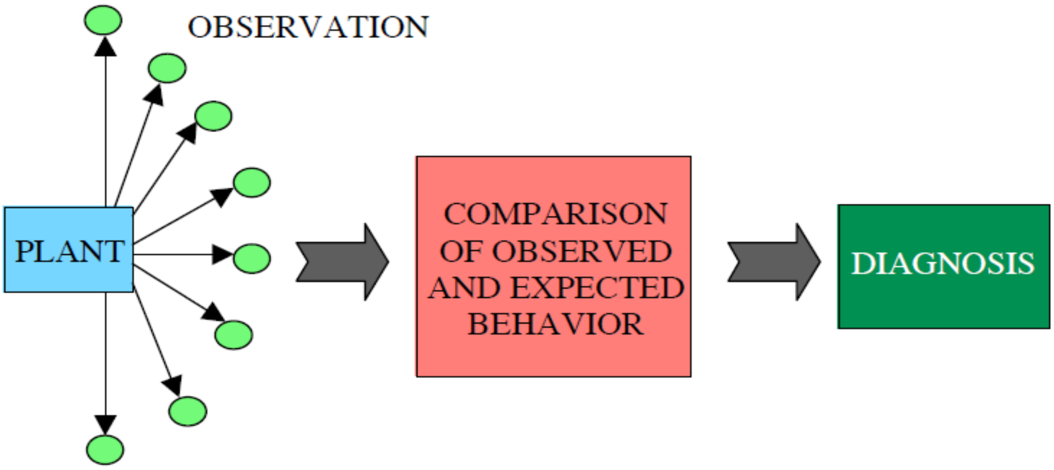


Figure 2-3 General process of diagnosis [12]

Referring to G. Vachtsevanos's book [6], the available techniques can typically be divided into two main categories: model-based and data-driven methods. As shown in Fig.2-4 [6], the model-based method can be used for unforeseen faults diagnosis but must begin with an accurate model. Although a data-driven method is normally used in detecting anticipated faults only, there is no model needed in data processing.

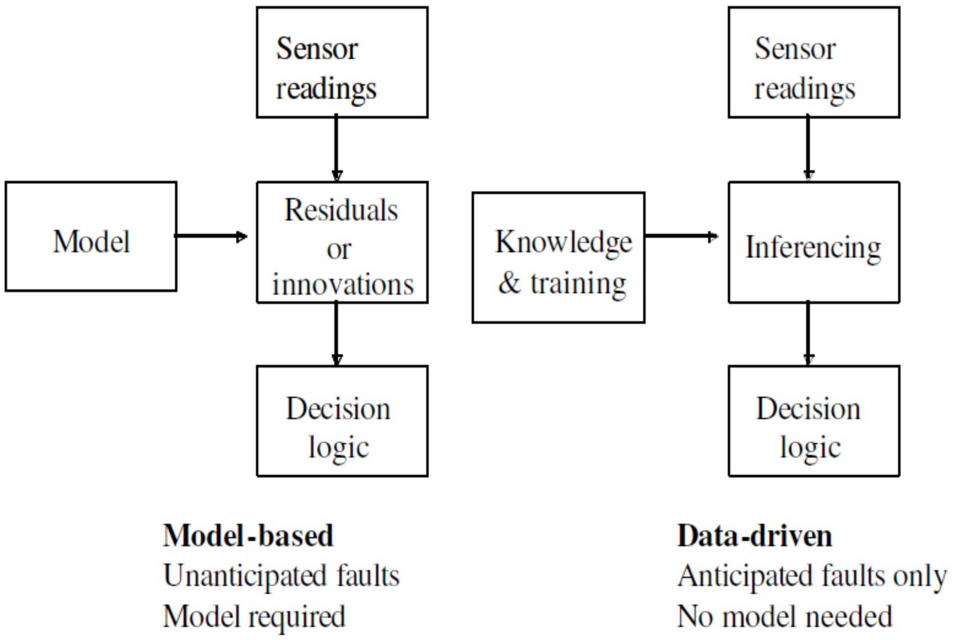


Figure 2-4 Model-based and data-driven diagnosis techniques [6]

Different authors use different classifications of diagnosis techniques. After a comprehensive consideration, a brief introduction of the following four commonly used methods will be given.

2.3.1 Rule-based Expert System

These methods are mainly used when there is a lack of specific physical properties for the diagnostic object but expertise is available from historical experiences. The “rule” used in expert system can be described simply as “if the fault symptom is observed, then action is required.” Figure 2-5 shows the reasoning chaining of rule-based expert system. If the observed facts match one established rule from the rule database, the diagnosis is simple and direct. A set of conflicts will arise when more than one rule matches. Then a pre-determined strategy will determine which rule has priority and is applied in the diagnostic results.

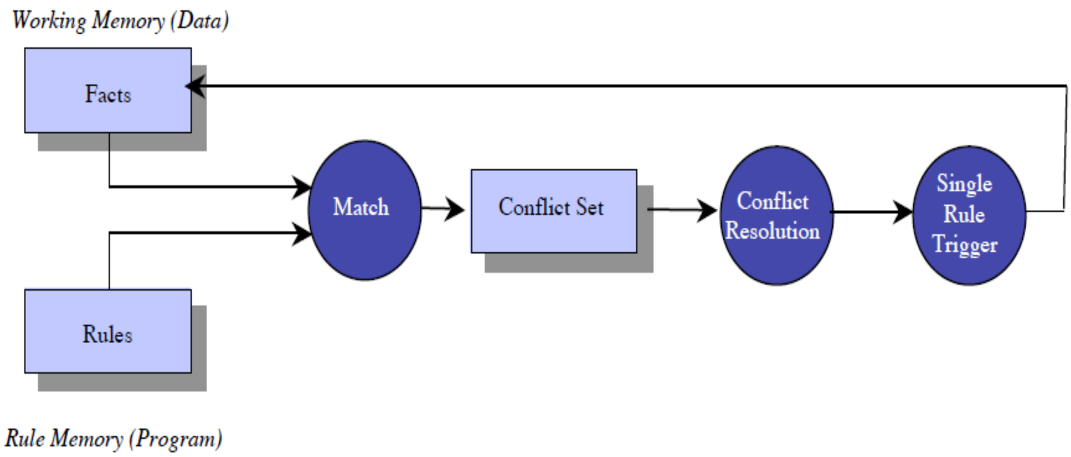


Figure 2-5 reasoning chaining of rule-based expert system [12]

2.3.2 Case-Based Reasoning

The reasoning engine of a case-based reasoning system (CBR) solves new problems by reference to solutions used in previous problems [6]. Similarly to rule-based systems, CBR utilize the experience of system behavior to build a case library. This method is mainly used in cases where the problem areas are difficult to understand. A basic CBR cycle is presented in the following chart, and the diagnostic process can be divided into four steps:

- Retrieve —— retrieve the best or the most similar past case for the new problem.
- Reuse —— attempt to solve the problem using the selected old case.
- Revise —— modify the proposed solution if it cannot solve the new problem.
- Retain —— the modified solution will be incorporated into the case-base as a new solution.

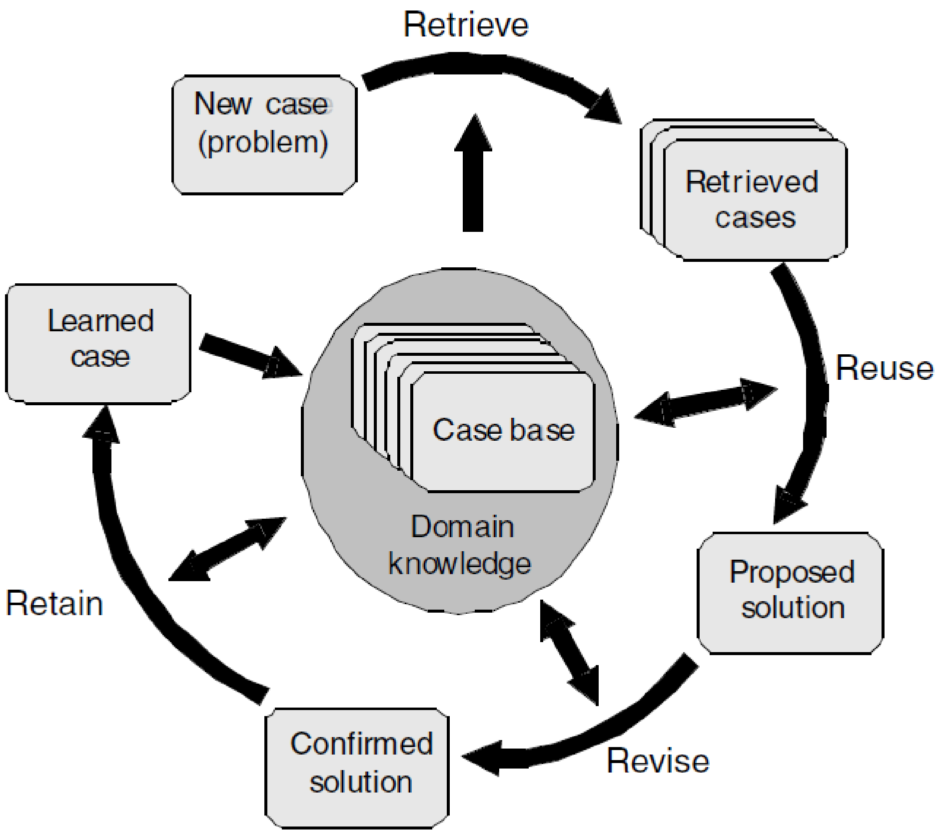


Figure 2-6 Case-based Reasoning System cycle [13]

2.3.3 Model-Based Reasoning

A model-based reasoning (MBR) system primarily detects fault symptoms by comparing the observed data with the expected data predicted by modeling. This is more suitable for dynamic systems fault diagnosis. Typically, MBR diagnostics technology can be illustrated as in figure 2-7. The input signals are processed through the physical system in parallel with the system model. Then the observed output signals are compared with the predicted signals from modeling. Discrepant result will imply the occurrence of faults.

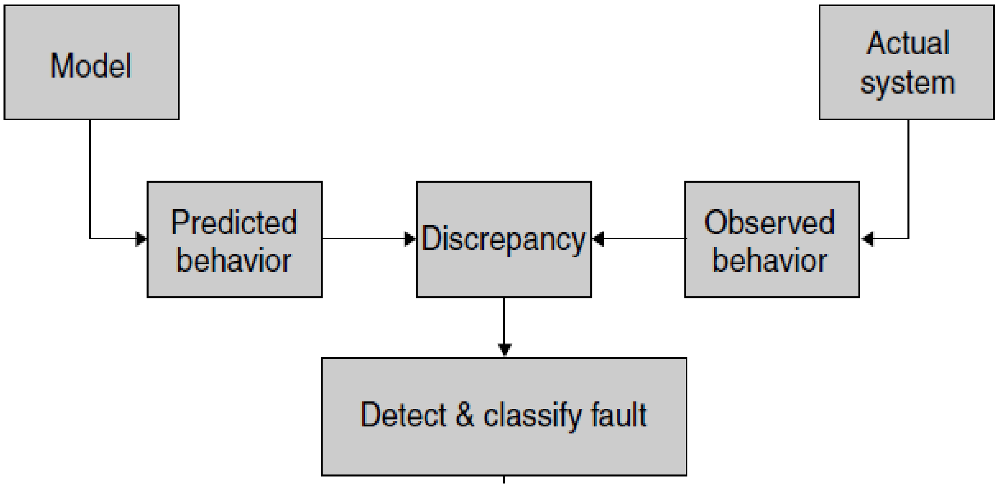


Figure 2-7 A Model-based Reasoning approach [6]

2.3.4 Learning Systems

Learning systems can be data-driven diagnosis approaches, which are derived directly from routinely system operational data. [12] In which, the characteristics of the statistical data are assumed stably, except when an unanticipated failure occurs in the system. The data-driven methods have ability to transform the high-dimensional noisy data into lower-dimensional information when fault detection and diagnosis decisions making. The main disadvantage of learning systems is that their efficacy and accuracy is highly relays on the quantity and quality of monitored system operating data.

2.4 Classification of Prognostic Technologies

Prognostics can be considered as diagnostic capabilities updates, which work to assess the current health of the system and predict its remaining life by monitoring system operating features or the results of diagnostics. Prognosis techniques are important for improving safety, mission reliability and maintainability. Currently, there are many prognostic techniques used in various industrial fields. Most prognostic methods fall into the following three categories:

2.4.1 Model-based Prognostic

The model-based prognosis techniques predict the condition of system health by checking the observed signals of the real system against the simulation results of a system model. In this case an accurate mathematical model is absolutely necessary. A typical example of model-based prognostic approach is given in Figure 2-8.

These approaches have the advantage that they have the ability to incorporate physical models into the remaining useful life (RUL) of system estimation even if there is a lack of measurable events. The accuracy of prediction will accordingly increase as the system degradation features understanding improves.

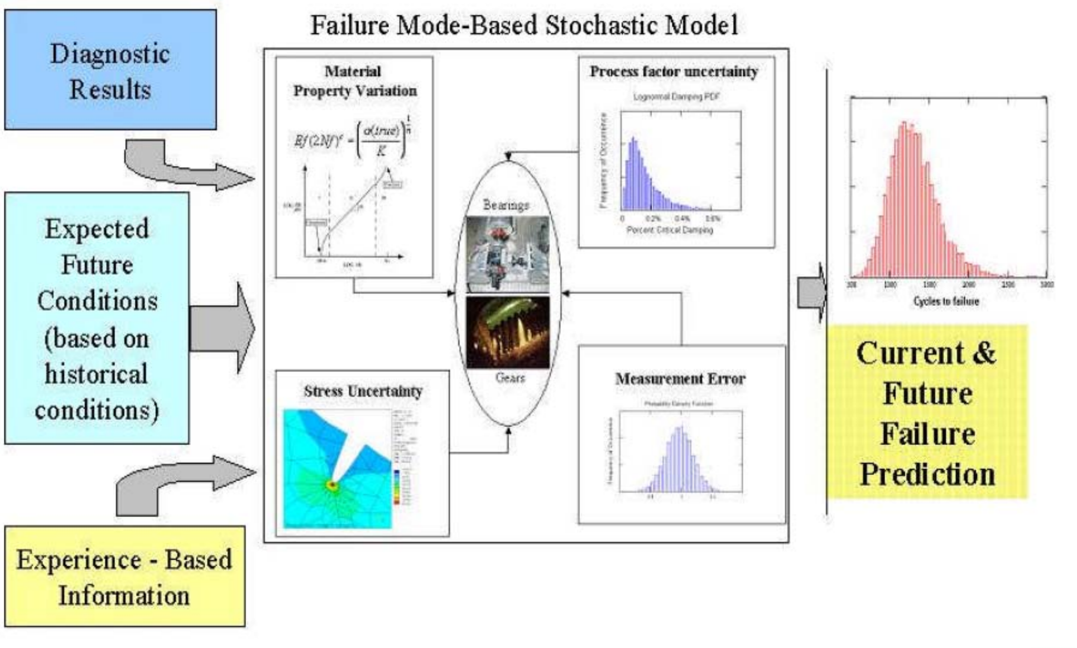


Figure 2-8 A typical example of Model-based prognostic approach [15]

2.4.2 Probability-based Prognostics

Probability-based prognosis methods establish the change in parameters and the probability of failure damage model through historical data, and then determine the system health status and trend analysis by comparing the detected abnormal key parameters with that of the current probability space of multi-parameter state .Compared to the model-based methods which rely on mathematical equations, less information required in probabilistic-based prognosis which is based on various probability density functions (PDFs). Meanwhile, these PDFs are easily abstracted by statistics from experimental or historical data. Figure 2-9 illustrates the schematic diagram of this method.

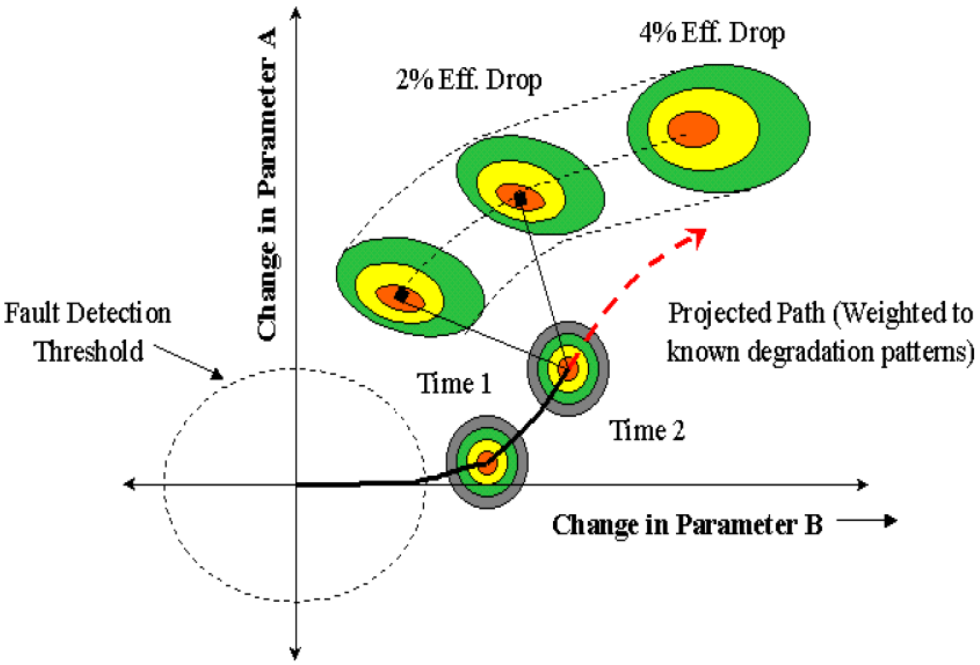


Figure 2-9 Probability-based prognostic approach [16]

2.4.3 Data-driven Prediction Approach

Data-driven methods are used in some situations where the prediction model is not easily established through statistical data or it is too expensive to do so. In such cases, a nonlinear network approach provided by Data-driven prognostic can produce the required output data. Nonlinear networks mainly include the neural network and fuzzy-logic systems.

Artificial neural network (ANN) is an interconnected group of nodes that maps complex features or fault indicators to their respective fault modes [6]. This is an artificial intelligence technology inspired by the function and structure of biological neural networks [14]. ANN tools are usually applied in non-linear statistical data modeling as they can model complex relationships between inputs and outputs.

A typical fault prognosis scheme by ANN is shown in Fig.2-10. Compared to single direction or simple layer logical prognosis, ANN is better at multi input and output and systems prognostics even those which have multi-directional feedback. Overall, algorithms are used to determine how the function is organized in the system programme. Meanwhile, artificial neural networks have the ability to become learning systems which can be self taught by rule base or learned from input.

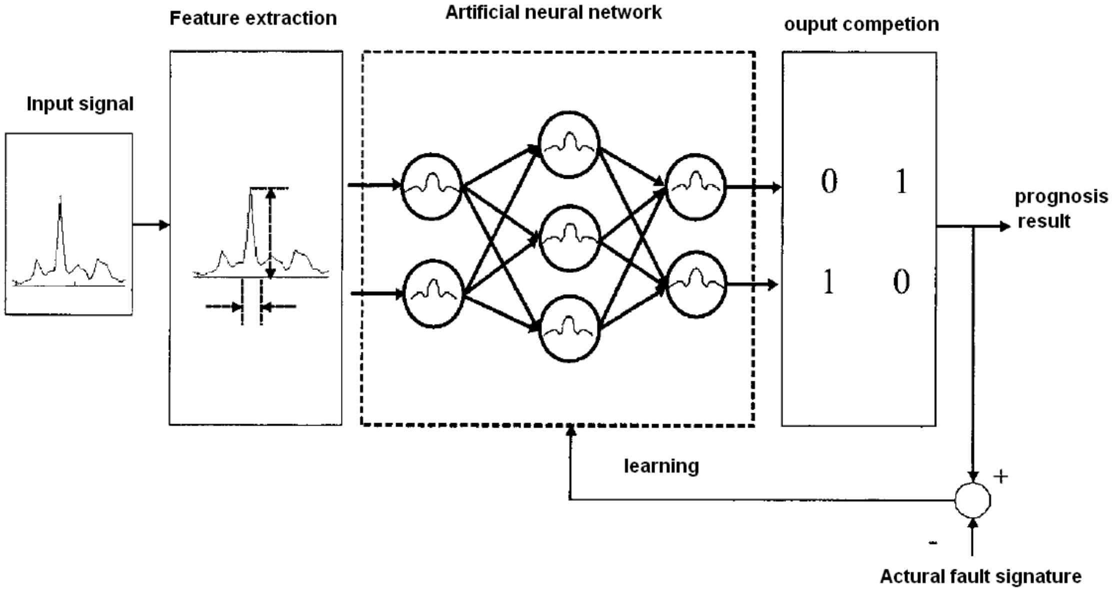


Figure 2-10 The ANN prognostic paradigm [6]

The main advantage of data driven approaches is that they can often be applied more quickly and cheaply than other methods. The main disadvantage is that there are greater demands of data training before employing a prognostics approach.

2.5 Summary

A set of diagnostic methods and prognostic approaches has been described in the previous section. Each method has its own advantages in some areas while having drawbacks in other fields. For diagnostics, the advantages and disadvantages of each method have been summarized as shown in table 2-2.

Table 2-2 Advantages and disadvantages of diagnostics methods [17]

Diagnostics Approaches	Advantages	Disadvantages
Rule-based expert system	Increased reliability for diagnostic decision making	Coverage of domain knowledge
Case-based reasoning system	Use past problems in case library to solve current problems	Hard to obtain a new completeness of case base
Model-based reasoning system	Efficient and accurate in linear dynamic systems	Less effective with non-linear complex behavior
Learning systems	Lower the dimension of noisy data and provides the monitoring	Requires long term historical data record

For prognostic approaches, the range of system applicability and the cost of applying different methods are illustrated in Figure 2-11. As the accuracy of the different prognostics methods improves, the scope of application decreases and the costs increase.

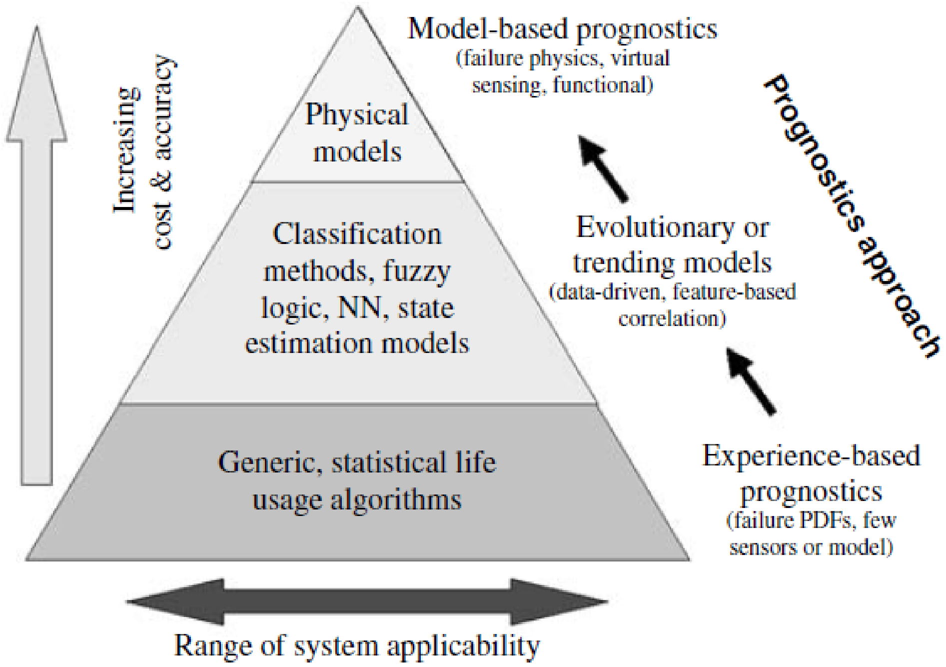


Figure 2-11 Prognostic technical approaches [6]

3 Hydraulic Power System Functional and Failure Modes Analysis

According to the research objectives, a hydraulic power system will be designed in preliminary phase for the FW-11 aircraft which has been finished the conceptual design in the GDP. All research in this thesis is based on this hydraulic system. In this chapter, hydraulic power system architecture and functional description will be given firstly. Then a set of safety analyses for this system will be performed in order to ascertain the critical components and their associated parameters.

3.1 FW-11 Hydraulic Power System Design

The FW-11 aircraft is a designed as a next generation new configuration airliner, with a range of 7500nm and 250-seat capacity. The maximum take-off weight and range are similar to the Airbus 330 and Boeing 767-200ER. To compete with those aircraft, the FW-11 adopts a new configuration and new technology to make it more competitive. A hydraulic power system is defined as a secondary power system, in which, pressurized fluid is used to drive actuation mechanisms, thus providing a source of energy to the user system. PHM technology application in the hydraulic system will provide better maintainability and reduced operating costs.

3.1.1 Design Requirement

The FW-11 is a twin-engine flying wing airliner which will be in service in the 2020s. As an indication of future trends it can be seen that more-electric systems will be applied on aircraft such as the B777 and A380. These requirements together with the type of aircraft, determine the design of a hydraulic system. [25] The following three aspects are considered for the design requirement in this phase:

a) Safety and reliability consideration

For safe flight, three channel subsystems ensure that the hydraulic system includes sufficient redundancy. Meanwhile, the hydraulic power system design for FW-11 needs to meet the airworthiness requirements of FAA, EASA and CAAC. [22][23][24]

b) Functional requirements

Hydraulic power is widely used for a variety of functions in most aircraft today, such as flight controls, undercarriage operating mechanical, braking and gear steering mechanisms. The control surface configuration of FW-11 is shown in Figure 4-1. As a more-electric aircraft, the GDP work assumes that the flaps and wheel brake use electric power. Electrical-Hydrostatic Actuators (EHAs) or the Electromechanical Actuators (EMAs) are employed for flaps control. The conventional hydraulically actuated brake system is replaced by an E-Brake Suite, which operates with electro-mechanically actuated brakes and electronic motor actuation control units. [31]

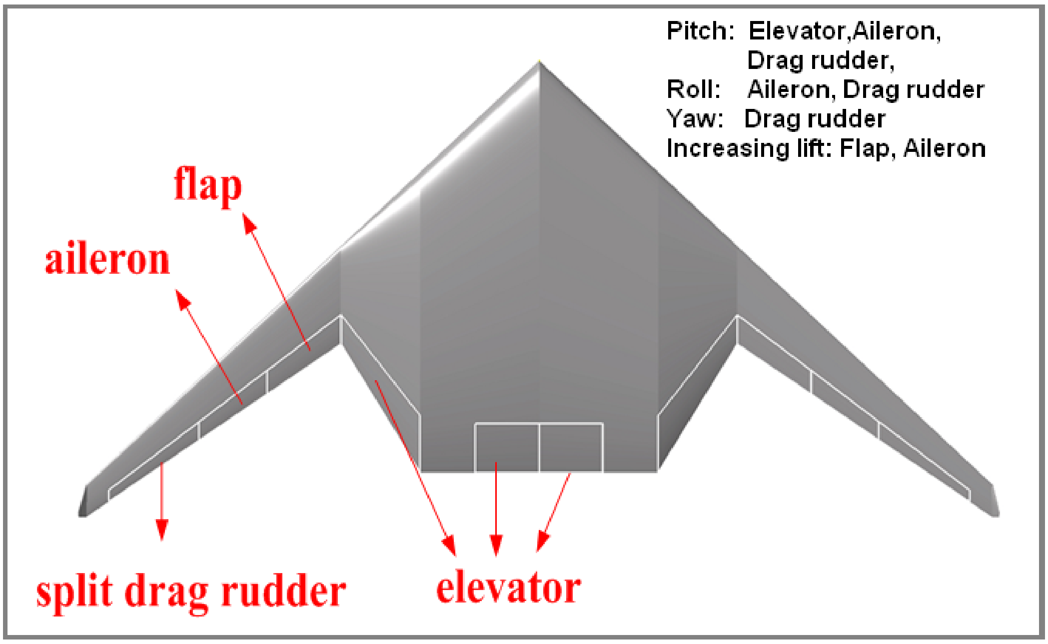


Figure 3-1 FW-11 control surface

At present, the functions which need be powered by the hydraulic system are as follows:

- Flight controls
    - Aileron
    - Split Drag Rudder
    - Elevator
- Utility systems
    - Landing Gear
    - Nosewheel steering

- Thrust Reversers
- Cargo doors

c) Economical efficiency consideration

The FW-11design aims to provide enhanced economical efficiency in future civil aircraft markets. Higher pressure can significantly reduce component-size which in turn means significant weight saving.

3.1.2 Hydraulic System Architecture

After comprehensive consideration, the hydraulic power system schematic is depicted in Figure 3-2.

There are three independent sub-systems (LEFT, RIGHT and CENTRE) in the FW-11 aircraft hydraulic power system. The three systems operate continuously and power the customs at a pressure of 5000 psi.

The LEFT or RIGHT system is pressurized by one Engine Driven Pump (EDP) and one Electric Motor Pump (EMP).In the Centre system, two large power EMPs operate as the main power resource instead of ADP used in previous planes. In an emergency condition, a Ram Air Turbine (RAT) provides hydraulic power for Centre system services.

The detail schematics for each sub-system is represented in Figure 3-3 and 3-4.

Table 3-1 expresses the main components of this hydraulic power system.

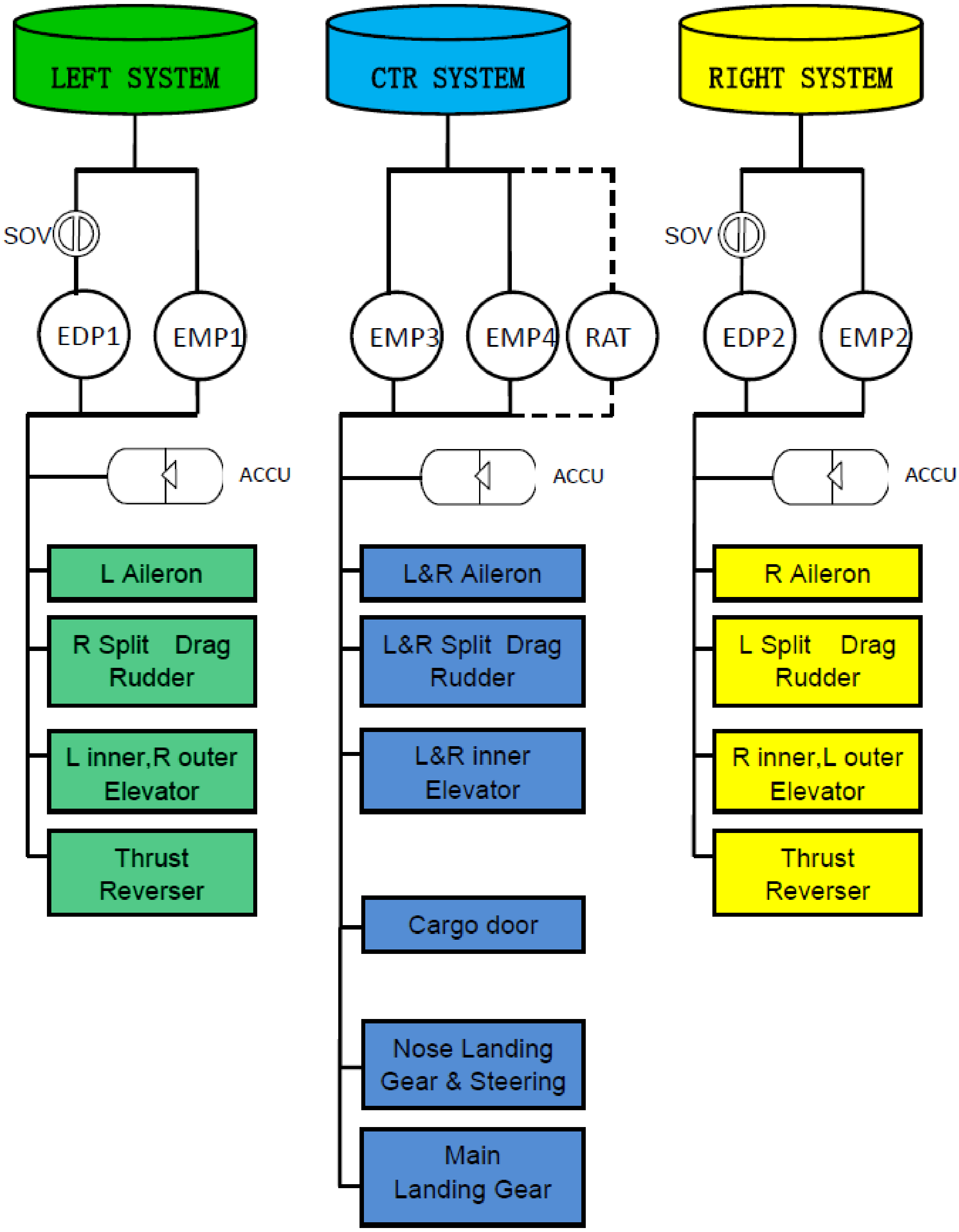


Figure 3-2 FW-11 Hydraulic System Functional Diagram

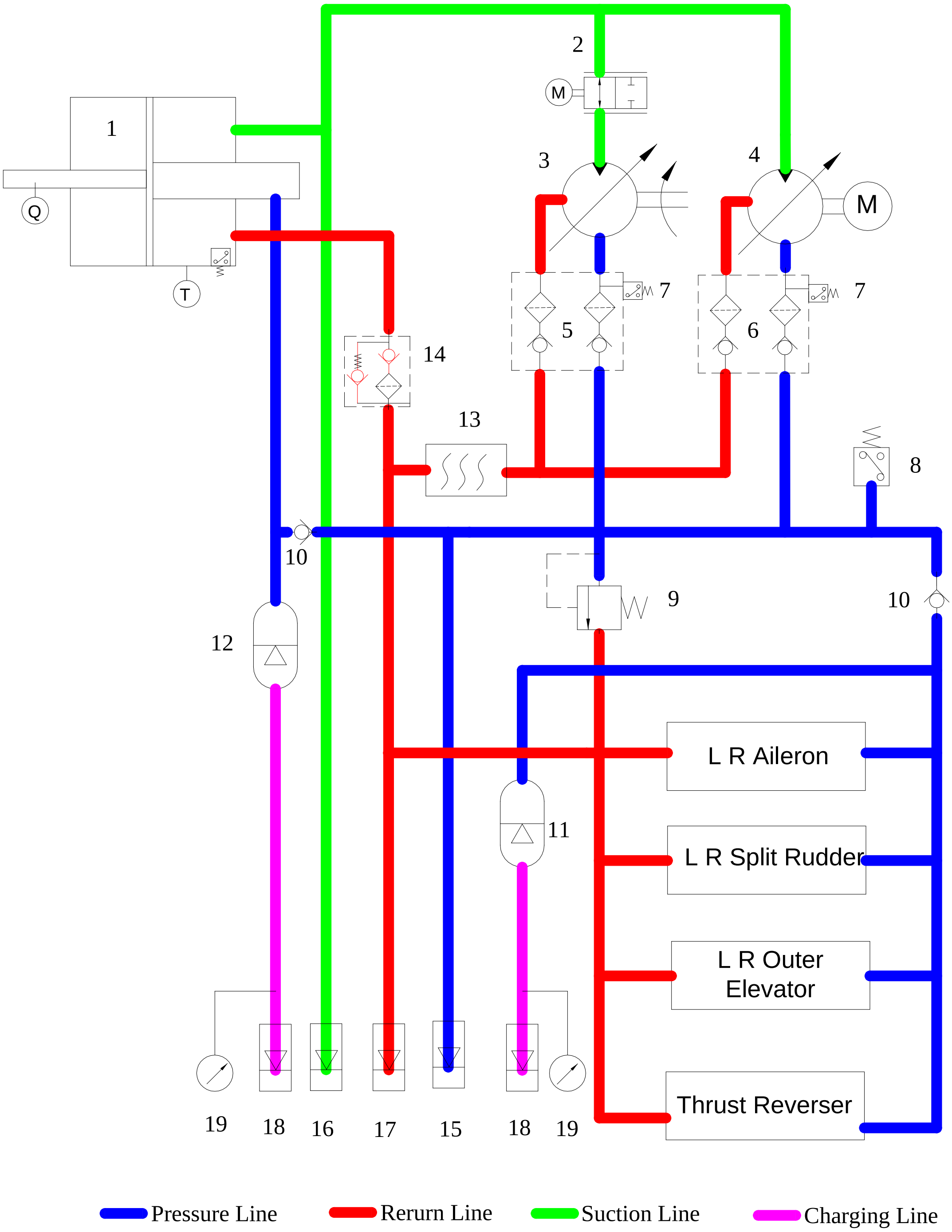


Figure 3-3 LEFT or RIGHT hydraulic power system schematic

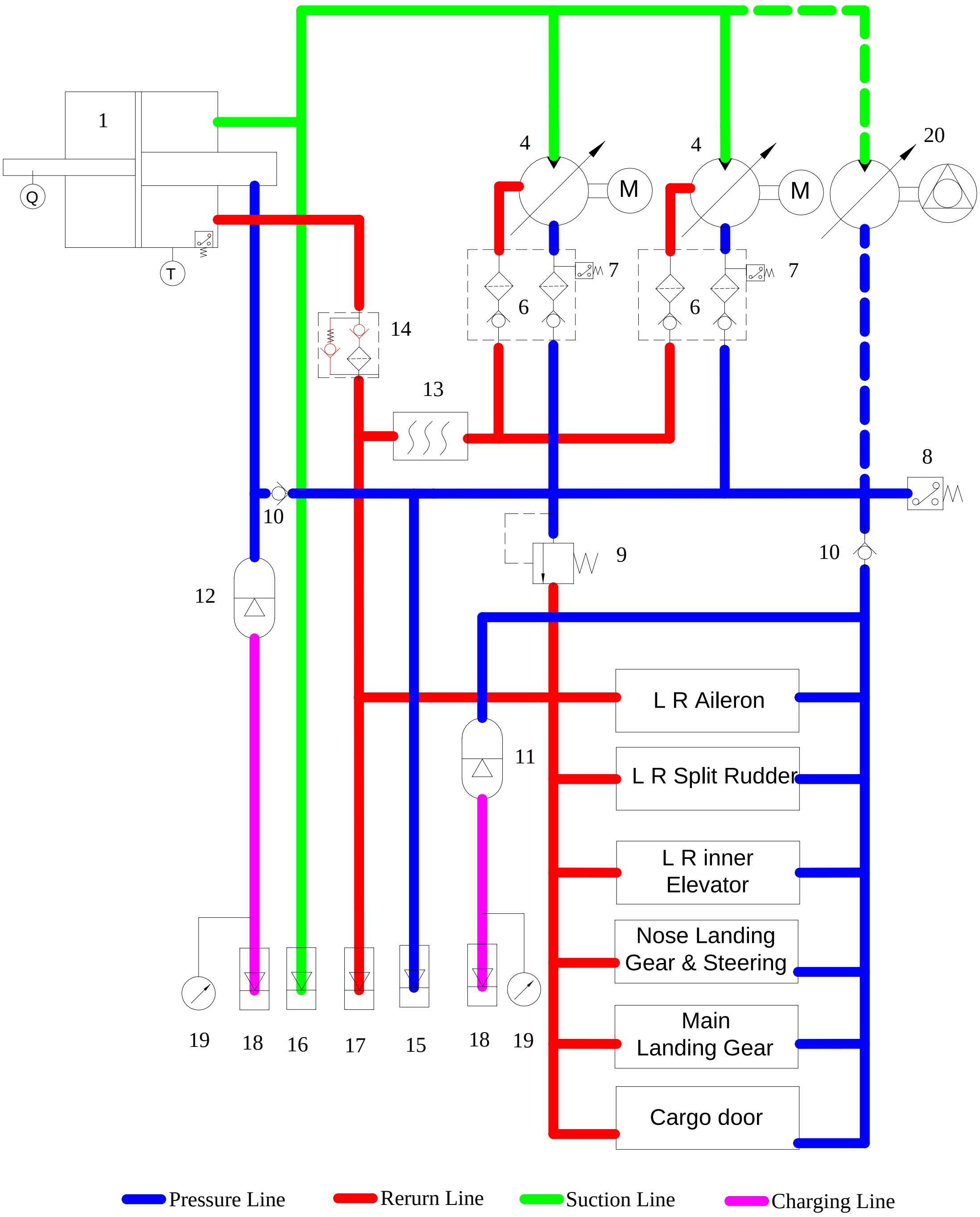


Figure 3-4 CENTRE hydraulic power system schematic

Table 3-1 Hydraulic power system components list

Item	Components	Item	Components
1	Hydraulic Reservoir	11	System Accumulator
2	Fire Shut-off Valve	12	Reservoir Pressure Accumulator
3	Engine Driven Pump	13	Heat Exchanger
4	Electric Motor Pump	14	Return Filter Module
5	EDP Pressure and Case Drain Filter Module	15	Ground-Pressurization Connection
6	EMP Pressure and Case Drain Filter Module	16	Ground-Suction Connection
7	Low Pressure Switch	17	Filling Connection
8	System pressure sensor	18	Ground- charging Connection
9	System relief valve	19	Pressure Gauge
10	Check valve	20	Ram Air Turbine

3.1.3 Hydraulic Power System Functions

In the LEFT and RIGHT system, the EDPs work continuously when the engines are operating. The EMP works as a backup hydraulic power source for the EDP. The EMP starts when system pressure is low, or when control logic anticipates a high system flow demand especially during take-off and landing phases. Two EMPs in the CENTRE system work alternately and backup each other during every flight. The electric pumps in all systems can provide hydraulic pressure on ground when all engines are off.

The pumps receive pre-pressurized fluid from reservoirs. Pump fluid output flows through pressure filter module to the services. Reservoir fill fluid and system return fluid flow through the system return filter and then to the reservoir. Case drain fluid flows to the case drain module, through the heat-exchanger to the system return filter and then returns to the reservoir. A differential pressure indicator on either filter indicates filter contamination.

Fuel-hydraulic heat exchangers are located in collector tanks for case drain fluid cooling.

A hydraulically pressurized reservoir is used in each system to store fluid, which can maintain the pressure of pumps input flow at all altitudes. A temperature sensor and reservoir low level sensor are also installed, and are located at the correct level to provide a warning message.

A System Accumulator is placed in the pressure circuits of each system. This can maintain the system pressure for a short period in the event of drops in the system pressure caused by flow demands beyond maximum displacement. A Reservoir Pressure Accumulator is placed in the reservoir pressure line to pressurize fluid in the reservoir.

There is a Fire Shut-off Valve in the suction line of each EDP. Normally the valves are open. Closing the fire shut-off valve prevents hydraulic fluid from flowing into the pump and hence sustaining a fire.

A System Pressure Relief Valve will open in the event of an increase in system pressure to a dangerously high level. Upon relief valve opening, fluid is ported to return line.

The RAT can be deployed automatically or manually in flight and must be retracted on the ground.

Low pressure switches, located in each pump output line, provide low pressure signals when relative pump output pressure is low. A System pressure transmitter sends the combined pressure of the EDP and EMP to the related hydraulic power system indication. All signals detected by sensors or probes are sent to a Hydraulic System Management Unit (HSMU) which process signals and communicates the relevant information through data bus.

3.2 Hydraulic Power System Functional Hazard Assessment

3.2.1 Introduction

The following paragraphs give a Functional Hazard Assessment (FHA) for the hydraulic power system architecture. The designed hydraulic power system is required to provide hydraulic power to all system users during aircraft operation, and to meet other design safety objectives compatible with the development of the aircraft level requirements. The purpose of this part is to perform a systematic and comprehensive examination of the function of the hydraulic power system, and to identify all the failure conditions caused by malfunction, failure to operate, or as a normal response to any unusual or abnormal external factor.

The FHA also provides a starting point for more in-depth Failure Modes, Effects and Criticality Analysis (FMECA) and related analyses, which in turn provide the data on fault symptoms needed to test the system. The FHA table is constructed according to SAE ARP 4761[26].

3.2.2 Failure Condition Severity and Effect Classifications

To measure the worst potential effect caused by product failures, the severity of every potential failure mode shall be classified. The severity classification describes a standard for the worst potential result from the product failure. Table 3-2 lists the failure condition severity and qualitative effect classifications used in this thesis. A more user friendly quantitative definition for failure condition severity is expressed in table 3-3.

Table 3-2 Failure Condition Severity and Effect Classifications [2]

Failure Condition Severity	Failure Condition Effect
Minor	Failure conditions that would not significantly reduce airplane safety and which involve crew actions that are well within their capabilities.
Major	Failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or some discomfort to occupants.
Hazardous	Failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be: I - A large reduction in safety margins or functional capabilities; II - Physical distress or higher workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or III - Serious or fatal injury to a relatively small number of the occupants.
Catastrophic	All failure conditions which would prevent continued safe flight and landing.

Table 3-3 Overview of failure classification and safety objectives [25]

Failure condition classification	*Development assurance level*	*Safety objectives*	*Safety objectives quantitative requirement (probability per flight hour)*
Catastrophic	A	Required	$< 1 \times 10^{-9}$
Hazardous/Severe	B	May be required	$< 1 \times 10^{-7}$
Major	C	May be required	$< 1 \times 10^{-5}$
Minor	D	Not required	None
No safety effect	E	Not required	None

3.2.3 FHA Summary

The detailed analysis of functional failure conditions, flight phases, effect of failure condition and hazard class for the hydraulic power system is presented in Appendix B. Because the catastrophic and hazardous events will greatly influence the flight safety and system performance, the failure condition related to these two classes of severe events shall be pointed out for the next step research purpose. The table below summarizes the failure condition the severity of which is catastrophic or of hazardous class.

Table 3-4 Hydraulic power System Severe Failure Condition Summary

Failure Condition	**Severity**
Loss of all hydraulic power supply	Catastrophic
Loss of low-pressure warning when LEFT, RIGHT and CENTRE hydraulic power subsystem failure	Catastrophic
Loss of low-pressure warning when any two hydraulic power subsystem failure at take-off or landing	Hazardous
Loss of ability to shut off EDP suction flow in case of fire	Hazardous

From the above table, it can be seen clearly that "loss of all three hydraulic power systems together" or "loss of ability to shut off EDP suction flow in case of fire" will have a serious effect on aircraft safety. Therefore, the research work will pay particular attention to analysing these failure conditions.

3.3 Hydraulic Power System FMECA

3.3.1 Introduction

In the following sections, a Failure Mode, Effects and Criticality Analysis (FMECA) will be presented for the hydraulic power system. FMECA is an important method of system reliability analysis, and is also the basis of maintainability analysis, safety analysis and testability analysis. It is an inductive analysis of all possible failure modes of system, components, or functions and their possible effects, and determines the rank of each failure mode according to the severity of effects on aircraft and the probability of occurrence.

An FMECA is a systematic, bottom-up approach that traces the effects of crucial component failures through the system. [26] Usually, the purposes of FMECA include the following two elements:

a) Failure modes and effects analysis (FMEA)

It is used to identify all possible failure modes, causes and effects of the product, so as to detect weaknesses of design cycle and take compensatory measures for design improvements.

b) Criticality analysis (CA)

The CA is an extension or supplement of the FMEA and is based on the FMEA result. In order to give a comprehensive evaluation of the effects in all possible failure modes, each failure mode is classified based on the combined effect of severity and probability of occurrence.

3.3.2 FMECA Approaches and Process

FMECA analysis should be carried out simultaneously with system design. At the conceptual design phase and the early stage of the preliminary design phase, analysis is functional and FMECA mainly focuses on the composition of the system functions. When it comes to the detailed design phase, a hardware or software FMECA should be carried out based on each component in the system with several functions. In terms of the FW-11 aircraft hydraulic power system, a combination of the functional and hardware FMECA will be considered in this research.

Typically, a FMECA process can be described as the flowchart in Figure 3-5:

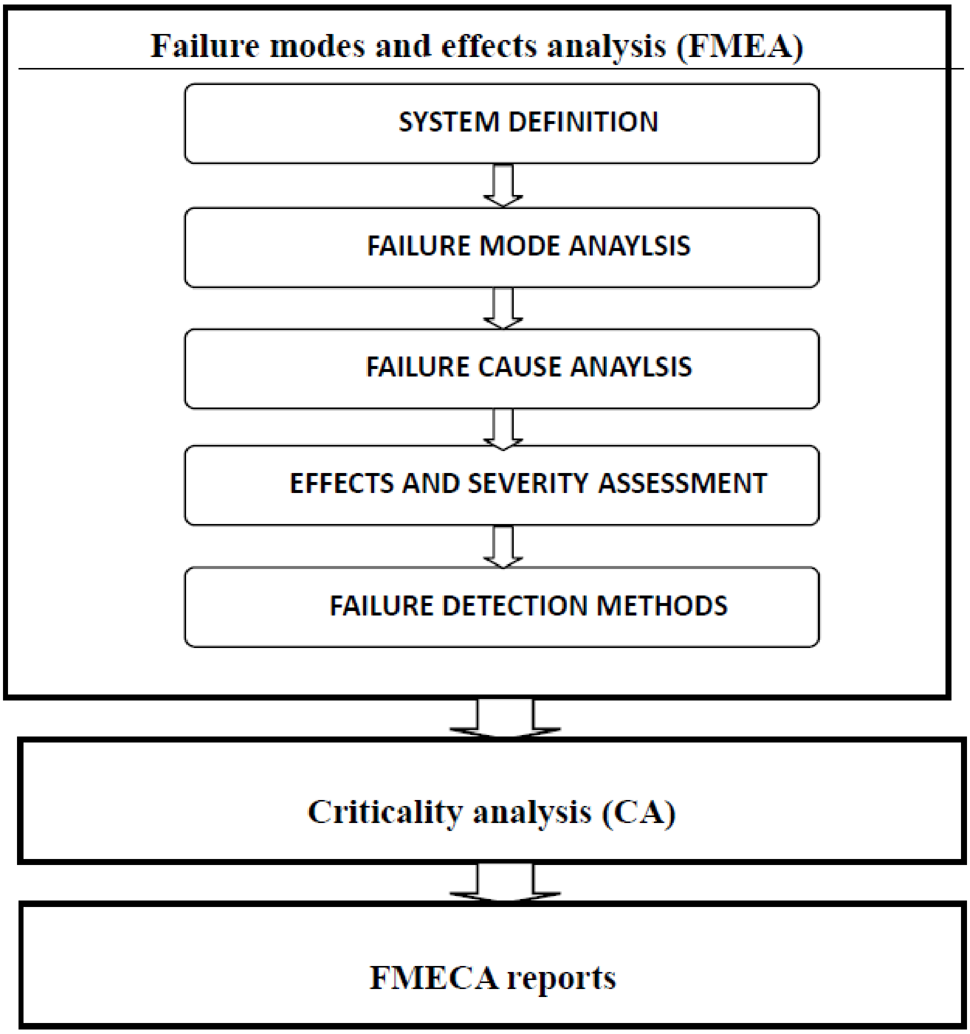


Figure 3-5 FMECA process

The FMECA process starts with system definition, which consists mainly of the system function description and drawing a scheme diagram [27]. The system functions should be identified for various mission phases simultaneously. Then each failure mode should be analyzed based on the functional analysis in different operational modes. The failure mode shall be presumed as the only failure in the complex system in each analysis process. Failure cause analysis aims to identify the causes of each failure mode, which will help in taking appropriate measures for design improvement. For each possible failure mode, the effects on the system level and aircraft level need be analyzed. Failure Severity classifications should be determined by the ultimate impact of each failure mode.

Criticality Analysis (CA) aims to classify the combined effects according to the severity and probability of occurrence for each failure mode, in order to give a comprehensive evaluation of all the effects of possible failure modes. The CA normally has a qualitative approach and a quantitative approach. The first is suitable in cases where there is insufficient failure rate data while the quantitative approach is suitable where failure rate data is available [28]. As the failure rate data cannot be acquired at the conceptual design phase of the FW-11 aircraft, the qualitative approach is chosen in this analysis.

Finally, a FMECA worksheet is completed and is the core of FMECA report. Typically, a FMECA worksheet should include the following elements:

a) The identification and the function(s) of the components

b) A list of failure modes description of function or hardware

c) Failure effects on system level and aircraft level

e) Means available for failure detection

f) The flight phase when the failure occurs

g) Failure severity level

3.3.3 FMECA Summary

The FMECA work should be continued during the whole aircraft design process and be updated in different design phases repeatedly. A combination of the functional and hardware FMECA analyzed in this research based on the preliminary architecture of the FW-11 hydraulic power system. The result of the FMECA is given in Appendix C.

3.4 Hydraulic Power System Fault Tree Analysis

3.4.1 Introduction

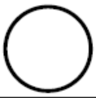
After the failure conditions are indentified in the FHA and FMECA, a Fault Tree Analysis (FTA) is described for the hydraulic power system in this section. An FTA is a deductive analysis which focuses on one particular undesirable event and provides a method for determining causes of this event. It is a “top-down” evaluation process in which an undesirable event is formed into a qualitative logical model. [26] All credible failures in next level may cause the top level undesired event should be determined in fault tree step by step.

In this research, each catastrophic and hazardous failure condition should be analyzed by FTA based on the FHA and FMECA results.

3.4.2 Definition of FTA symbols

A fault tree uses a set of Boolean logic symbols to describe the relationship between causes and the top events caused by basic failure modes. The definition of common logic symbols is illustrated in Table 3-5.

Table 3-5 Definition of FTA symbols [26]

Symbol	Name	Definition
	Description Box	Description of an output of a logic symbol or of an event
	AND-gate	Boolean logic gate - event can occur when all the next lower conditions are true
	OR-gate	Boolean logic gate - event can occur if any one or more of the next lower conditions are true
	Basic event	Event which requires no further development
	Transfer	Indicates transfer of information

3.4.3 FTA Probability Calculation

Probability calculation aims to produce a quantitative result to the fault tree analysis. Boolean algebra is used to calculate the probability of a top event for such a complex system.

The basic event probability calculation can use the following mathematical equation:

$$P = 1 - e^{-\lambda t} \quad \text{.............................. Equation 3-1}$$

$$\lambda = 1/MTBF \quad \text{..............................Equation 3-1}$$

$$R = 1 - P \quad \text{................................ Equation 3-2}$$

Where P is the probability of failure, λ is the failure rate of the component associated with statistical data, MTBF is the abbreviation of Mean Time between Failures and t is the time interval, such as exposure time or miss time. R refers to probability. [29]

The output event probability of a gate is based on the probability of an input event. The AND gate output is given by:

$$P(A \text{ and } B) = P(A \cap B) = P(A)\,P(B) \quad \text{............Equation 3-4}$$

An OR gate output event probability can be calculated as follow:

$$P(A \text{ or } B) = P(A \cup B) = P(A) + P(B) \quad \text{.........Equation 3-5}$$

3.4.4 FTA Summary

The detailed hydraulic power system fault tree architecture is presented in Appendix D. The root causes of each catastrophic or hazardous failure condition are located at the LRU level which is achieved the required diagnostic purpose. According to the FTA results, it can be see that any catastrophic occurrence cannot be caused by a single failure. Generally, the architecture of the hydraulic power system is reasonable in this phase. However, the basic events failure rate cannot be obtained at this design phase. The calculation will be updated when reasonable parameters can be obtained in detail design for future work.

3.5 Summary

In this chapter, a hydraulic power system is designed initially for the FW-11 aircraft as the case of this research. Then the key parameters and crucial components are identified from the analysis results of FHA, FMECA and FTA. Based on these analysis results, the crucial components that may lead to catastrophic or hazardous failure are identified and the key parameters and detection methods can be obtained. The detailed information is shown in following tables:

Table 3-6 FHA, FMECA and FTA results

<table>
<tr><th colspan="3">Failure condition</th></tr>
<tr><td colspan="3">Loss of all hydraulic power supply</td></tr>
<tr><th>Severity</th><th>Related component</th><th>Failure detect method</th></tr>
<tr><td>Catastrophic</td><td>EMP, EDP, Reservoir, Relief Valve, Return filter, RAT,</td><td>Low pressure switch
System Pressure sensor
EPS information</td></tr>
<tr><th>Parameters</th><td colspan="2">pressure signal, Reservoir fluid quantity, electrical power signal, filter contamination indicator signal, temperature signal</td></tr>
<tr><th colspan="3">Failure condition</th></tr>
<tr><td colspan="3">Loss of low-Pressure warning when LEFT, RIGHT and CENTRE hydraulic power subsystems failure</td></tr>
<tr><th>Severity</th><th>Related component</th><th>Failure detect method</th></tr>
<tr><td>Catastrophic</td><td>Low pressure switch
System Pressure sensor</td><td>HSMU</td></tr>
<tr><th>Parameters</th><td colspan="2">Low pressure switch test signal, System Pressure sensor test signal</td></tr>
<tr><th colspan="3">Failure condition</th></tr>
<tr><td colspan="3">Loss of low-pressure warning when any two hydraulic power subsystems failure at take-off or landing</td></tr>
<tr><th>Severity</th><th>Related component</th><th>Failure detect method</th></tr>
<tr><td>Hazardous</td><td>Low pressure switch
System Pressure sensor</td><td>HSMU</td></tr>
<tr><th>Parameters</th><td colspan="2">Low pressure switch test signal, System Pressure sensor test signal</td></tr>
<tr><th colspan="3">Failure condition</th></tr>
<tr><td colspan="3">Loss of ability to shut off EDP suction flow in case of fire</td></tr>
<tr><th>Severity</th><th>Related component</th><th>Failure detect method</th></tr>
<tr><td>Hazardous</td><td>Fire Shut-off Valve</td><td>Low pressure switch
Engine FEDAC
EPS information</td></tr>
<tr><th>Parameters</th><td colspan="2">Valve status signal, EDP outlet pressure, electrical power signal</td></tr>
</table>

4 Diagnostics Research for a Hydraulic Power System

The diagnostic approaches which are one of the main functions of DPHM techniques will be discussed in this chapter. Based on the characteristics of different diagnosis methods which have been introduced in the literature review chapter, Case-based reasoning (CBR) is first selected for hydraulic power system diagnosis. Then a generic CBR diagnosis process and structure are presented in depth. Based on the features of hydraulic power system failures, suitable diagnosis architecture for the hydraulic power system was built. Finally, a case study for a common failure mode is presented to demonstrate how CBR diagnostic works.

4.1 Choice of Diagnostic Methods

Rule-based expert systems diagnose faults by matching the observed symptoms to failure hypotheses stored in a rule base. The rule-based method is widely used as it can reduce the cost by increasing the availability and reusability of the expertise acquired, its quick response and by increasing the reliability of decision making. However, it's difficult to completely translate domain knowledge into a large amount of terse rules for a complex system. And there are challenges in managing a large rule base and maintaining accuracy over the life cycle.

Model-based reasoning (MBR) systems detect fault symptoms by comparing the observed data with the expected data as indicated by modelling. The MBR diagnostic process heavily depends on the mathematical model of objective systems. The efficiency and accuracy of this method is significant when used for a linear system whereas for a complex system, building a comprehensive diagnosis model seems impossible. There always lack of parameters for modelling at the beginning of system design, so the MBR approach cannot be applied at the preliminary phase. In addition, the cost of an MBR application is higher than that of other methods.

Learning systems have ability to detect faults and diagnose failure by identifying the noise of monitored system operating data. However, the efficiency and accuracy are highly relay on the quantity and quality of monitored data, which means the learning systems require long term historical data record.

A case-based Reasoning (CBR) approach solves current problems by reference to solutions applied to past problems. For an aircraft hydraulic power system, a great amount of experiential failure data from historical maintenance information is available. Of course, CBR is also deficient in the establishment of a complete case base while compared to a rule-based system the case revision processes in CBR mean it has a partial learning capability. Furthermore, it can work well in some problem areas which are poorly understood.

In summary, for a comprehensive consideration, case-based Reasoning system is much more suitable for an aircraft hydraulic power system PHM application. A detailed research into the CBR diagnostic approach for a hydraulic power system will be presented next.

4.2 Case-based Reasoning Approach

4.2.1 Introduction

Case-based Reasoning diagnostics method solve new problems based on the experience of previous cases, which resembles the human thinking process in solving a problem. [34] When a problem occurs in real life, people always ask: "Have you seen this problem before?" If a similar problem has occurred, then the previous solution for this problem can be used to solve the new one. Even if this is a new problem, people always try to find similar problems and where possible refer to their solutions. When it comes to the engineering area, previous experience can be summarized as a failure case and broken down into its three main component parts: the problem, symptoms and solutions. Once similar failure symptoms are found in a case-library, reuse of the solutions for those problems is suggested.

4.2.2 CBR Diagnosis Process

The case-based reasoning diagnosis process can be organized in an information cycle, and is usually represented as the "4Rs" mentioned before. (Aamodt & Plaza, 1994) A CBR schematic illustrate the typical diagnosis process as shown in Figure 4-1.

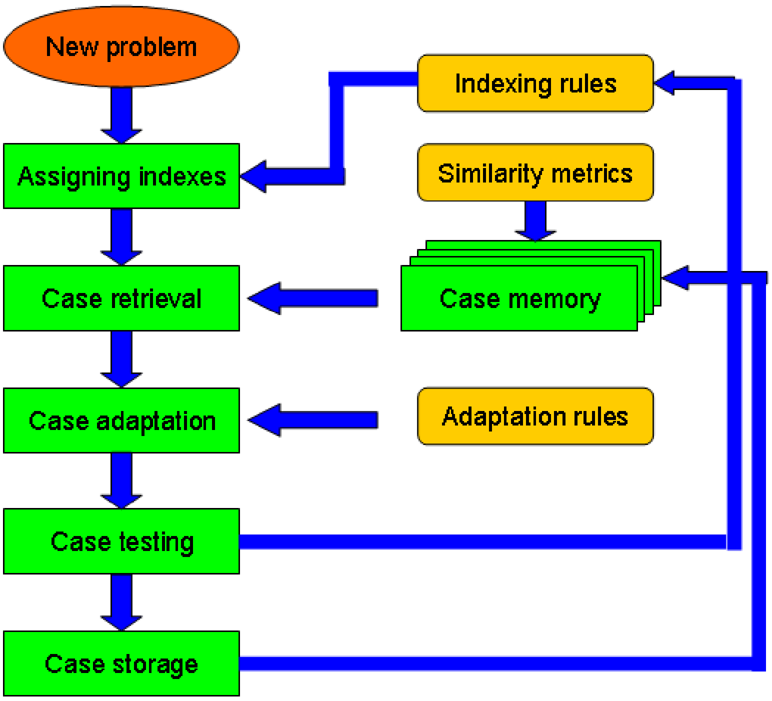


Figure 4-1 CBR diagnosis cycle [6]

When failure occurs, the features of the fault are monitored and processed into a special format which is defined as a new case. Then similar previous cases are retrieved from the case-base by a pre-set similarity function. The solutions for this retrieved case are reapplied to the new problem. Not all new cases can be completely solved by the retrieved cases. Sometimes they must be adapted to the new conditions in the revision stage of CBR. The solution for the adapted case will be evaluated by user feedback and then this learned case will be retained in the case-base.

Compared to the other data-base method, CBR can be more accurate in identifying similar problems. This means that even if the latest problem is not in the case-base under similar circumstances, CBR can still provide useful information regarding solutions. When this occurs, the solution can be adapted to new problems and added to the case base. The case base will be improved continuously as time goes on by acquiring input from more problems and solutions.

4.2.3 Constituent Elements of CBR

In accordance with the description of CBR functions, the three elements forming the core of CBR can be summarised as follows:

a) Case coding

b) Similarity metrics

c) Case adaptation

The detailed information of these constituent elements is described as follows:

- Case coding

In a case-based reasoning system, the cases stored in the case library are the foundation of a diagnostic engine. In order to improve the accuracy of similarity assessment in case retrieval, it is essential to construct the case properly. Normally, a case must include the problem and its solution. It should describe the failure information specifically and in an easily indexed manner. The related condition and symptoms should be considered both quantitatively and qualitatively in case coding. Figure 4-2 shows a simple case structure.

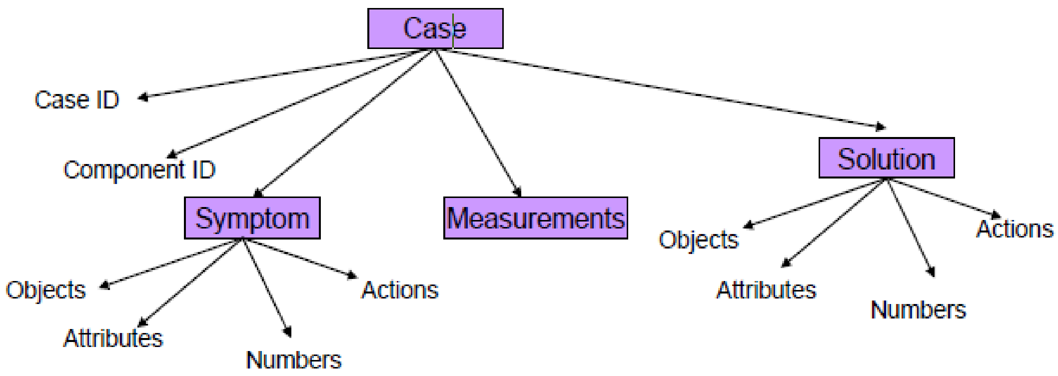


Figure 4-2 A simple case structure [35]

In this research, each case will be coded into the following form and stored in the case-base.

(Case ID) (Components ID) $(S_1\ M_1)(S_2\ M_2)\ldots(S_n\ M_n)\ (w_1, w_2, \ldots w_n)\ (A_1, A_2, \ldots A_n)$ *(Date)*

Where the *(Case ID)* is the mark of the case in the case library, the *(Components ID)* indicate the components which produce the fault, the *(Date)* records the time of case storing, $(S_1\ M_1)\ (S_2\ M_2)\ \ldots\ (S_n\ M_n)$ describe the features and measurements of related failure symptoms , $(w_1, w_2, \ldots w_n)$ is the weighting assigned to the related symptom, $(A_1, A_2, \ldots A_n)$ describe what solutions are suggested.

- Similarity metrics

Similarity metrics can be defined as the basis of a case-based diagnosis. To improve the speed of Case Retrieval in the diagnosis process, all the measurements of hydraulic system failure symptoms are encoded into the most simple words ——" 0 "and "1" which represent the working status of the components. For example, *(S_1 1)* for EMP indicates that the pump is operating and *(S_1 0)* indicates that the pump is off. *(S_2 1)* means that the EMP outlet pressure is low while *(S_2 0)* means that the pressure is normal.

Similarity assessment for a new case and existing cases stored in a case-base is a significant challenge. Generally, a failure has various symptoms with corresponding measurements. To measure the similarity between the old case and the new query case, we use a simple function given in Equation 4-1 combined with weighting factor. [36]

$$S(N,O) = \sum_{i=1}^{n} w_i \cdot sim_i(S_{in}, S_{io}) \times 100\% \qquad \text{Equa. } 4-1$$

Where S_{in} and S_{io} is the symptoms of the new case and the old case, w_i is the weight of symptom S_i obtained from domain knowledge and will be updated when the case is successfully reused, sim_i (S_{in} , S_{io}) refers the similarity of symptoms between two cases. If (S_{in} m_{in}) equal (S_{io} m_{io}), sim_i (S_{in} , S_{io}) =1, If (S_{in} m_{in}) not equal (S_{io} m_{io}) or a symptom is only found in one case, then we define sim_i (S_{in} , S_{io}) =0.

A simplified illustration is given to show the similarity assessment as follows:

For a new case:

(Case n) (S_1 1) (S_2 1) (S_3 0) (S_4 1)

The following three old cases exist in the case library:

(Case 1) (S_1 1)(S_2 1)(S_3 0)(S_4 1)(S_5 1) (w_1=0.4,w_2=0.2 w_3=0.1,w_4=0.2, w_5=0.1)

(Case 2) (S_1 0)(S_2 1)(S_3 0)(S_4 1) (w_1=0.4,w_2=0.2 w_3=0.3,w_4=0.1)

(Case 3) (S_1 1)(S_2 1)(S_3 0)(S_4 1) (w_1=0.4,w_2=0.2 w_3=0.3,w_4=0.1)

Using the metric introduced here, the similarities between the new case and the past ones can be evaluated as follows:

Sim-value Case 1: (1*0.4 + 1*0.2 + 1*0.1 + 1*0.2+0*0.1) *100%= 90%

Sim-value Case 2: (0*0.4 + 1*0.2 + 1*0.3 + 1*0.1) *100%= 60%

Sim-value Case 3: (1*0.4 + 1*0.2 + 1*0.3 + 1*0.1) *100%= 100%

Based on the calculated similarity value, old case 3 is recommended as it is more similar to the new case than the other two cases. The similarity assessment results seem unreliable for the process looks very simple. However, the accuracy of CBR diagnosis results depends on the number of symptoms and their weighting based on the historical database and domain knowledge.

- Case adaptation

Compared to other conventional diagnostics methods, CBR has the advantage of solution adaptation capability. [6]This also presents a challenge. Once there are no old cases in the case-base providing an exact match to a new query case, the solution applied to the most similar case will be modified for the new situation. Usually some intelligence-based tools, such as fuzzy logic, neural networks, etc., are used to devise domain-specific modification rules. However, it is difficult to design modification rules for a complex failure condition. When a modified case is created automatically, there is a big risk in applying it to aircraft fault resolution without human intervention. Adaption mechanism may be given an incorrect or invalid solution update. In this research, the author tends to revise case by seeking expert advice for which would be more easily achieved.

4.3 Design of CBR for a Hydraulic Power System

Based on the function and the constituent elements of the CBR diagnostics method, a CBR framework for systems is sketched for the hydraulic power system. Figure 4-3 illustrates the detailed diagnosis workflow.

As shown in the chart, a typical diagnostic process can be described as follows:

- Step 1: System monitoring

The diagnosis process starts with real-time monitoring of the hydraulic system. All the system operating conditions observed by sensors and relative signals are transferred into the computer for signal diagnosis processing.

- Step 2: Case Retrieval

When the abnormal signals are detected, a set of cases related to this fault symptom are retrieved from the case library.

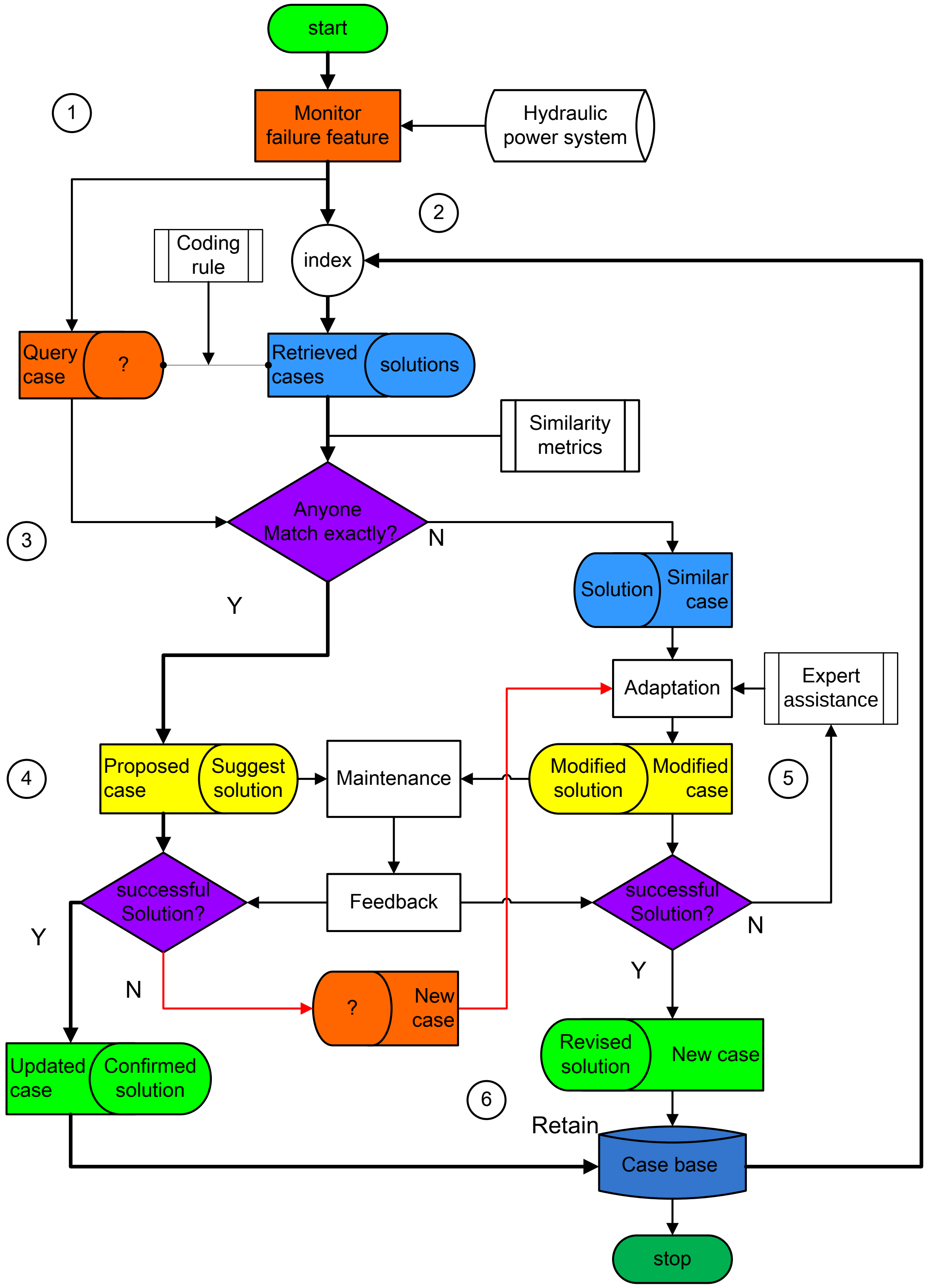


Figure 4-3 CBR Diagnostics workflow for hydraulic power system

- Step 3: Similarity matching

Based on each retrieved case and coding rule, the failure features are coded into a query case. Using similarity metrics, the similarity of cases is calculated and sequenced.

- Step 4: Reuse case

If a case is matched exactly, then the corresponding solution will be recommended for this situation. This case success rate will be updated after the maintenance feedback has confirmed the outcome of applying this solution.

- Step 5: Case adaption

If no exact match can be retrieved or if the maintenance feedback indicates that the proposed case does not provide a solution to this problem, a new fault warning will be issued and expert assistance sought. Simultaneously, the most similar cases with solutions will be suggested to the adaption process in order to revise the solutions.

- Step 6: Retain case

If the problem is successfully solved by the modified solution, then it will be retained as a new case and saved in case-base. Otherwise if the solution fails, the case adaption mechanism will seek expert help again.

4.4 Case study

In this section, a case study based on an Electric Motor Pump is presented to validate the CBR diagnosis approach discussed in the previous section. In this research, the author focuses on system level diagnosis in which the failure symptoms detection is based on functional and safety analysis. The LRU will be replaced after making the diagnosis. It can be seen from the FHA and FMEAC analysis result that the EMP plays an essential role in the FW-11hydraulic power system. Therefore, a failure mode of an EMP is selected for the case study.

4.4.1 Introduction to EMP

Four EMPs are employed in the FW-11 hydraulic power system, in which two large power alternating current motor pumps (ACMP) work continuously in the CENTRE subsystem at a pressure of 5000 pis. A typical external view of an electric motor pump and an internal view of the pump are shown in Figure 4-4 and 4-5.

Figure 4-4 AC Motor pump [43]

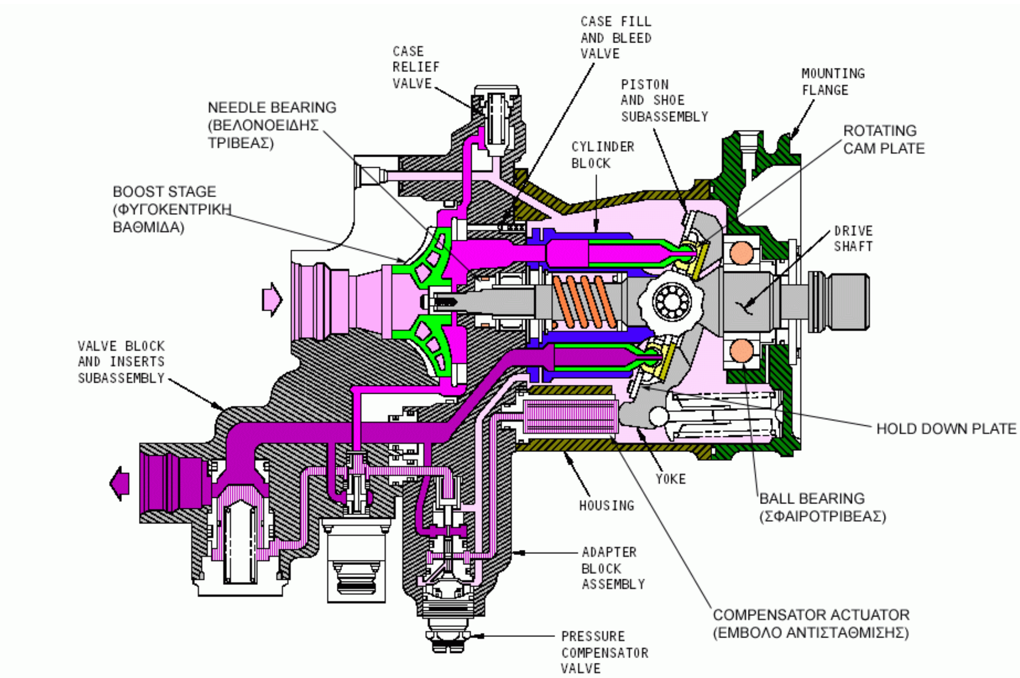


Figure 4-5 Cross section view of piston pump [44]

The ACMP is a complex electromechanical product consisting of a variable delivery-constant pressure piston pump and an alternating current motor. The pump is composed of an inlet boost impeller, a revolving cylinder barrel containing several pistons, bearings and a set of valves while the motor is also a complex piece of electromachinery. According to the statistics reported in previous publications, seal leakage, bearing and piston wearing and motor failure are major causes of pump faults. [37]The failure effects on the function of the pump are primarily a loss of output flow or overheating.

4.4.2 Pump Failure Analysis and Detection

Based on the failure modes effects analysis result, a summary of EMP failure modes is shown in Table 4-1.

Table 4-1 Summary of FHA, FMEA

Failure modes	Cause of failure	Effects on system
Loss of output flow	Bearing or piston failures Motor failure to drive	Loss of relative subsystem EMP output flow
Internal leak	Seal aging or degradation, Corrosion	Reduced relative EMP output flow
External leak	Case crack, Seal failure	Loss of relative subsystem EMP output flow, reduce system fluid quantity
Pump Overheat	Dry running, Wearing or abrasion Case drain port blockage	Seal failure and fluid leakage
Motor overheat	Short-circuit, Defective motor winding	Loss of relative EMP output flow

Comments: The failure modes and causes are listed briefly for a system level diagnosis consideration. The real causes of EMP failure at LRU level are actually more complicated.

To detect these failure features, a set of sensors and probes are employed in system monitoring.

However, pump failures cannot be determined simply by these sensor signal failures. The operating conditions of other components and environmental conditions associated with this pump should be considered in any CBR diagnosis. In addition, Fault Tree Analysis may contribute to define these factors.

Table 4-2 Pump failure detection

Failure modes	Detection	Sensor designation
Loss of output flow	Pressure Flow rate	Low Pressure Switch in pressure outlet System Pressure Sensor
Internal leak	Pressure Outlet flow rate	Low Pressure Switch in pressure outlet
External leak	Reservoir fluid quantity	Low Pressure Switch, Reservoir Low-level Sensor
Pump overheat	Temperature	Temperature Sensor in pump case port
Motor overheat	Temperature	Temperature Sensor in motor Current sensor

4.4.3 Diagnostic Process

A pump failure mode "Loss of EMP1 output flow" is selected for CBR diagnosis process. Using the fault tree analysis and system function, the symptom of "pump fails to output" can be detected from the following signals: suction pressure of pump, outlet pressure of pump, reservoir fluid quantity and EMP 1 Contactor Switch signal.

As shown in Figure 4-6， a case structure of this failure mode and the case-base index is outlined. Table 4-3 lists the sensors and features that may appear in this diagnostic process

The following diagnosis processes are based on the supposition that all of the sensors work correctly and the signals acquired from the data bus reflect the actual status.

a) When EMP1 fails to output, an abnormal pressure signal in the EMP1 outlet is detected by the EMP1 Low Pressure Switch. The feature signal of "pressure is low" is converted into case form— "(F019, 1)" in the diagnosis processor.

b) A set of cases with the appropriate symptoms are retrieved from the case-base as shown in Figure 4-6.

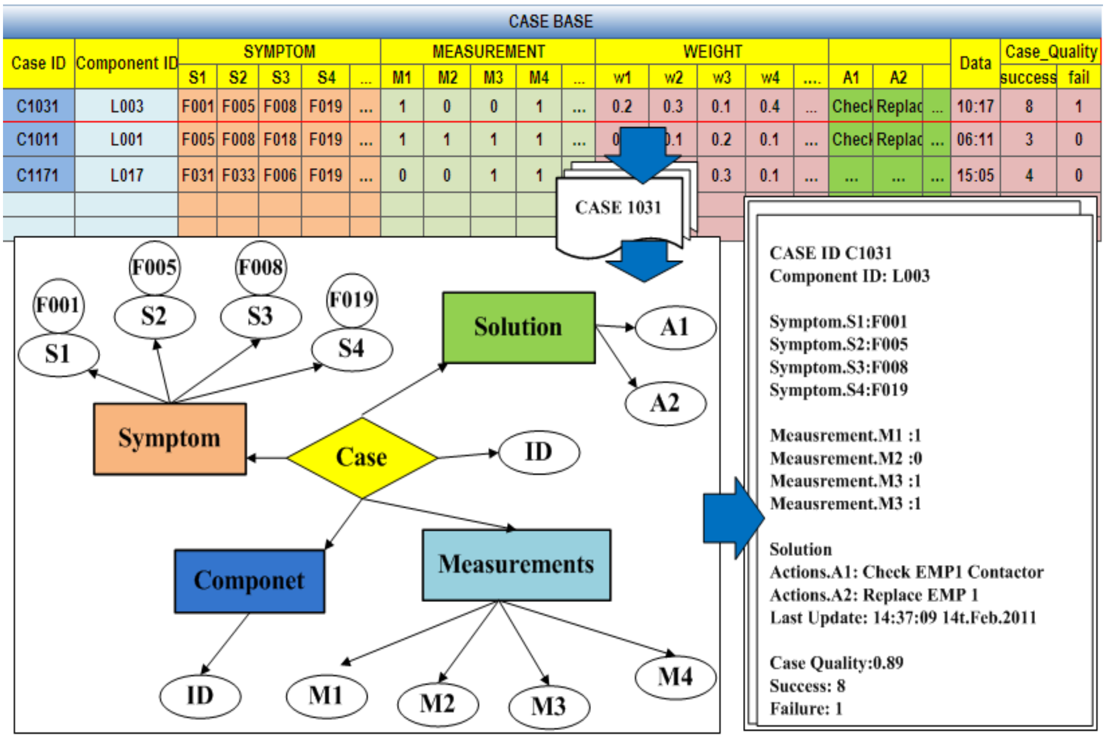


Figure 4-6 Examples of case-base and the EMP failure Case-structure

Table 4-3 Sensors and features look up table

Feature ID	Name	Measurements Description
F001	EMP 1 Contactor Switch signal	Switch ON=1, Switch OFF=0
F002	EMP 2 Contactor Switch signal	Switch ON=1, Switch OFF=0
…	…	…
F005	LEFT Reservoir Low-level Sensor	<15%=1,>15%=0
F006	CENTRE Reservoir Low-level Sensor	<15%=1,>15%=0
F007	RIGHT Reservoir Low-level Sensor	<15%=1,>15%=0
F008	LEFT Reservoir Pressure Sensor	<400 psi=1,>400psi%=0
…	…	…
F011	Temperature sensor in EMP1 Motor	Overheat =1, Normal =0,
F013	Temperature sensor in EMP1 case drain port	Overheat =1, Normal =0,

Feature ID	Name	Measurements Description
…	…	…
F018	EDP1 Low Pressure Switch	Low Pressure =1, Normal =0,
F019	EMP1 Low Pressure Switch	Low Pressure =1, Normal =0,
…	…	…

c) Using the coding rule mentioned previously, the query case is coded and compared in turn with each retrieved case. An example of similarity assessment is given below:

The retrieved case C1031 is stored in the case-base as follows:

(C1031) (F001, 1) (F008, 0) (F008, 0) (F019, 1) (0.2, 0.3, 0.1, 0.4)

This indicates that the electric power for EMP1 is normal, the fluid quantity is not low, the pressure of pump input flow is normal and the pressure of pump outlet flow is low.

The corresponding query case coding is as follow:

(Case q_1) (F001, 1) (F008, 0) (F008, 0) (F019, 1)

Running the similarity assessment:

Sim-value=(1*0.2 + 1*0.3 + 1*0.1 + 1*0.4) *100%= 100%

----

d) The result means that case C1031 closely matches the query case, so solution of C1031 is recommended as the proposed solution.

e) Receive the maintenance feedback. If the problem is solved successfully, case C1031 is confirmed and the success rate will be updated in the case-base.

4.5 Summary and Discussion

In this paper, a diagnostics approach for a hydraulic power system is developed, using the case-based reasoning method. The constituent elements of CBR are discussed specifically and a diagnosis workflow is developed for the hydraulic power system. An EMP failure mode was chosen as a case study to demonstrate the diagnosis process in detail. Using the CBR method, the cause of failure is diagnosed by matching the detected symptoms with past cases. Appropriate solutions are recommended to solve the new problem. It can be seen that learning capability is a very important feature of CBR. With the case base being updated, the accuracy and confidence of diagnosis will gradually increase.

5 Prognostic Research for Hydraulic Power System

In this chapter, the author intends to apply prognosis approaches to the hydraulic power system. Firstly, a comparison and discussion of three commonly used prognostic methods are presented. Then the suitable approaches are recommended for the hydraulic system components based on their failure characteristics analysis. Finally, a discussion of the case study is given briefly due to limited time.

5.1 Prognostics Methods Investigation

Knowing how to detect the failure symptoms accurately at a very early stage so as to predict the remaining useful life of systems or components is a great challenge to the PHM system designer. Therefore, some people refer to prognostic as the Achilles' heel of the PHM system. [6] The following figure illustrates the main goal of the prognosis as well as the difference between it and the diagnosis already discussed.

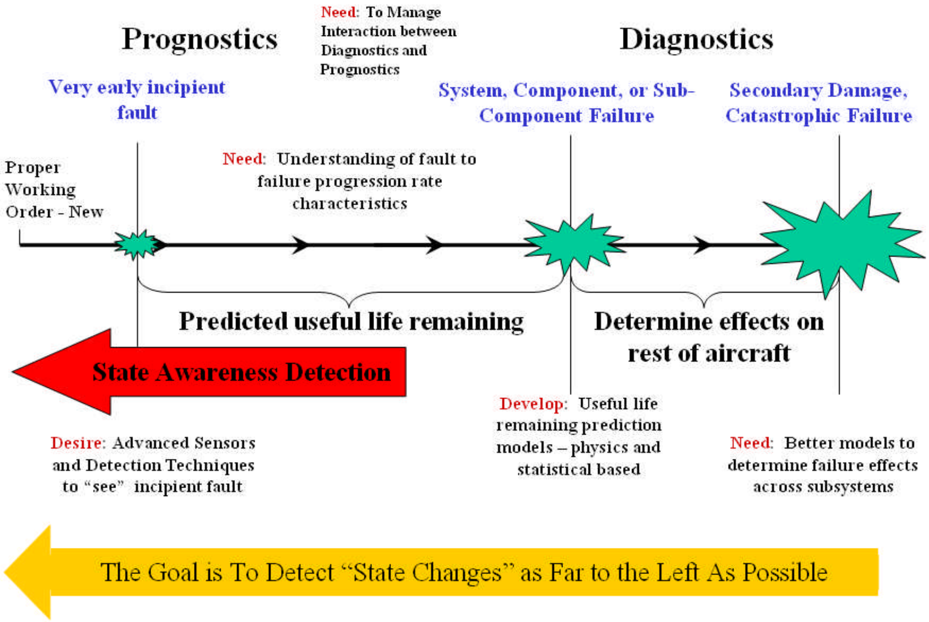


Figure 5-1 Failure Progression Timeline [38]

In accordance with different condition and failure features, varied prognosis approaches are suitable for different products and situations. Three prognostic methods widely used for aircraft systems will be presented in turn as follows.

Model-based approaches employ a dynamic model of an objective system or component, to predict the RUL by checking the simulation results against the observed real output data. It is a very popular prognosis method due to its higher prediction accuracy in recent years, especially for linear systems. An accurate mathematical model is required for a model-based prognostic application. Simultaneously, lots of sensors need to be used to monitor the corresponding input and output data. Therefore, the cost of model-based prognosis for a complex system is a restriction also.

Probability-based approaches are widely used in such a situation: there is less detailed information of system to build mathematical model but lots of historical statistical data from previous failures. It is a basic prognosis method which can give confidence boundaries regarding the prediction results. Normally, the cost is the lowest compared to other methods. However, the precision and accuracy of the prognosis need be improved. A statistical reliability and usage-based approach are usually employed to predict the RUL of these components which have lower failure rates and fewer sensed parameters associated with them.

Data-driven prediction methods are used when a dynamic system model is not easily established because of the many signals which may indicate the failure. In such instance, Data-driven approaches are employed to form special algorithms which can provide the relationship between the desired output and multi-inputs. One of the most popular Data-driven prognostics is artificial neural networks (ANN) which has been introduced in chapter 2. Compared to the above two methods, this approach uses the available data most efficiently to obtain fault prediction as well as the related confidence limits.[6]

As shown in the above discussion of the characteristics of different prognostic approaches, choosing the appropriate methods needs a comprehensive consideration of system features and costs. An example of the application of these methods in a gas turbine performance prognosis is illustrated in Figure 5-2. It can be seen that no one prognostic method can be used for all systems or components. Different choices of prognosis approach are selected for the different monitored elements based on their features.

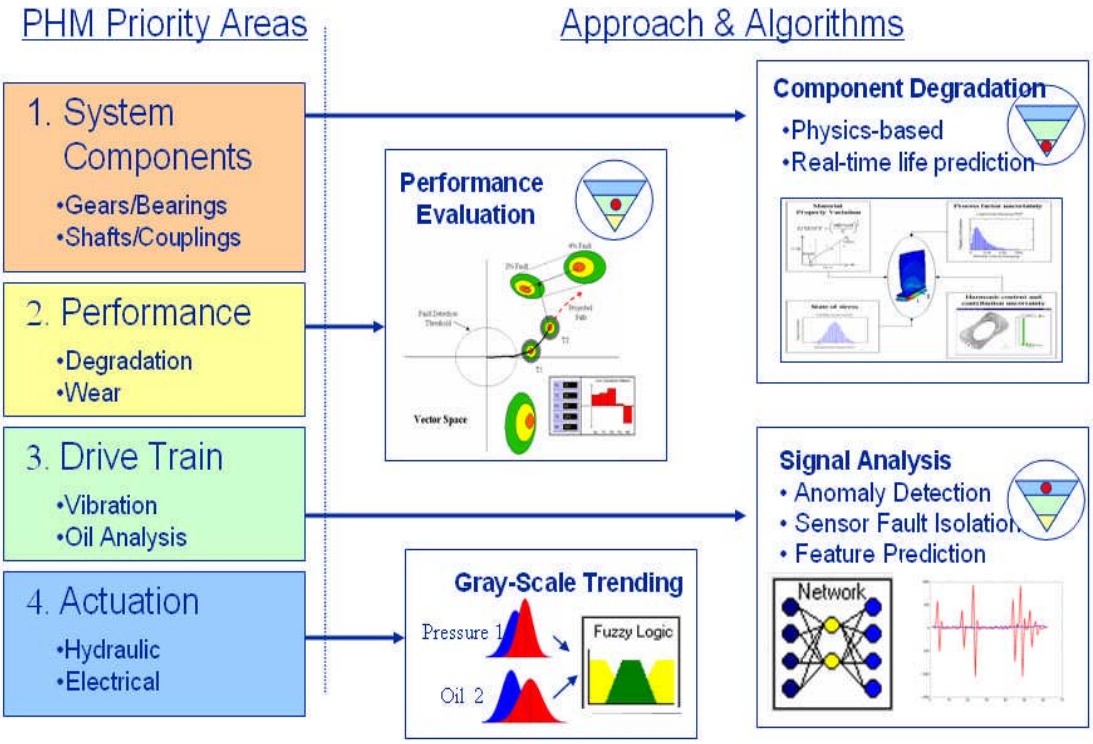


Figure 5-2 Prognosis Approaches Application [2]

5.2 Prognostic Application for Hydraulic Power system

Based on the characteristics and cost considerations, these prognosis approaches are suitable for different types of components. Hydraulic power systems consist of different types of components, such as pumps, valves, filters and sensors. As for most valves and accumulators, they are totally mechanical products and no signals can reflect their state of health directly. Simultaneously, these components always provide higher reliability, the Probability-based approach based on historical data or maintenance experience is an appropriate prognostic method in these cases.

Though the contamination of a filter module can be detected by differential pressure indicators, the other failure modes are not easily found. A Probability-based approach is suitable for them as well.

In addition, in the case of other mechanical components, such as pumps, fire shut-off valves and Heat Exchanger, lots of sensors can be used to monitor their operational performances for they are critical elements of the system. So a fusion Model-based and Data-driven prognostic approach is a desirable choice for them.

With regard to the electronic components, one of the data-driven methods, ANN is a reasonable approach because of the difficulty in modelling these components. In conclusion, the hydraulic power system prognostic approaches are summarized as follow:

Table 5-1 Hydraulic power system prognostic methods

Components	Type	Detection methods	Prognostic approach
System relief valve, System Accumulator, Reservoir Pressure Accumulator, Ground-Pressurization Connection, Ground-Suction Connection, Filling Connection, Ground-charging Connection, Reservoir, Pressure Gauge, Auto Bleed Valve	Mechanical	None	Probability-based approach
EDP Pressure and Case Drain Filter Module, EMP Pressure and Case Drain Filter Module, Return Filter Module,	Mechanical	Filter differential pressure indicator	Probability-based approach
Heat Exchanger, Engine driven pump, Ram Air Turbine	Mechanical	Low Pressure Switch, System Pressure Sensor, Temperature Sensor,	Fusion prognostic with Model-based & Data-driven
Electric Motor Pump, Fire Shut-off Valve	Electromechanical	Low Pressure Switch, System Pressure Sensor, Temperature Sensor, HSMU	Fusion prognostic with Model-based & Data-driven
Low Pressure Switch, System Pressure Sensor, Reservoir Temperature Sensor, Reservoir low level sensor	Electronic	HSMU	ANN

5.3 Case Discussion

As the pumps are widely recognized to be the most critical components in hydraulic power systems, the author intends to continue with this case study for pump failure prediction.[40] Unfortunately, it is hard to finish this case study completely due to limited time and a shortage of data. However, several aspects of hydraulic power system prognostic approaches are discussed here.

a) PUMP Failure Feature Analysis

- Performance degradation (Low Bandwidth signals) Analysis

  The remaining useful life of the pump can be predicted by analyzing performance degradation. As the pump pressure, flow speed, and the fluid viscosity parameters are given, a model-based approach can be established to simulate the pumps output performance characteristics using the real-time input values. By comparing the simulation results with the actual output data, the evidence of increasing internal leakage due to wear can be identified

- Dynamic (High Bandwidth signals) Analysis

  On the other hand, the anomalous features can be extracted by analyzing the high frequency signals in pump pressure flow and case drain flow data. In this way, the data process uses the high bandwidth part of signals instead of their mean value. Normally, ANN or fuzzy logic approaches are employed to solve the prediction problem in uncertain situations. In addition, the vibration signal of bearing can reflect the damage progression directly. [17] [30]

b) Fusion prognostic process

In accordance with the above discussion, a fusion prognosis workflow is established to estimate the remaining use life (RUL) of pumps by detecting the potentially intermittent faults and any abnormal behaviour.

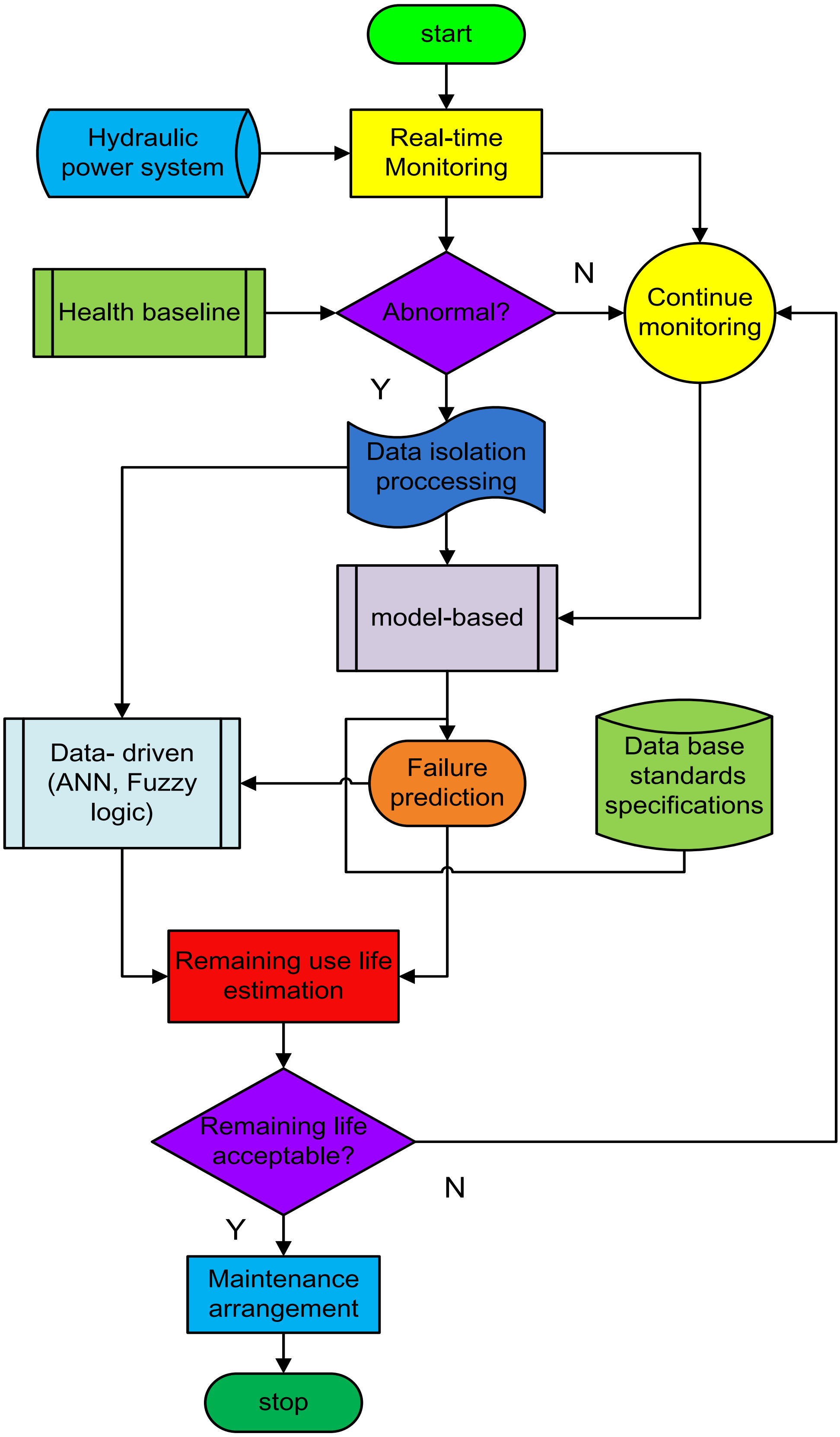


Figure 5-3 A fusion prognosis workflow for pumps

As shown in figure 5-3, the prognosis process begins with the system real-time monitoring which is the same as the diagnosis process. Simultaneously, a health baseline to identify the input healthy status of components or systems must first be determined. The baseline can be a composed of the various operating conditions collected from the system when performing normally or the threshold value from the standards and specifications. By comparing the monitored states signals with the baseline parameters, the anomalous signals will be isolated and processed as the input of the model-based prognosis engine and the data-driven prognosis engine. As discussed before, the pumps' operating signals can be the mean value or high-band frequency waves acquired by dynamic analysis. Through system performance modeling, the potential failure can be detected beforehand by RUL prediction. The unhealthy conditions estimated from model-based approach can be used as a part of data-driven input. Finally, the combined information from the model-based approach and data-driven approach prognosis results can provide a reasonable RUL assessment.

c) New sensing technologies

For failure prognostic approaches, it is very important to choose appropriate sensors for system monitoring. The traditional detectors used in a diagnosis process cannot meet the accuracy requirements of failure prediction. Some new sensing technologies have been developed for on-line system monitoring, such as Fluid Property Sensors (MEASUREMENTS SPECIALTLIES ™) and Ferrous Wear Debris Sensor (Kittiwake Developments). [41][42]

- Fluid Property Sensors

  Fluid Property Sensors can measure the viscosity, density, dielectric constant, and temperature of fluids directly and simultaneously, and are especially suitable for pumps fluids properties analysis using model-based approaches. Using of this type sensor, the sensing components of system can be reduced which means of the reduction of failure mode. Figure 5-4 shows the FPS2800B12C4 Fluid Property Sensors.

Figure 5-4 Fluid Property Sensors [41]

- On-Line Wear Debris Sensor

  This type of sensor can be used to analyse contamination of the pumps' case drain fluid in real time. Ferrographic or spectroscopic analysis methods are employed in this technology to analyze particle size and materials, which can reflect the wear condition of the internal components of pumps. By combining these sensing results and the pump operating conditions, the pump's remaining use life can be predicted. The following figure illustrates a ferrous wear debris sensor mounted on a system pipeline.

Figure 5-5 Ferrous wear debris sensor [42]

5.4 Summary

Prognostic technology has been employed in various industrial fields and plays a very important role in PHM systems. In this chapter, three main prognosis methods and their characteristics were first discussed. Based on the hydraulic power system design features and different types of component failure analysis, an appropriate prognosis approach was selected for each component. In addition, the pump's RUL prediction methods and sensing techniques were discussed and used as a case study. Although prognostic methods have been developed for many years and widely applied in different fields, there still remain, due to their uncertainty and complexity, great challenges in applying it to an on-board PHM system. As mentioned before, it is difficult to complete detailed prognosis research for an aircraft hydraulic system in the short term. However, the basic objective was achieved as described in the above analysis and discussion.

6 Hydraulic Power System DPHM Architecture

In this chapter, based on the above diagnostics and prognostics technology, an integrated DPHM architecture is established for the hydraulic power system. The main functions and the operating process will be discussed, along with the interface between the hydraulic power system DPHM and the aircraft level Integrated Vehicle Health Management (IVHM) system.

6.1 Hydraulic Power System DPHM Framework

Normally, DPHM systems are highly integrated, incorporating advanced sensors, a host of diagnostics and prognostic processing modules, related software and hardware technologies, human-machine interaction interface, and off-board maintenance and management support systems [32]. That is to say, the DPHM systems do not just consist of the application of diagnostics and prognostic, but also include the interface to crew and maintenance operators. Based on the diagnostics and prognostics approaches previously discussed, an integrated DPHM system framework is developed for the FW-11 hydraulic power system.

As shown in Figure 6-1, hydraulic power system DPHM can be a part of the aircraft level health management system — IVHM. The IVHM may also include other health management applications on airframe structure or systems, such as avionics, fuel systems, electrical systems and flight control systems etc. Accordingly, the on-board DPHM of the hydraulic power system communicates with the flight crew and the off-board maintenance system simultaneously via the aircraft IVHM manager.

The on-board DPHM system includes the following elements. A set of sensors and probers are employed to monitor the hydraulic power system operating conditions. A diagnostics and prognostic module works to carry out the system healthy status. A data base is used to stow all the required data and information relevant to the diagnostics and prognostic process. In addition, an interface device is needed to connect the avionic equipment with system managers. It should be noted that, it is impossible to monitor the health condition of each component in a hydraulic power system, for which may increase the failure probability and the cost. Simultaneously, some complex components integrated with sensors can provide monitoring interface directly to the DPPM system.

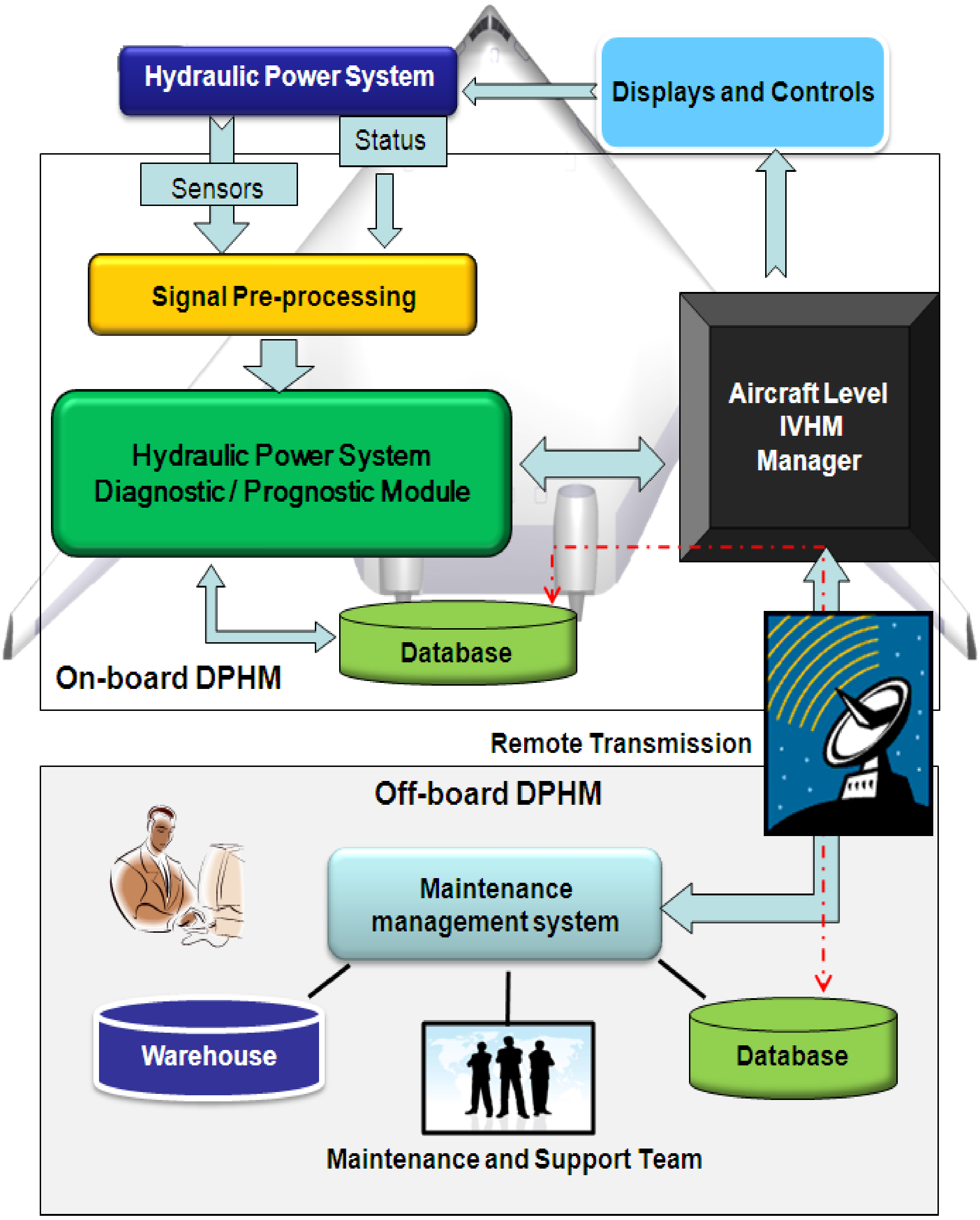


Figure 6-1 FW-11 Hydraulic Power System DPHM Framework

The off-board system mainly consists of ground-maintenance management system, maintenance supports team and the spare parts warehouse. In proportion to the on-board system database, a database also exists in the ground maintenance management system. Both the vehicle health state and maintenance feedback information will be updated continuously.

6.2 Functional Classification of DPHM

As with the DPHM system framework described above, the hydraulic power system DPHM consists primarily of the on-board system and off-board system. Their respective operational functions are listed as follows:

a) On-board DPHM system:

- System real-time monitoring;
- Data capture, process, retention and transmission;
- Fault diagnosis and prognosis;
- Warning faults and forecasting incipient failure;
- Recommending solutions;
- In-flight communication with aircraft level IVHM.

b) Off-board DPHM system:

- Communication with aircraft level IVHM;
- System health state analysis and recording;
- Ground maintenance arrangement and action;
- Expert technical assistance;
- Spare parts storehouse management;
- Maintenance feedback and database update.

6.3 Operating Process of DPHM

The hydraulic power system DPHM works when the system starts operating. The system and components operating conditions are monitored by sensors. The performance parameters will be pre-processed before being transferred into a Diagnosis/Prognosis module. Simultaneously, other systems or environment information can be acquired from the data bus.

Based on this monitored data and related information, the system health condition will be determined by means of the diagnosis/prognosis reasoning engine. When abnormal signals are detected, the CBR diagnosis programme works out the root cause of the failure and recommends the solutions. On the other hand, the prognosis programme provides the capability to identify potential issues before they become critical. The on-board database furnishes data and recommends solutions in real time.

At the same time, the hydraulic power system failure warning and display signals are transferred to avionics via aircraft level IVHM which also takes responsibility for remote communicating with ground base.

When the off-board system receives the system health status data in real-time, it will run certain programmes to check and confirm the failure conditions. If a failure and solution are clear, the ground maintenance arrangement and action will be implemented. If the failure condition is brand new or complex enough that cannot be solved automatically by the diagnostic engine, ground technical assistance might be furnished. Simultaneously, feedback of the successful solution and case should be provided to update the database. The warehouse system manages the supply chain of spare parts in accordance with the condition-based maintenance schedule.

6.4 Benefits and Challenges of DPHM Application

With the application of DPHM technology to the aircraft hydraulic power system, system health information will be collected and processed throughout every phase of operation. From pre-flight, in-flight and post-flight activities, appropriate actions can be taken as DPHM enables flight crew and ground serviceman to make informed decisions. To sum up, the following aspects are the main benefits of the DPHM application.

- Safety and mission reliability improvement

  The hydraulic power system supplies the power to flight-control surfaces and landing gear actuators, which directly affect flight safety. DPHM, applied in the hydraulic power system, enables the crew to take corrective actions quickly, which may result in more rapid fault identification response. That is to say, the DPHM system can provide more accurate awareness to crew or operator, which in turn means that aircraft safety can be significantly improved. The mission reliability can also be increased due to more effective condition-based maintenance.

- Cost reduction

DPHM applied in aircraft system design will result in a significant decrease in life-cycle cost. Firstly, the processing and operational manpower requirement will be reduced due to more intelligence in DPHM to help in diagnosis/prognosis failure and maintenance action. Secondly, less actual maintenance will be carried out due to the prognostic and diagnostic capability. This predictive maintenance will result in a reduction in both maintenance frequency and turnaround time. A collateral benefit is that the cost of spare components will decrease due to fewer maintenance actions.

However, the efficiency of the DPHM system depends mainly on the accuracy of diagnosis and prognosis results which are related to the acquisition of signal, signal processing and the diagnosis /prognosis engine. Although the above section describes several benefits, there are challenges still remaining to develop more reliable and more effective DPHM systems:

- Sensing and signal processing techniques

With the development of hydraulic system technology, sensing and signal processing techniques, there is, due to system complexity and the level of integration, a requirement for greater accuracy and intelligence capability. Although the development of sensor technology can provides adequate information on sensing mechanical performance and structural health conditions, there still a lack of enough effective means for self-health diagnosis of sensors or electronic components by means of in-situ monitoring. In addition, higher pressure and temperature operating conditions pose a challenge for the reliability of sensors.

- Accuracy of diagnosis /prognosis engine

The CBR diagnosis approach and fusion prognosis approaches are employed in hydraulic power system DPHM. It is sufficiently accurate and efficient to deal with common failures. But for a complex system, completing the case base so as to improve CBR diagnosis confidence is a significant challenge. Simultaneously, the precision prediction model and algorithm affect the accuracy of prognosis results directly. Currently, the higher cost of hardware and software is a barrier to achieving a more accurate diagnosis/prognosis capability.

6.5 Summary

The DPHM system employs on-board and remote resources, both hardware and software, to monitor, capture, and analyze system health conditions. Based on the above diagnostics and prognostics research, the hydraulic power system DPHM architecture is established which contains all primary elements of a health management system. The functions and operational process are described specifically. Finally, the benefits and challenges of the DPHM application are discussed briefly. In relation to the aircraft hydraulic power system, system design with DPHM technology will greatly increase flight safety and mission reliability.

7 Conclusions and Further Work

7.1 Conclusions

The objective of this research was to develop a diagnostics, prognostic and health management approach to a flying wing aircraft hydraulic power system as an extension of the Group Design Project (GDP). Aircraft systems with DPHM technology will improve system safety, mission reliability and reduce life-cycle costs efficiently, which will enable the new airliner — FW-11 designed in the GDP to be more competitive in a future aviation market. The detailed GDP task and the author’s contributions are presented in Appendix A.

In this research, a literature review of health management technology was given at first. By means of this review, the history and status of DPHM technology and the main functions were studied. Simultaneously, the various diagnostics and prognostic methods were presented and analyzed to achieve the objectives of this research.

In accordance with the research objectives, a hydraulic power system was established for the FW-11 aircraft. All research works in this thesis were based on this hydraulic system. The hydraulic power system was designed to provide a source of energy to primary flight controls, landing gear and other utility services. In this, three subsystems operate continuously to supply high pressurized fluid to users so as to maintain aircraft safety with redundancy design. Meanwhile, it must meet the airworthiness regulation requirements of FAA, EASA, and CAAC. The main components and structure were illustrated in a schematic diagram of each subsystem. The operational functions of the system were also represented.

Depending on the functional description of the hydraulic power system, a set of safety assessment approaches were employed to analyse the failure conditions of the system. Functional hazard Assessment (FHA) was conducted for the whole system to identify all function failure conditions and associated severity levels. The results show that “loss of all three hydraulic power systems together” or “loss of ability to shut off EDP suction flow in case of fire” will have a serious effect on aircraft safety. The failure modes effect and criticality analysis (FMECA) was performed for each component of the hydraulic power system to identify the critical components and their potential failure modes. Fault Tree Analysis (FTA) for the selected failure modes which have higher hazard levels was carried out in order to determine the root cause and the probabilities of failure. Finally, the crucial components that may lead to catastrophic or hazardous failure were summarized and the key parameters and detection methods were identified.

Based on the failure features from the analyses results, a comparison of different diagnostic methods was performed. After that, a case-based reasoning diagnostic approach was chosen for the hydraulic power system. The author researched the coding mechanism and similarity metrics of CBR specifically and designed a diagnosis workflow accordingly. Using the CBR method, the cause of failure was diagnosed by matching the detected symptoms with past cases. Appropriate solutions were recommended to solve the new problem. With the case-base being updated continuously, the accuracy and confidence of diagnosis will gradually increase. The electric motor pump was chosen as a case study to demonstrate the diagnosis process in detail, which showed that the CBR is a reasonable solution for hydraulic power system diagnosis.

Three main prognosis methods and their characteristics were first discussed. Based on the hydraulic power system design features and different types of component failure analysis, the appropriate prognosis approach was selected for each component. In addition, the pump's RUL prediction methods and related sensing techniques were discussed as a case study. A fusion prognosis approach was discussed to carry out the hydraulic power system prognostics practically and efficiently.

Finally the hydraulic power system DPHM architecture was developed. This consisted of the integration of the above diagnostics and prognostics research and the interface between the hydraulic power system DPHM and the aircraft level IVHM. The accuracy and cost of DPHM application was considered and discussed.

To sum up, this research completely developed an integrated DPHM system for the FW-11 aircraft hydraulic power system. Appropriate diagnosis/prognosis methods were used to identify faults/potential failure quickly and accurately. Aircraft safety was improved significantly due to the crew having accurate information to enable them to take appropriate corrective action. With the capability of remote signal transmission, system operating status was transmitted from the onboard to ground base in real-time, the maintenance philosophy was changed from the "On failure or per schedule" to "on condition". The aircraft mission reliability improved and the life-cycle cost decreased. In general, the research objectives were achieved.

7.2 Future Work

As a new and progressive technology, DPHM was applied in various industrial fields gradually. The related research works can be broad concepts which cover various aspects and different levels. It is impossible to complete a comprehensive study on hydraulic system from top level to a detailed level in a short time. There are several issues which will be studied in future research:

The diagnostics and prognostic research in this thesis focused on the system level application. The system failure mode analysis and detection were only concerned with LRU level in this design phase. In order to improve the accuracy of diagnosis and prognosis results, the detailed failure modes of hydraulic components and advance sensing techniques should be researched in-depth.

Furthermore, the prognosis approach mainly focused on the feature research and recommendation of different methods. Due to limited time and a shortage of data it just comprised a qualitative analysis. With the development of more detailed design, a mathematical model could be established for critical components. The actual calculation and analysis should be conducted to demonstrate the remaining useful life prediction method.

Lastly, the evaluation of the DPHM application was also given briefly and qualitatively. Uncertainty is actually a critical element of the diagnosis and prognosis approaches. The quantitative assessment and validation methods should be studied further. Meanwhile, the cost analysis of DPHM system will also pose a challenge. Although we predict that the maintenance cost of aircraft will be saved by using of DPHM technology, the net cost benefit may not actually be easily achieved. A quantitative estimation should take the cost of the DPHM system installation and operation into consideration in future work.

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APPENDICES

Appendix A Group Design Project Report

Conceptual Design of Flying Wing Airliner FW-11

Fuel Mass Calculation, Mass Breakdown and Landing Gear Design

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LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

AVIC	Aviation Industry Corporation of China
APU	Auxiliary Power Unit
C	Specific Fuel Consumption
CG	Centre of Gravity
ECS	Environmental Control System
FCS	Flight Control System
GDP	Group Design Project
L/D	Lift to Drag Ratio
M_{OE}	Operating Empty Mass
MTOW	Maximum Take-off Weight
MLG	Nose Landing Gear
NLG	Main Landing Gear
sfc	Specific Fuel Consumption
TET	Turbine Entry Temperature

A.1 Introduction

A.1.1 Background of GDP

This Group Design Project is the 4th year cooperation programme between Aviation Industry Corporation of China (AVIC) and Cranfield University. It is the first year of another three-year MSc training Programme of civil aircraft design. Three groups from AVIC will accomplish a commercial aircraft design, from conceptual design to preliminary design and then detail design respectively. In this year, 22 AVIC students work together to finish the conceptual design of the flying wing airliner—FW-11.

A.1.2 FW-11

According to the national strategy of china civil aviation industry, they are attempting to manufacture advanced aircraft to meet the huge domestic demand. As we know, the regional jet ARJ21 has been taken its initial flight and the single-aisle narrow body airliner C919 wish to be put into service in five years. The government is also very urgent to design a kind of long-range and larger airliner to satisfy increasing demands of international aviation market.

In the past three years, 3 AVIC groups have accomplished a conventional airliner design as their GDP training programme in Cranfield University. As the expectation of AVIC, our group attempts to design a new concept aircraft. Therefore, the GDP programme aims to design a flying wing aircraft—FW-11, which is a long range, 250-seat, next generation airliner. With the long range capability of 7500 nautical miles, it is designed to reach most of the major cities from Beijing or London.

A.1.3 Design Process of GDP

The GDP design process was divided into three phases. The main task and objective of each phase is shown in figure A1-1.

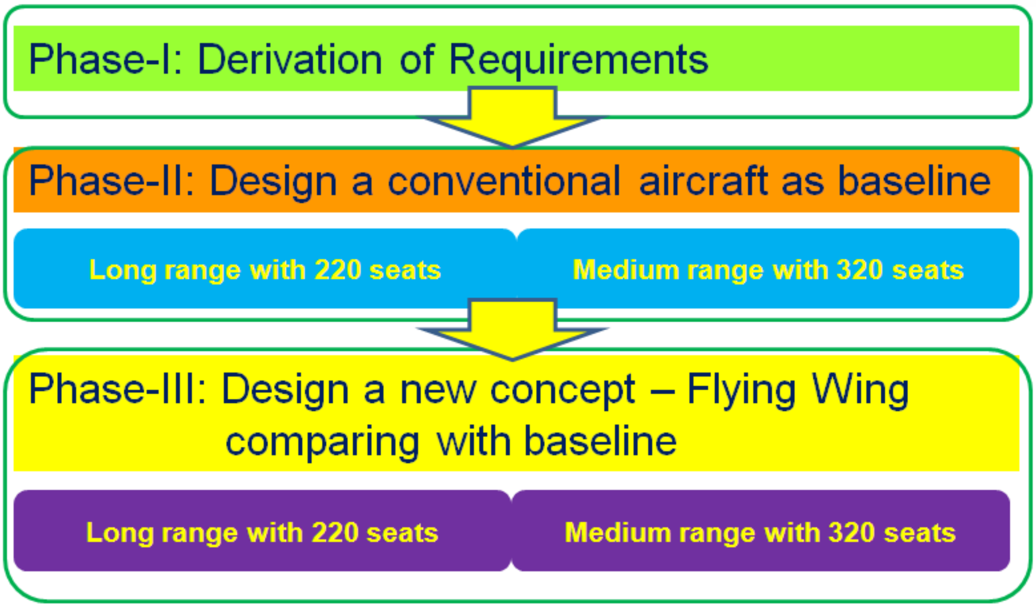


Figure A1-1 FW-11 Conceptual Design Process

In phase I, the main task was to analyse and define the specific design requirements. The design group was divided into 7 teams to make a survey in following subjects:

- General Characteristics;
- Performance Characteristics;
- Aerodynamic / Static Stability Characteristics;
- Geometric Design Characteristics;
- Manufacturer and Operator Investigations;
- Engine General Characteristics;
- Engine Performance Characteristics;

After a comprehensive analysis and discussion of the collected data and information, the design requirements were worked out. In this stage, the author was allocated to the Engine Performance Characteristics team and worked for engine performance estimation.

In phase II, a conventional aircraft was designed in conceptual phase to practice the design flow of civil aircraft. Two type range aircraft were designed simultaneously as a family issue. The final characteristics of this aircraft were used as a baseline. In this stage, the author was in charge of fuel mass calculation and system mass breakdown.

In phase III, a flying wing aircraft was developed base on the same design requirements. A comparison of it and the baseline was given to see the benefits and challenges of the new concept. In this stage, the author mainly contributed to the landing gear design of FW-11.

The author’s contributions and the main achievements of each phase were represented in following chapters.

A.2 Derivation of Design Requirements

A.2.1 Introduction

In order to gain a comprehensive design requirement, seven teams worked to survey in different aspects. The author was allocated to the Engine team and was in charge of engine performance estimation.

A.2.2 Engine Performance Estimation

A 2.2.1 Task

Compile a set of estimated engine performance data tables for a wide range of engines which determined by the Engine General Characteristics team. These should include Thrust and the specific fuel consumption (sfc) as a function of altitude, Mach number and throttle setting. A level of fidelity appropriate to the conceptual design phase is anticipated. Estimation/analysis methods can be consistent with this objective.

Finally, four engines which were widely used in current aircraft were chosen. The main parameters of these engines are shown in table A2-1.

Table A2-1 Main parameters of engines currently in service

TYPE	BPR	OPR	Mass Flow (Kg/s)	Net Thrust (N) TO
CFM56-5B2	5.5	35.4	433.6	137940
V2530-A5	4.6	36.4	384	139740
CF6-80C2	5.05	31.5	800	267480
RB211-524GH	4.3	33	729	269470

A 2.2.2 Engine Modelling

According to the engine decks obtained from Jane’s Engine Handbook, engine mode structure was established firstly. The models are similar for CFM56-5B2, V2530-A5 and CF6-80C2, which is illustrated in Figure A2-1. The engine model of RB21-24GH was shown in Figure A2-2.

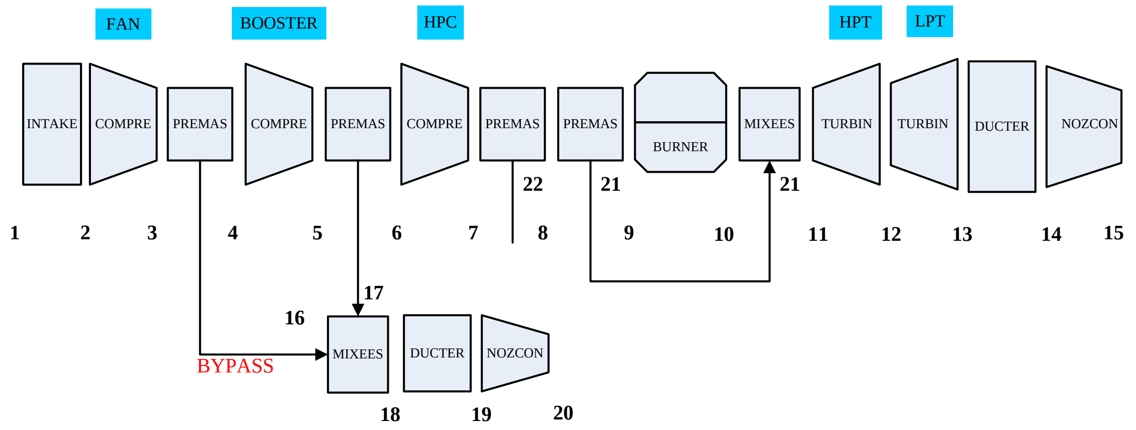


Figure A2-1 Engine model A

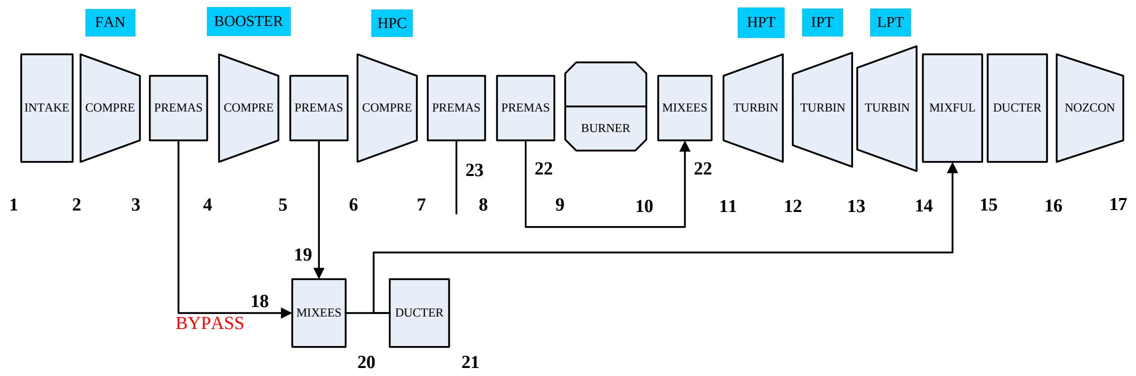


Figure A2-2 Engine model B

A 2.2.3 Simulation Result

With these initial parameters, the engine design point and off-design point performance are simulated. All these tasks are carried out by using simulation software TURBOMATCH. Taking into account the length of report, the programme language and the intermediate process are not given. The following figures illustrate the simulation results of CF6-80C2 engine.

Figure A2-3 described the design point simulation results, which shown the variation of Net Thrust and SFC with Turbine Entry Temperature (TET) change. Figure A2-4 and A2-5 illustrated the off-design point simulation results.

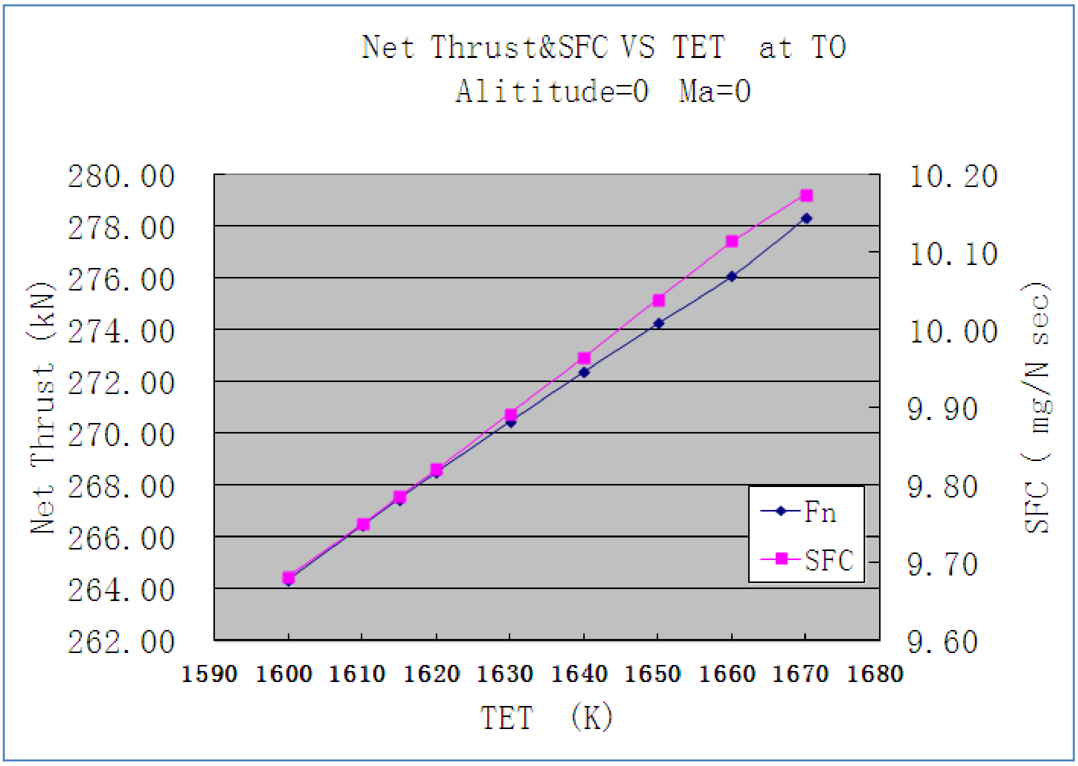


Figure A2-3 Variation of Net Thrust and SFC with TET

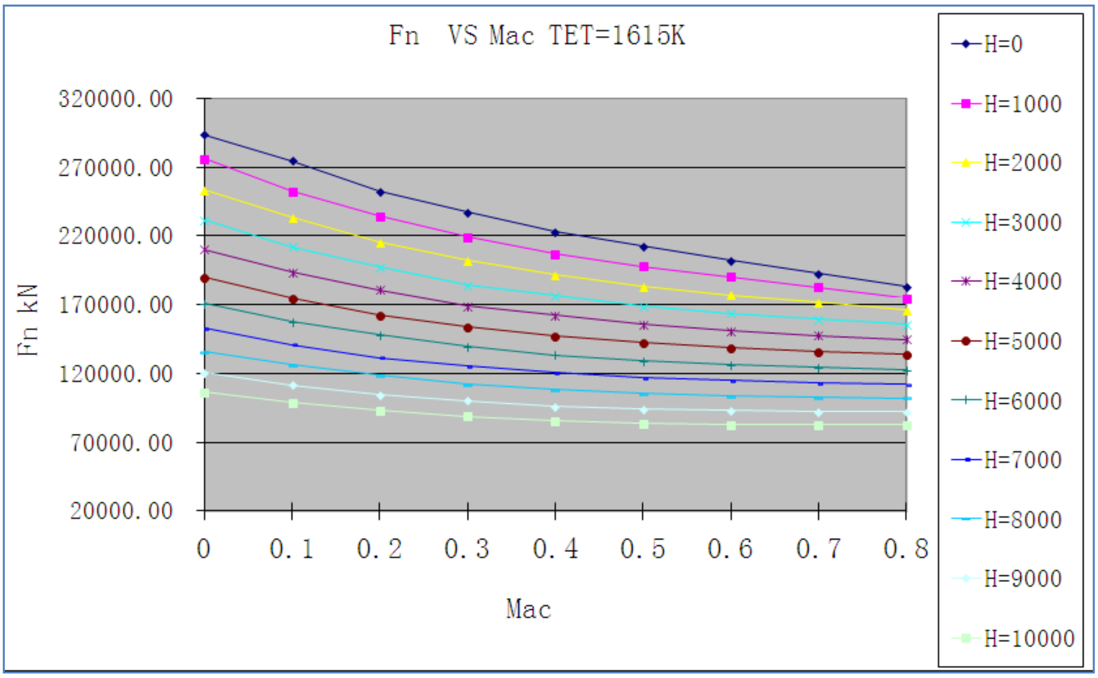


Figure A2-4 Variation of Net Thrust with Altitude and Mach number

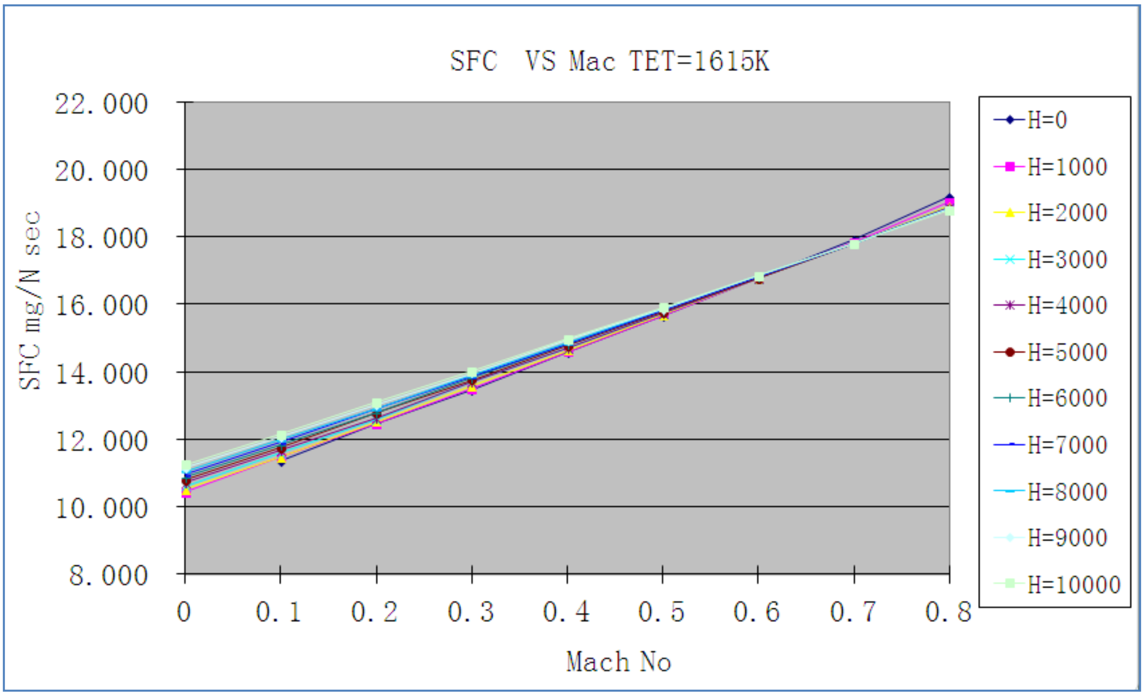


Figure A2-5 Variation of SFC with Altitude and Mach number

Finally, the simulated performance characteristics of four engines are represented in table A2-2.

Table A2-2 Engine performance characteristics estimation

TYPE	Mass Flow (Kg/s)	Net Thrust (N) TO	SFC (mg/Ns) Simulated	SFC (mg/Ns) Public data
CFM56-5B2	433.6	137940	19.1	18.23
V2530-A5	384	139740	17.04	16.26
CF6-80C2	800	267480	9.785 (TO)	9.63 (TO)
RB21-524GH	729	269470	17.74	16.48

It is can be seen that the simulation SFC data is a little higher than the value from publication. However, the fidelity is located within the acceptable level. Accordingly, these models can be used as the baseline engine to simulate the propulsion performance in next phases.

A.2.3 Phase Summary

Seven teams collected data from geometric, aerodynamic/static stability performance, engine performance, manufacturer and operator aspects, made a compensative survey and market analysis. To sum up, the specific design requirements of FW-11 aircraft shall be:

- 250seats international aircraft;
- 7500 nm range;
- M 0.80-0.85 cruise speed;
- Taking-off and Landing at 4E airports;
- Competitive price, Unit price less than $185 million;
- Better fuel efficiency, 25% fuel reduction;
- 20.5 dB noise reduction;
- Lower life cycle costs;
- Higher reliability and safety;
- Flexible operating capabilities;
- Entry service 2020.

A.3 Conventional Aircraft Design

A.3.1 Introduction

As the design requirement was determined, conceptual design of a long range and a medium range conventional civil aircraft processed in parallel. The author was allocated to the Mass and CG team in this phase.

The maximum take-off weight of the aircraft can be broken down as:

$MTOW = M_{OE} + M_F + M_{PL}$

M_{OE} —— Operating Empty Mass of the aircraft

M_F —— Mass of the mission fuel

M_{PL} —— Mass of the payload

The author contributes to the aircraft fuel mass estimations and system mass breakdown work.

A.3.2 Fuel Mass Calculation

In order to calculate the mission fuel mass of the aircraft, a typical mission profile is drawn as below. The method that was adapted is Dr. Jan Roskam's method is a rapid approach to calculate the fuel mass of the aircraft in conceptual design phase. [18]

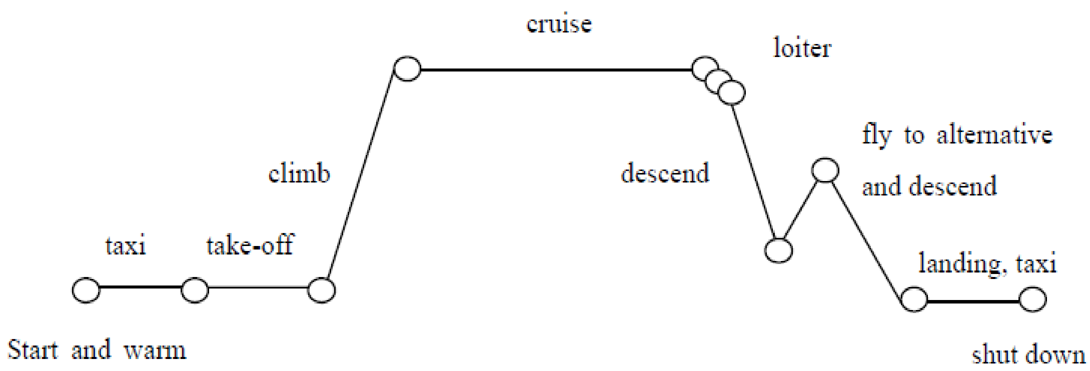


Figure A3-1 Typical mission Profile

A 3.2.1 Calculation Methodology

A typical mission profile is considered as follow for the calculation of the aircraft fuel mass.

STEP 1: Engine start and warm up.

The mission begin from M_{TO}, the mass at the end of the phase is M_1. According to empirical data, M_1/M_{TO} is s 0.99 typically.

STEP2: Taxi.

The mass of start point and finish point of this period are M_1 and M_2 respectively. According to empirical data, M_2/M_1 is 0.99.

STEP3: Take-off.

The mass of start point and finish point of this period are M_2 and M_3 respectively. According to empirical data, M_3/M_2 is 0.995.

STEP4: Climbing to cruise attitude and cruise speed.

The mass of start point and finish point of this period are M_3 and M_4 respectively. According to empirical data, M_4/M_3 is 0.98.

STEP5: Cruise.

The mass of start point and finish point of this period are M_4 and M_5 respectively. The mass of the fuel consumed during this flight segment can be calculated using Breguet's range equation.

$R_{cr} = (v/cj)_{cr} \times (L/D)_{cr} \times \ln(M_4/M_5)$

R_{cr} —— range

V —— airspeed of cruise

Cj —— cruise SFC of the engine

L/D —— lift to drag ratio

STEP6: Loiter.

The mass of start point and finish point of this period are M_5 and M_6 respectively. The mass of the fuel consumed during this flight segment can be calculated using Breguet's range equation.

$E_{ltr}=(1/ cj)_{ltr}\times(L/D)_{ltr}\times\ln(M_5/ M_6)$

E_{ltr} —— loiter time

STEP7: Descent.

The mass of start point and finish point of this period are M_6 and M_7 respectively. According to empirical data, typical M_7/ M_6 is 0.99.

STEP8: Fly to alternate and descent.

The mass of start point and finish point of this period are M_7 and M_8 respectively. The calculation of fuel mass consumed during this flight segment can be same as Cruise segment.

$R_{cr}=(v/cj)_{cr}\times(L/D)_{cr}\times\ln(M_7/ M_8)$

STEP9: Landing, taxi and shut down.

The mass of start point and finish point of this period are M_8 and M_9 respectively. According to empirical data, typical M_9/ M_8 is 0.992.

Hence,

$MFF=(M_1/M_{TO})\times(M_2/M_1)\times(M_3/M_2)\times(M_4/M_3)\times(M_5/M_4)\times(M_6/M_5)\times(M_7/M_6)\times(M_8/M_7)\times(M_9/M_8)$

The fuel used during the mission will be:

$M_{FUSE}=(1- M_{FF})\times M_{TO}$

Accordingly, some parameters need be given by the performance team, such as the cruise speed, lift to drag ratio and SFC in different flight phase. The airspeed of cruise is 490kts, the time of loiter is 0.75hours.

A 3.2.2 Calculation Results

According to the initial maximum take-off mass and other input parameters given by other teams, the fuel mass for two type aircraft was calculated. Table A3-1 shows the final results of fuel mass estimation.

Table A3-1 Conventional aircraft fuel mass calculation results

Items	Seats	Range (nm)	M_{fuel} (kg)	MTOW (kg)
Long range aircraft	220	7000	86426	188181
Medium range aircraft	327	4000	65668	192415

A.3.3 System and Equipment Mass Breakdown

For the system mass prediction, some empirical equations is used in mass predication. The author employs the method from lecture notes of cranfield university which are similar with the Roskam's method. [19]

Accordingly, the mass of systems and equipments can be considered as the sum of powerplant mass, fuel and oil system mass, mass of power services, mass of furnishings and equipments mass:

$M_{sys}=M_{pi}+M_{f}+M_{psfc}+M_{fur}+M_{eq}$

A 3.2.1 Calculation Methodology

The calculation methodology is presented as follow:

- For the powerplant, the factor for turbofan engines to calculate power installation is 1.3, hence

  $M_{pi}=1.3M_{p}$
  M_{p} —— mass of engines

- For fuel and oil systems, the mass include the mass of the fuel tank (M_{tank}), is the mass of residual fuel (M_{rf}) and the mass of fuel system (M_{fs}).

  The volume of fuel can be calculated from the mass of fuel given before.

  The tank is blend with the structure of wing box. Sealing for integral tanks is likely to amount to about 10V kg.

  $M_{tank}=10V$ kg

  Residual fuel can amount to about 0.25% of take-off mass, which is $M_{rf}=0.0025M_{to}$.

  The mass of fuel system can be calculated as $M_{FS}=0.05M^{0.8}$

  Thus the total mass of fuel and oil system is:

  $M_{f}=M_{tank}+M_{rf}+M_{fs}$

- For the mass of the APU, it can be calculated by the equation:

  $M_{apu}=0.005M_{to}=290$kg

- For the mass of hydraulics with powered controls, it can be calculated by:

  $M_{hyd}=3.2Mto^{0.5}$

- For the mass of electrics, it can be calculated by:

  $M_{ele}=0.75Mto^{0.67}$

- For the mass of powered flying control systems, it can be calculated by:

  $M_{fc}=0.11Mto^{0.8}$

- For the environmental control systems mass calculation:

  $M_{en}=M_{ac}+M_{di}$

  M_{ac}—— mass of air-conditioning system

  M_{di} —— mass of de-icing system

  $M_{en}=M_{ac}+M_{di}=0.035Mto^{0.88}+0.16Mto^{0.7}$

  Thus the total mass of power services including flying controls is:

  $M_{psfc}=M_{apu}+M_{hyd}+M_{ele}+M_{fc}+M_{en}$

- The mass of furnishings includes the mass of cabin furnishings and the mass of seats. Since the design number of passengers is N_p, the total mass of furnishings is:

  $M_{fur}=45N_p$ kg

- The mass of equipment is made up of instruments & automatic controls which is about 250kg for civil aircraft with automatic flight system, radio & radar & navigation equipments which is about 1000 kg, fire precautions $M_{fp}=0.003M_{to}$, wing area is 276m^2 and external paint M_{ep}= 0.5s = 138kg**.** Thus the total mass of equipment is:

  $M_{eq}=M_{ia}+M_{rrn}+M_{fp}+M_{ep}$

A 3.2.2 Results

All of these methods are based on empirical formula. So, the outcome of calculation using these methods might not conform to the real figure. The process of mass calculation is iterating during conceptual design phase. The fuel mass and system mass calculation results are showing in Table 2.

Table A3-2 Conventional aircraft system mass calculation results

Part	Mass (kg)	Percentage of MTOW	Mass (kg)	Percentage of MTOW
	Long range aircraft Max-Seat:327 Range: 7500		Medium range aircraft Max-Seat:224 Range: 4000	
MTOW	188181.6		192415.1	
Total system mass	35960	19.11%	39983	20.78%
Powerplant	12441	6.61%	12441	6.47%
Fuel System	1937.1	1.03%	1685.9	0.88%
FCS	1824.1	0.97%	1856.85	0.97%
Hydraulic System	1388.1	0.74%	1403.67	0.73%
Electrical system	2564.6	1.36%	2603.1	1.35%
Accessory Drives	564.5	0.30%	577.23	0.30%
APU	300	0.16%	300	0.16%
ECS	1907.6	1.01%	2434.9	1.27%
Instrument	250	0.13%	250	0.13%
Radio	1000	0.53%	1000	0.52%
Fire Precaution	564.5	0.30%	577.23	0.30%
External paint	138.35	0.07%	138.35	0.07%
Furnishing	10080	5.36%	14715	7.65%

A.3.4 Phase Summary

In this phase, a long range aircraft and a medium range aircraft was designed concurrently. They shared the same wing but different length of body. The author contributed to the aircraft fuel mass calculation and system mass breakdown. The mass estimation process is a continual optimization. Finally, the fuel efficiency was estimated based on the mass calculation results. From the table A3-3, it can be seen that the designed conventional aircraft have a better fuel efficiency than the similar size civil airliner in service.

Table A3-3 Conventional aircraft system mass and fuel efficiency

Items	B767-200ER	A330-200	A310-300	A330-300	Long range	Medium range
seats	255	303	243	335	220	327
weight/pax(kg)	115.7	115.7	115.7	115.7	115.7	115.7
MTOW(kg)	175540	233000	150000	233000	188181.6	192415.1
OEW(kg)	82377	109100	79207	119931	78537	91060
payload(kg)	29496	35048	28108	38749	25447	37824
Payload&OEW(kg)	111873	144148	107315	158680	103984	128884
Payload Range(nm)	5600	5656	3700	4500	7721	5391
fuel capacity(kg)	63667	88852	42685	74320	81294	70439
Fuel used(kg)	60484	84409	40551	70604	75604	65508
Fuel/pax/nm(kg)	0.042	0.049	0.045	0.047	0.044	0.037

A.4 Flying Wing Aircraft Design

A.4.1 Introduction

In phase Ⅲ, a new concept, flying wing aircraft is designed based on the same design requirements. The author contributes to the aircraft landing gear design work. It is a big challenge for the author to design a flying wing aircraft landing gear.

A.4.2 Landing Gear Design

The landing gear design of the FW-11 aircraft in conceptual phrase is mainly considered in follow aspect, which is heavy reliance on Norman S. Currey’s book: *Aircraft Landing gear Design.* [20]

1) Landing Gear Disposition
2) Tires selection
3) Ground Operation capability

For FW-11 aircraft landing gear, a tricycle configuration is used as almost all of the civil transport aircraft. And there is no serious reason to derive from it.

With the estimated maximum take-off weight of around 190 tons, the landing gear strut and tire numbers were determined based on the past aircraft data. The nose landing gear is composed of one strut and two tires. The main landing gear has two struts, with four tires per strut.

A4.2.1 Landing Gear Disposition

The landing gear disposition depends on various factors:

a) Loading requirements
b) Stability requirements
c) Structure compatibility

- Loading consideration

For the loading, it is preferable to place 8% to 15% of aircraft weight on the nose gears when the aircraft is on ground. However, the main landing gear position is limited by the aft CG location and the stability requirements; the nose landing gear position is limited by the structural layout.

- Stability requirements

For the longitudinal stability, a tail-down angle of more than 15 degree is needed. It can prevent the aft CG move back to the main gear when brake. [21]

After trading off, the landing gear location is shown as following:

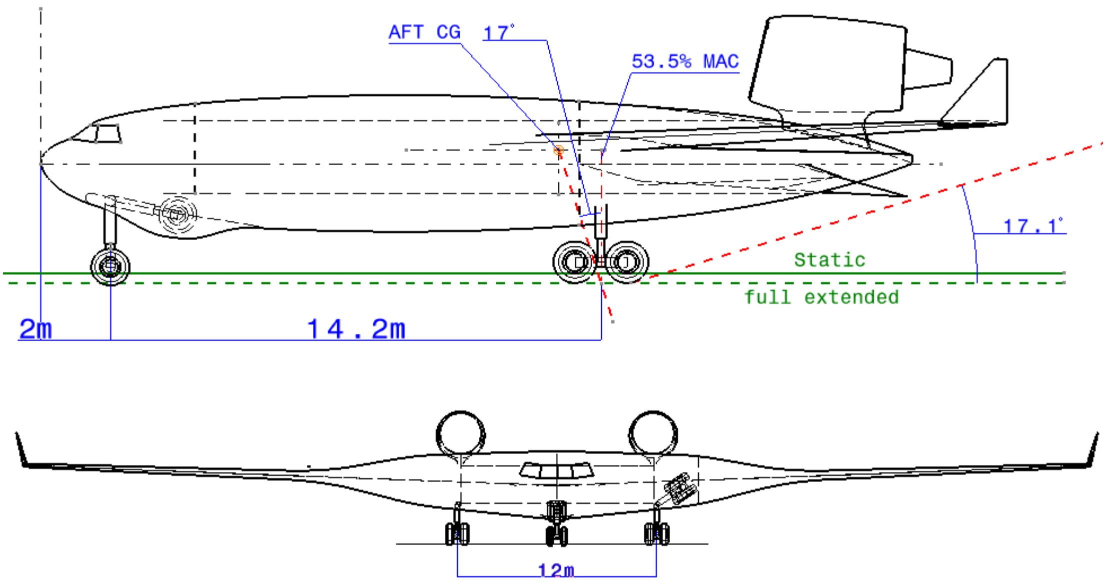


Figure A4-1 Landing Gear Location

As can be seen from the above figure, the load on the nose gear is 8.75% with the aft CG, and 17.4% with the forward CG. The loading range is within required limits. The landing gear tail-down angle of the FW-11 is exactly 17.1 degrees, which is above the limit.

For the lateral stability, the figure A4-2 illustrates the design situation:

The calculated turnover angle of the aircraft is 34 degrees, which is reasonable when compared with other transport aircraft.

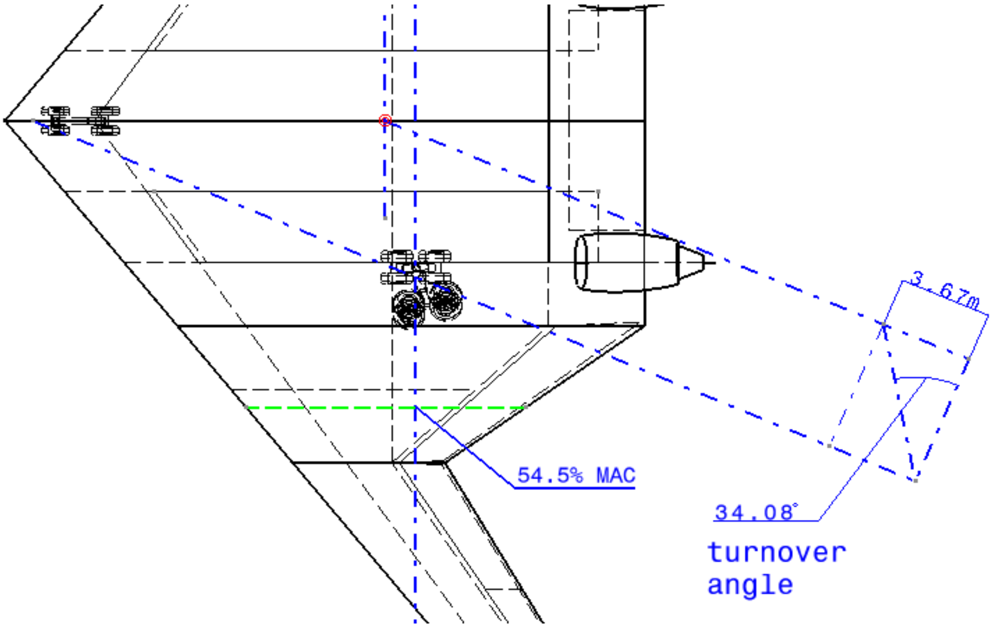


Figure A4-2 Landing Gear Turnover Angle

- Structure compatibility

For structural Compatibility, The nose landing gear swings backward into the fuselage because of the nose gear is located at 2m form nose for reduce the load on it. For the feature of flying wing structure, there is no space under the cabin in the centre of fuselage. The main gears retract outboard back of cargo bay and make a little turn back to avoid interferes with the middle spar.

The following figure shows the design situation and the landing gear position relative to the supporting structures.

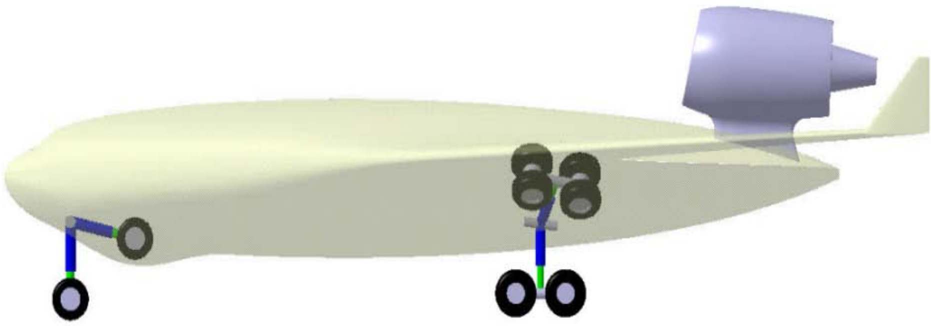
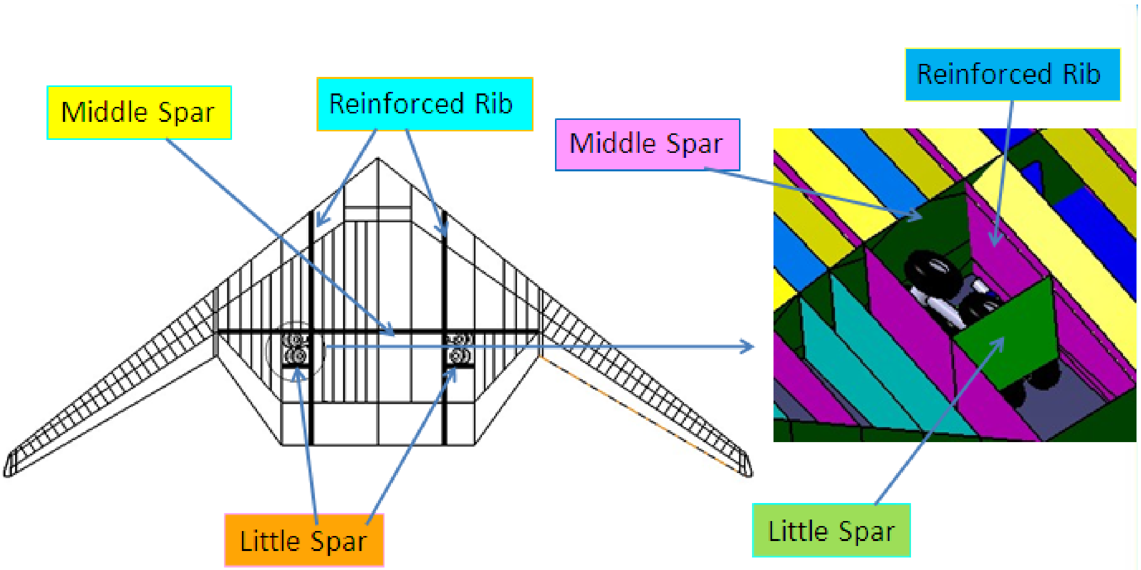
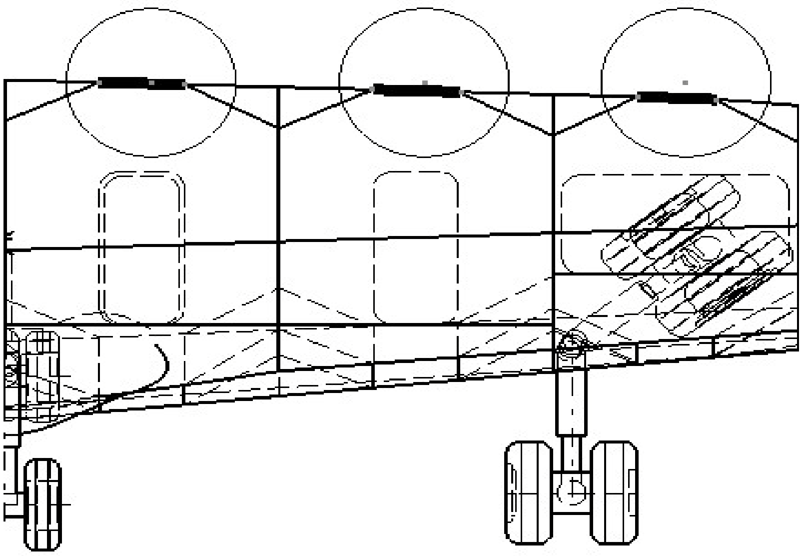


Figure A4-3 Landing Gear Stowage 3D Model



FigureA4-4 Main Landing Gear Structural Compatibility (a)



FigureA4-5 Main Landing Gear Structural Compatibility (b)

A4.2.2 Tires selection

For the landing gear tires selection, the loading on each wheel should be calculated. The following table shows the landing gear loading datasheet.

Table A4-1 Landing Gear Loading Datasheet

Item	Value	unit
Wheel Base	14.184	m
Distance AFT CG to NLG	12.969	m
Distance FWD CG to NLG	11.715	m
Load Percentage on NLG,AFT CG	8.57%	
Load Percentage on NLG,FWD CG	17.40%	
Maximum CG height	3.667	m
MTOW	176469.129	kg
number of main struts	2.000	
tires per main strut	4.000	
number of nose struts	1.000	
tires per nose strut	2.000	
deceleration speed	3.048	m/s/s
maximum speed on ground	225	km/hour
MLG maximum static load	34467.200	kg/strut
	17233.600	kg/tire
NLG maximum static load	34467.200	kg/strut
	17233.600	kg/tire
NLG braking load	17001.928	kg/strut
	8500.964	kg/tire
NLG dynamic load	51469.128	kg/strut
	25734.564	kg/tire

After calculation of the maximum load, radial tires were chosen. The following table shows the tire selection datasheet.

Table A4-2 Tire Selection Datasheet

Item	MLG Tires	NLG Tires	Unit
Tire Size	50x20-20	44x16.5-18	
Speed	225	225	mph
Max Load	53800	42500	lb
Inflation Press.	195	1 95	psi
Braking Load	77800	63750	lb
Weight	306.4	138.8	in
Dia.	50	44.5	in
Width	19	156.5	in
Rad.	20.3	18.4	
Aspect Ratio	0.767	0.807	

A4.2.3 Ground Operation capability

The following figure and table shows the turning radii of the aircraft.

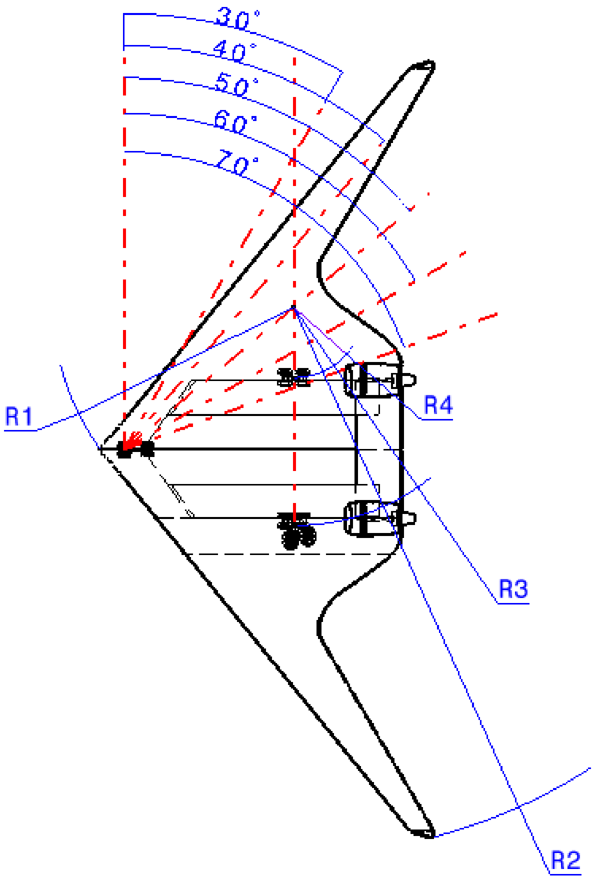


Figure A4-6 Ground Turning Radii

Table A4-3 Ground Turning Radii

Steering angle	R1	R2	R3	R4
30	29.45	58.31	29.28	16.62
40	23.42	50.24	22.43	10.92
50	20.1	45.96	18.31	5.91
60	18.14	42.37	15.6	2.2
70	16.99	39.47	13.74	0.84

This value is within the limitation of class 4E airports which is meets the design requirements.

A.4.3 Phase Summary

After several rounds of assessments and updates, the final configuration of a twin-engine flying wing aircraft is developed and frozen. The three-view drawing of the FW-11 aircraft is showing below.

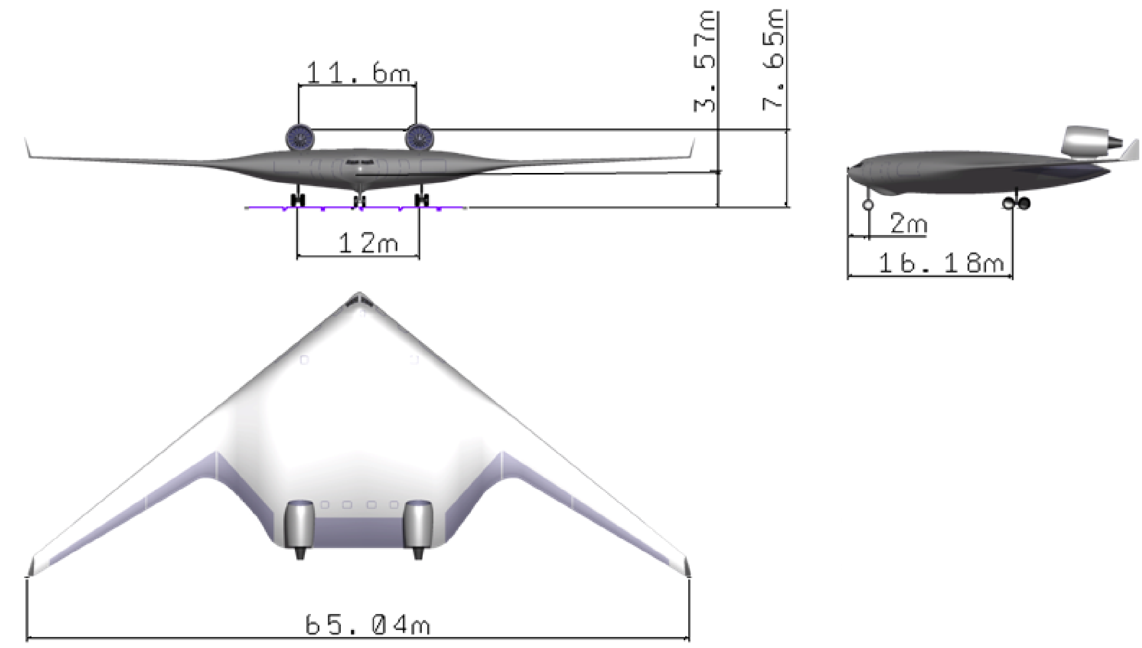


Figure A4-7 Three-view Drawing of the FW-11

According to the performance team estimation results, the comparison of fuel efficiency between the new concept and the baseline is shown as follow. Although there is little weak on stability operations, flying wing aircraft has unparalleled advantages in oil saving and noise reduction. This new concept aircraft research work is worthiness and challenged.

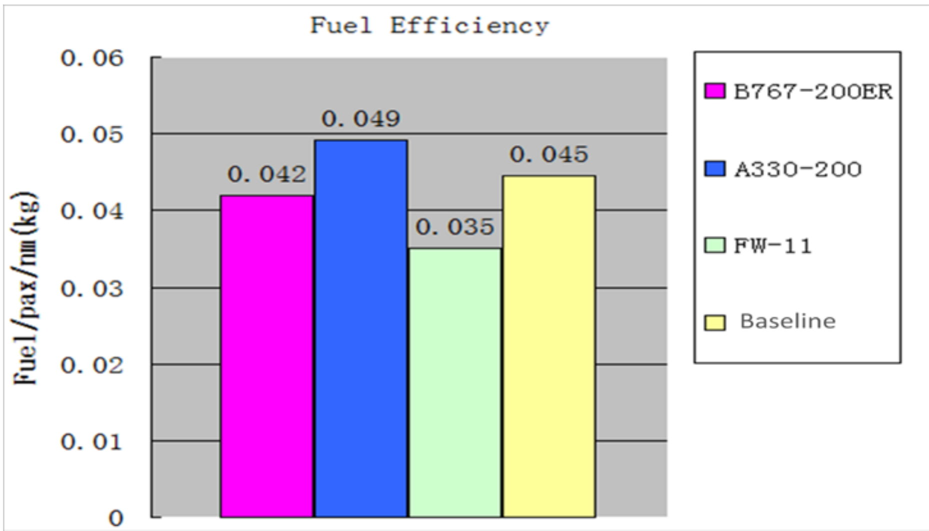


Figure A4-8 The Fuel Efficiency of FW-11

A.5 Conclusion

In this group design project, the author worked in a team to design a new concept civil aircraft. After five months work, the conceptual design of a flying wing airliner—FW-11is completed.

The GDP work was divided into three phrases. At the beginning, we collected data from different aspects to get the aircraft design requirements. Then we finished a conceptual design of a conventional civil aircraft in order to practice the design flow of the aircraft conceptual design. After that we developed a new configuration—flying wing aircraft in conceptual design phase. According to the performance assessments of the FW-11 with the existing aircraft, it can be seen that the whole research work is successful. The final configuration of aircraft was frozen and will be used as input of the preliminary design in next year.

Although the author made different contributions in different phases, the whole process was challenged and experienced. The author was in charge of engine performance characteristics estimation during the design requirements derivation phase. In conventional aircraft design phase, he made the fuel mass calculation and system mass breakdown for two configurations. Finally, the author finished the conceptual design of the landing gear for the flying wing aircraft and contributed to the poster and brochure design, as well as an imaginative video for the final presentation.

Appendix B Hydraulic Power system FHA Summary

Function Description	**Failure condition (hazard description)**	**Flight phase**	**Effect of failure condition on Aircraft/Crew/Occupants**	**hazard Classification**
1)Supply hydraulic power	1.1) Loss of all hydraulic power supply.	Take off， Flight , Landing	1. The aircraft will loss flight control capability. 2. The flight crew cannot control the aircraft continued safe flight takeoff and landing. 3. All the occupants might suffer serious injury.	Catastrophic
1)Supply hydraulic power	1.2) Loss of LEFT and RIGHT channel hydraulic power supply.	Take off， Flight , Landing	1. The aircraft will partially loss of the aircraft controllability and those function: ● L outer elevator ● R outer elevator ● L&R thrust reverser 2. The flight crew need to take the relative procedures to cope with this circumstance which will make the work load increased. 3. All the occupants might feel discomfort due to due to partly lose controllability of the aircraft.	Major

Function Description	**Failure condition (hazard description)**	**Flight phase**	**Effect of failure condition on Aircraft/Crew/Occupants**	**hazard Classification**
1)Supply hydraulic power	1.3) Loss of LEFT and CENTRE channel hydraulic power supply.	Take off，Flight , Landing	1. The aircraft will partially loss of the aircraft controllability and those function: ● L inner elevator ● L aileron ● R split rudder ● L thrust reverser ● Nose Landing Gear Steering ● Landing gear normal retraction/extension 2. The flight crew need to take the relative procedures to cope with this circumstance which will make the work load increased. 3. All the occupants might feel discomfort due to due to partly lose controllability of the aircraft.	Major

Function Description	**Failure condition (hazard description)**	**Flight phase**	**Effect of failure condition on Aircraft/Crew/Occupants**	**hazard Classification**
1)Supply hydraulic power	1.4) Loss of RIGHT and CENTRE channel hydraulic power supply.	Take off，Flight , Landing	1. The aircraft will partially loss of the aircraft controllability and those function: ● R inner elevator ● R aileron ● L split rudder ● R thrust reverser ● Nose Landing Gear Steering ● Landing gear normal retraction/extension 2. The flight crew need to take the relative procedures to cope with this circumstance which will make the work load increased. 3. All the occupants might feel discomfort due to due to partly lose controllability of the aircraft.	Major
1)Supply hydraulic power	1.5) Loss of CENTRE channel hydraulic power supply.	Take off，Flight , Landing	1. The aircraft will loss those control path: ● Nose Landing Gear Steering ● Landing gear normal retraction/extension 2. The flight crew will take measures to cope with this circumstance which will increase the work load. 3. The occupants might feel slight inconvenience.	Minor

Function Description	Failure condition (hazard description)	Flight phase	Effect of failure condition on Aircraft/Crew/Occupants	hazard Classification
1)Supply hydraulic power	1.6) Loss of LEFT channel hydraulic power supply	Take off，Flight , Landing	1. The aircraft will loss those control path: ● R outer elevator ● L thrust reverser 2. The flight crew will take measures to cope with this circumstance which will increase the work load. 3. The occupants might feel slight inconvenience.	Minor
1)Supply hydraulic power	1.7) Loss of RIGHT channel hydraulic power supply	Take off，Flight , Landing	1. The aircraft will loss those control path: ● L outer elevator ● R thrust reverser 2. The flight crew will take measures to cope with this circumstance which will increase the work load. 3. The occupants might feel slight inconvenience.	Minor
2）Provide annunciation to ECAS	2.1) loss of Low-Pressure warning when LEFT, RIGHT and CENTRE hydraulic power subsystems failure	Take off，Flight , Landing	1. The aircraft will loss flight control capability. 2. The flight crew cannot control the aircraft continued safe flight and landing. 3. All the occupants might be seriously injured due to lose controllability of the aircraft.	Catastrophic

Function Description	**Failure condition (hazard description)**	**Flight phase**	**Effect of failure condition on Aircraft/Crew/Occupants**	**hazard Classification**
2）Provide annunciation to ECAS	2.2) loss of Low-Pressure warning when two hydraulic power subsystems failure	Flight	1. The aircraft will lose some control path while the flight crew is not aware of it. 2. The flight crew work load will be increased excessively to deal with this emergency situation. 3. All the occupants might suffer injury or severe discomfort.	Major
		Take off，Landing	1. The aircraft will lose some control path while the flight crew is not aware of it. 2. The flight crew cannot control the aircraft continued safe flight and landing. 3. All the occupants might be seriously injured due to lose controllability of the aircraft.	Hazardous
2）Provide annunciation to ECAS	2.3)loss of Low-Pressure warning when one hydraulic power subsystem failure	Take off，Flight , Landing	1. The aircraft will loss few control path: 2. The flight crew need to take the relative procedures to cope with this circumstance which will make the work load increased 3. All the occupants might feel discomfort due to due to partly lose controllability of the aircraft.	Major

Function Description	**Failure condition (hazard description)**	**Flight phase**	**Effect of failure condition on Aircraft/Crew/Occupants**	**hazard Classification**
3）Fire Protection	3.1) loss of ability to shut off EDP suction in case of fire.	All phase	1. It may cause fire when engine when engine fire. 2. The flight crew work load will be increased excessively to deal with this emergency situation. 3. The occupants might be injured due to fire.	Hazardous

Appendix C Hydraulic Power system FMECA Summary

Component: Engine driven pump **Function: Provides pressured fluids**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Loss of output flow	Flight, ground	Loss of relative EDP output flow.	Decrease LEFT or RIGHT system power capability.	Major
Reduced output flow	Flight, ground	Reduce relative EDP output flow.	Decrease LEFT or RIGHT system power capability.	Minor
Internal leak	Flight, ground	Reduced relative EDP output flow.	None.	Minor
External leak	Flight, ground	Loss of relative subsystem EDP output flow.	Decrease LEFT or RIGHT system power capability. Impact on environment.	Major
Overheat	Flight, ground	Cause seal failure and fluid leakage. External fluid spillage.	Decrease relative system power capability. Impact on environment.	Major

Component: Electrical motor pump **Function: Provides pressured fluids**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Loss of output flow	Flight, ground	Loss of relative EMP output flow.	Decrease relative system power capability.	Major
Reduced output flow	Flight, ground	Reduce relative EMP output flow.	Decrease relative system power capability.	Minor
Internal leak	Flight, ground	Reduce relative EMP output flow.	None.	Minor
External leak	Flight, ground	Loss of relative EMP output flow.	Decrease relative system power capability. Impact on environment.	Major
Pump overheat	Flight, ground	Cause seal failure and fluid external leakage.	Decrease relative system power capability. Impact on environment.	Hazardous
Motor overheat	Flight, ground	Loss of relative EMP output flow.	Decrease relative system power capability. Impact on environment.	Hazardous

Component: Hydraulic reservoir **Function: store and pressure fluids for pumps, radiating, remove the air in fluids, sense the fluids temperature, detect the low level signal of fluids quantity, measure reservoir fluids quantity**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Fluid chamber leak	Flight, ground	Loss of relative subsystem power supply.	Loss of relative subsystem power capability. External fluid spillage.	Major
Pressure chamber leak	Flight, ground	Loss of reservoir fluids pressure. May cause relative pumps damage.	Decrease relative system power capability.	Major
Internal leak between fluid chamber and pressure chamber	Flight, ground	Reservoir fluids pressure decrease. May cause relative pumps damage.	None.	Minor

Component: Auto Bleed Valve **Function: discharge the air in fluid to depressurize reservoir automatically**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Auto Bleed Valve block	Flight, ground	Reservoir losses of auto bleed capability.	None.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Reservoir Temperature Sensor **Function: provide fluids temperature signal**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Reservoir Temperature Sensor failed to output	Flight, ground	Unable to provide fluids temperature signal.	Loss of reservoir fluids overheat warning message when temperature is high.	Minor
Reservoir Temperature Sensor inaccurate output	Flight, ground	Provide fluids overheat false warning signal.	Erroneous reservoir fluids temperature warning message.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Reservoir Low-level Sensor **Function: provide reservoir low level warning signal**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Reservoir Low-level Sensor failed to output	Flight, ground	Unable to provide reservoir low level warning signal.	Loss of reservoir low level warning message when system leak.	Major
Reservoir Low-level Sensor inaccurate output	Flight, ground	Provide reservoir low level false warning signal.	Erroneous reservoir low level warning message.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: EDP Pressure and case drain filter module Function: filtering the contaminants in fluids prevent system clogging, provide electrical and mechanical alarm signals when filter need to be cleaned or changed				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Pressure Filter block	Flight, ground	Filter loss of filtering capability, fluids flow bypass, Pollution the Relative components.	None.	minor
Case drain filter block	Flight, ground	Filter loss of Case drain filtering capability.	None.	minor
Contamination indicator switch failed to output	Flight, ground	Unable to provide filter contamination warning signal.	Loss of filter contamination warning message when filter block	Minor
Contamination indicator switch inaccurate output	Flight, ground	Provide filter contamination false warning signal.	Erroneous filter contamination warning message.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: EMP Pressure and case drain filter module

Function: filtering the contaminants in fluids prevent system clogging, provide electrical and mechanical alarm signals when filter need to be cleaned or changed

Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Pressure Filter block	Flight, ground	Filter loss of filtering capability, fluids flow bypass, Pollution the Relative components.	None.	minor
Case drain filter block	Flight, ground	Filter loss of Case drain filtering capability.	None.	minor
Contamination indicator switch failed to output	Flight, ground	Unable to provide filter contamination warning signal.	Loss of filter contamination warning message when filter block.	Minor
Contamination indicator switch inaccurate output	Flight, ground	Provide filter contamination false warning signal.	Erroneous filter contamination warning message.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Return Filter Module **Function: filtering the contaminants in fluids prevent system clogging, provide electrical and mechanical alarm signals when filter need to be cleaned or changed**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Return filter block	Flight, ground	Filter loss of filtering capability, fluids flow bypass, Pollution the Relative components.	None.	minor
Return filter bypass valve failed to open	Flight, ground	Relative filter output pressure decrease.	Decrease relative system power capability.	major
Contamination indicator switch failed to output	Flight, ground	Unable to provide filter contamination warning signal.	Loss of filter contamination warning message when filter block.	Minor
Contamination indicator switch inaccurate output	Flight, ground	Provide filter contamination false warning signal.	Erroneous filter contamination warning message.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Fire Shut-off Valve **Function: Cut off hydraulic fluid flowing into EDP**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Failed to close	Flight, ground	relative EDP suction flow unable to cut off.	May cause fire when failure on EDP.	Hazardous
Failed to open	Flight, ground	Loss of relative EDP output even damage pumps.	Decrease relative system power capability.	major
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Low Pressure Switch **Function: provide low pressure signals of pump outlet**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Never indicates low pressure	Flight, ground	Unable to provide relative pump low pressure warning signal.	Loss of relative pump low pressure warning message .	Major
always indicates low pressure	Flight, ground	provide pump low pressure false warning signal.	Erroneous pump low pressure warning message for pilots.	Minor
Seal fails	Flight, ground	External leak through the spar. Possible indication of pump failure.	Impact on environment.	Minor

Component: System Pressure Sensor **Function: detect system operating pressure**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Failed to output	Flight, ground	Unable to measure relative system pressure.	Loss of relative system pressure message.	Minor
inaccurate output	Flight, ground	System pressure cannot be monitor correctly.	Erroneous system pressure message for pilots.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Ram Air Turbine **Function: Provide emergency hydraulic power**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Pump fails to output	Flight, ground	Loss of RAT pump output flow.	Loss of emergency power.	Hazardous
Fails to deploy	Flight	Loss of RAT pump output flow.	Loss of emergency power.	Hazardous
Fails to retract	Ground	None.	None.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: System relief valve **Function: prevent pressure building up to a dangerously high level**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Failed to open	Flight, ground	Loss ability to relieve pressure when it building up , may cause components damage or seals blowing.	Decrease relative subsystem power capability.	Major
Failed to close	Flight, ground	System pressure cannot building up.	Loss of relative subsystem power capability.	Hazardous
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Check valve (in main pressure line) **Function: prevents the flow will not be a cross direction**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Failed to open	Flight, ground	System pressure cannot building up for the pressure flow bypass through relief valve.	Loss of relative subsystem power capability.	Minor
Failed to close	Flight, ground	Possible backflow from downstream.	Decrease relative subsystem power capability.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: Check valve (in front of reservoir pressure line) **Function: prevents the flow will not be a cross direction**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Failed to open	Flight, ground	Loss of reservoir fluids pressure. May relative cause relative pumps damage.	Decrease relative subsystem power capability.	Minor
Failed to close	Flight, ground	Possible backflow from downstream will effect reservoir fluids pressure.	Decrease relative subsystem power capability.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

Component: System accumulator **Function: maintain system pressure when flow demands beyond maximum output of pumps in a short periods**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Leak in fluid chamber	Flight, ground	Loss of relative subsystem power supply.	Loss of relative subsystem power capability. External fluid spillage.	Major
Leak in air chamber	Fight	Loss of ability to maintain the system pressure when large peak loads.	None.	Minor
Leak in air chamber	Ground	Cannot charge and the pressure gauge indicate zero.	None.	Minor

Component: Reservoir pressure accumulator **Function: maintain reservoir pressure when there is a demands**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Leak in fluid chamber	Flight, ground	Loss of relative subsystem power supply.	Loss of relative subsystem power capability. External fluid spillage.	Major
Leak in air chamber	Fight	Loss of ability to maintain the reservoir fluids pressure when large peak loads, Cannot charge on ground and the pressure gauge indicate zero.	None.	Minor
Leak in air chamber	Ground		None.	Minor

Component: Heat exchanger **Function: transfer heats of fluids to maintain a safety temperature**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Block in hydraulic line	Flight, ground	Over temperature of relative subsystem fluid.	None.	Minor
External leak	Flight, ground	Decrease relative subsystem power capability.	Decrease relative subsystem power capability. External fluid spillage may contaminate fuel and effect fuel system safety.	Major

Component: Ground-Pressurization connection **Function: port for ground pressure supply**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Valve fails to open	Ground	Loss of ground pressure supply capability.	None.	Minor
Valve fails to close	Ground	Possible fuel spillage.	Possible fuel spillage.	Minor

Component: Ground-Suction connection **Function: port for ground power connect**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Valve fails to open	Ground	Loss of ground pressure supply capability.	None.	Minor
Valve fails to close	Ground	Possible fuel spillage.	Possible fuel spillage.	Minor

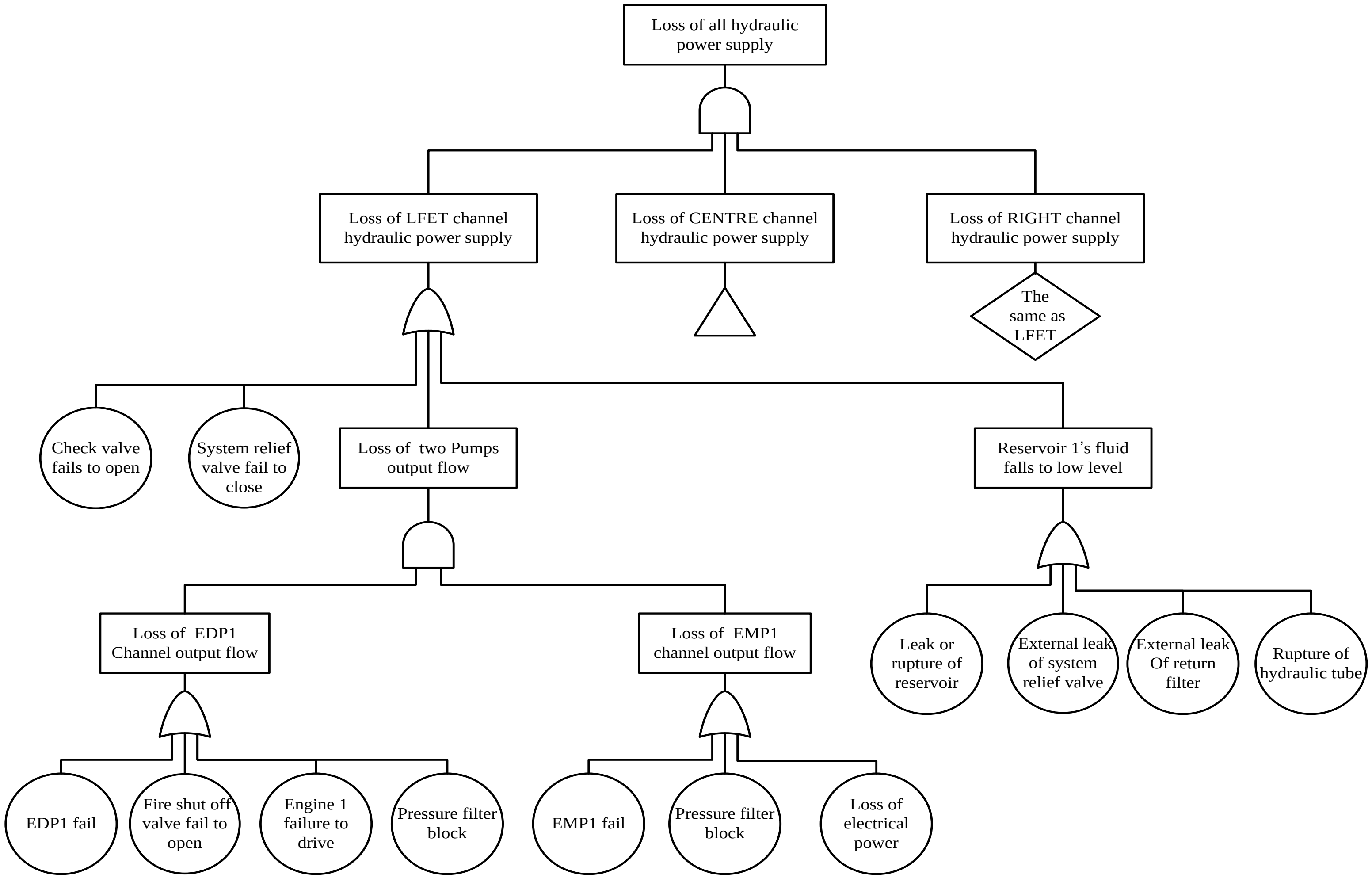
Component: Filling connection **Function: port for filling fluid into reservoirs**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Valve fails to open	Ground	Loss of reservoir filling capability.	None.	Minor
Valve fails to close	Ground	Possible fuel spillage.	Possible fuel spillage.	Minor

Component: Ground- charging connection **Function: port for charging the accumulator**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Valve fails to open	Ground	Loss of accumulator charging capability.	None.	Minor
Valve fails to close	Ground	Relative accumulator loss pressure.	None.	Minor

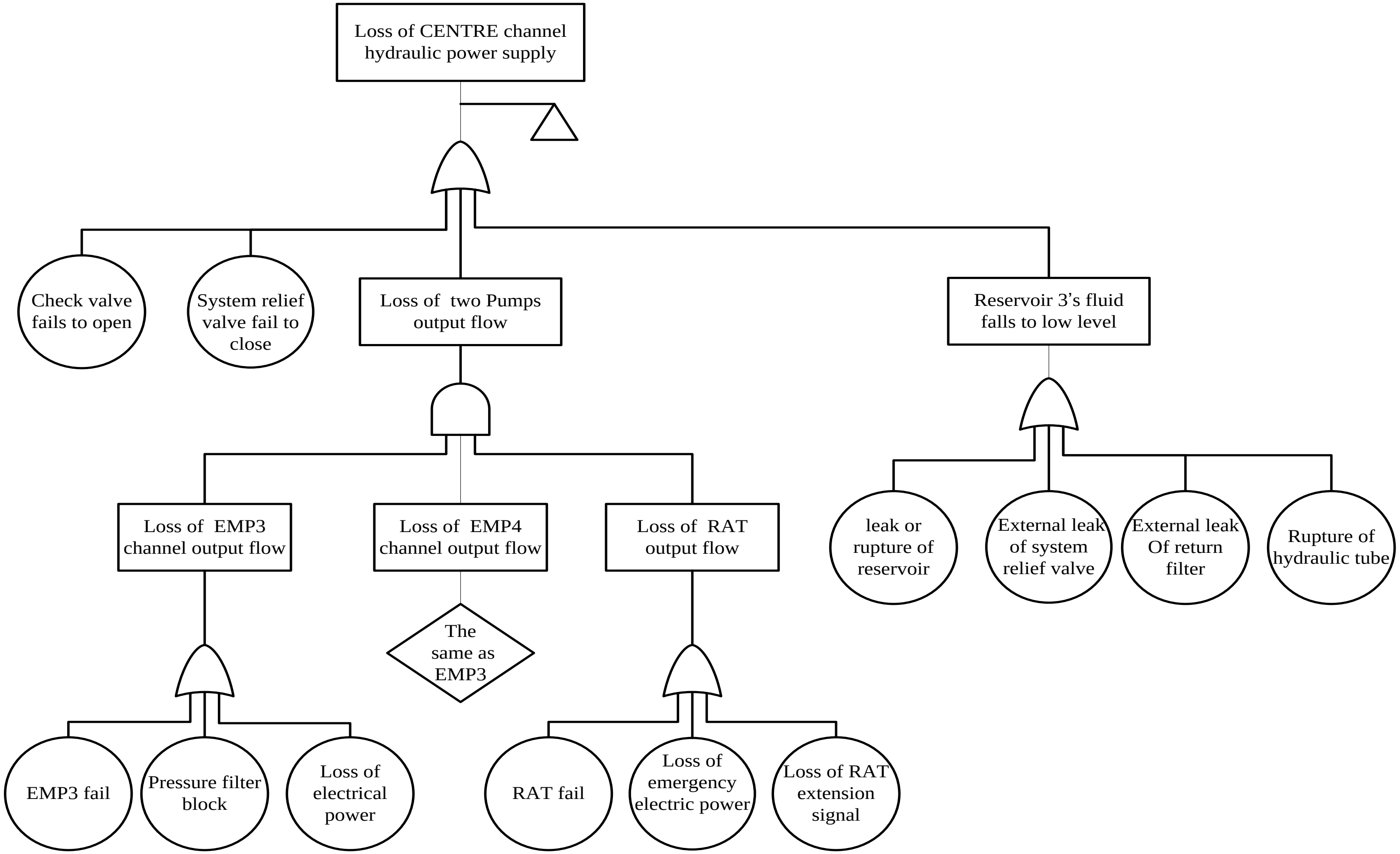
Component: pressure gauge **Function: port for charging the accumulator**				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
fails to indicate the pressure	Ground	Loss of information of accumulator pressure for operator.	None.	Minor
inaccurate indicate the pressure	Ground	Loss of information of accumulator pressure for operator.	None.	Minor
External leak	All phase	Relative accumulator loss pressure.	None.	Minor

Component: Reservoir Quantity Gauge **Function:** indicate the fluids quantity of reservoir				
Failure Modes	**Flight phase**	**Effects on system**	**Effects on Aircraft**	**Severity level**
Fails to indicate the fluids quantity of reservoir	Ground	Loss of information of fluids quantity of reservoir for operator.	None.	Minor
Inaccurate indicate the fluids quantity of reservoir	Ground	Loss of information of fluids quantity of reservoir for operator.	None.	Minor
Seal fails	Flight, ground	External leak through the spar.	Impact on environment.	Minor

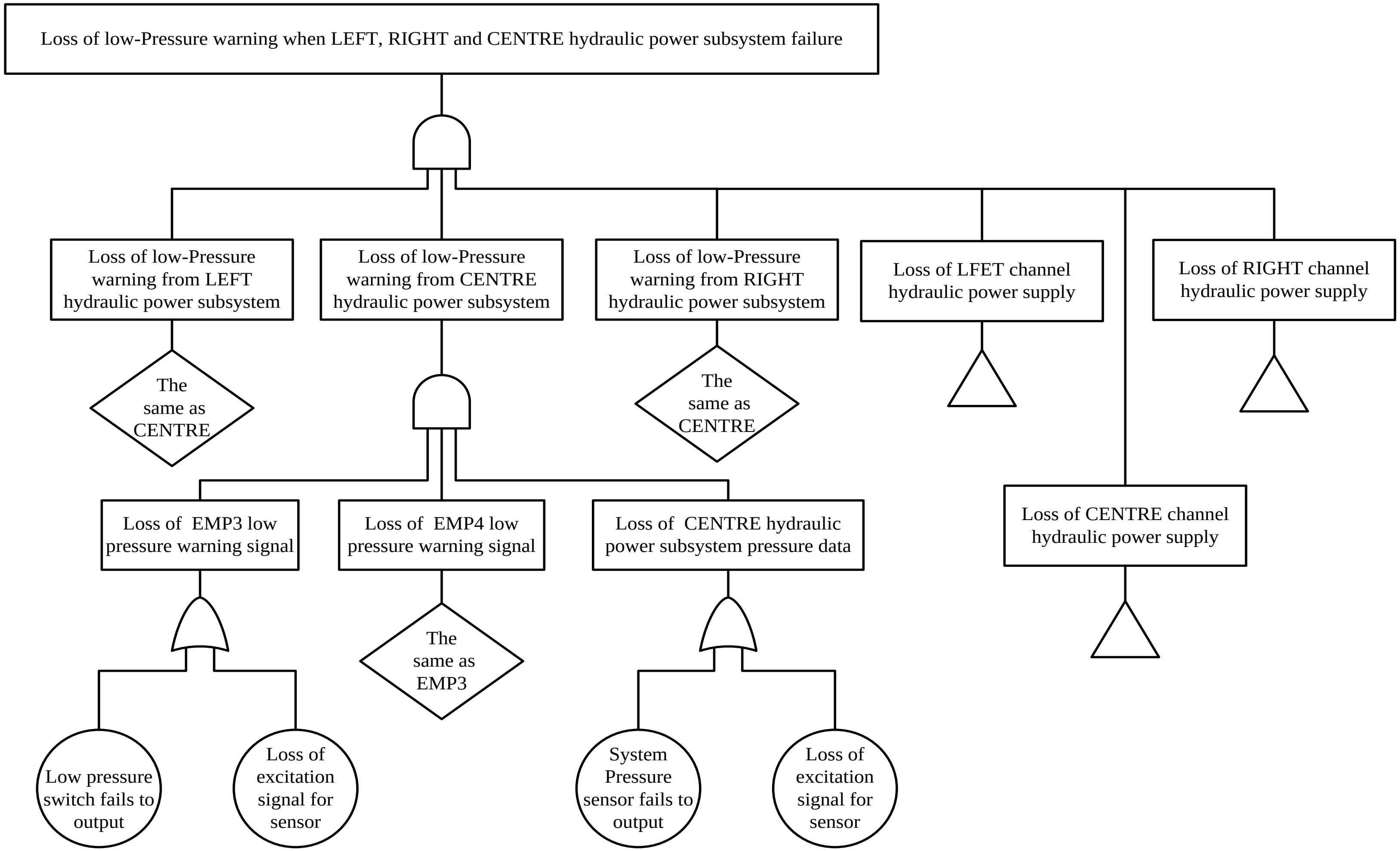
Appendix D Hydraulic Power system FTA Summary



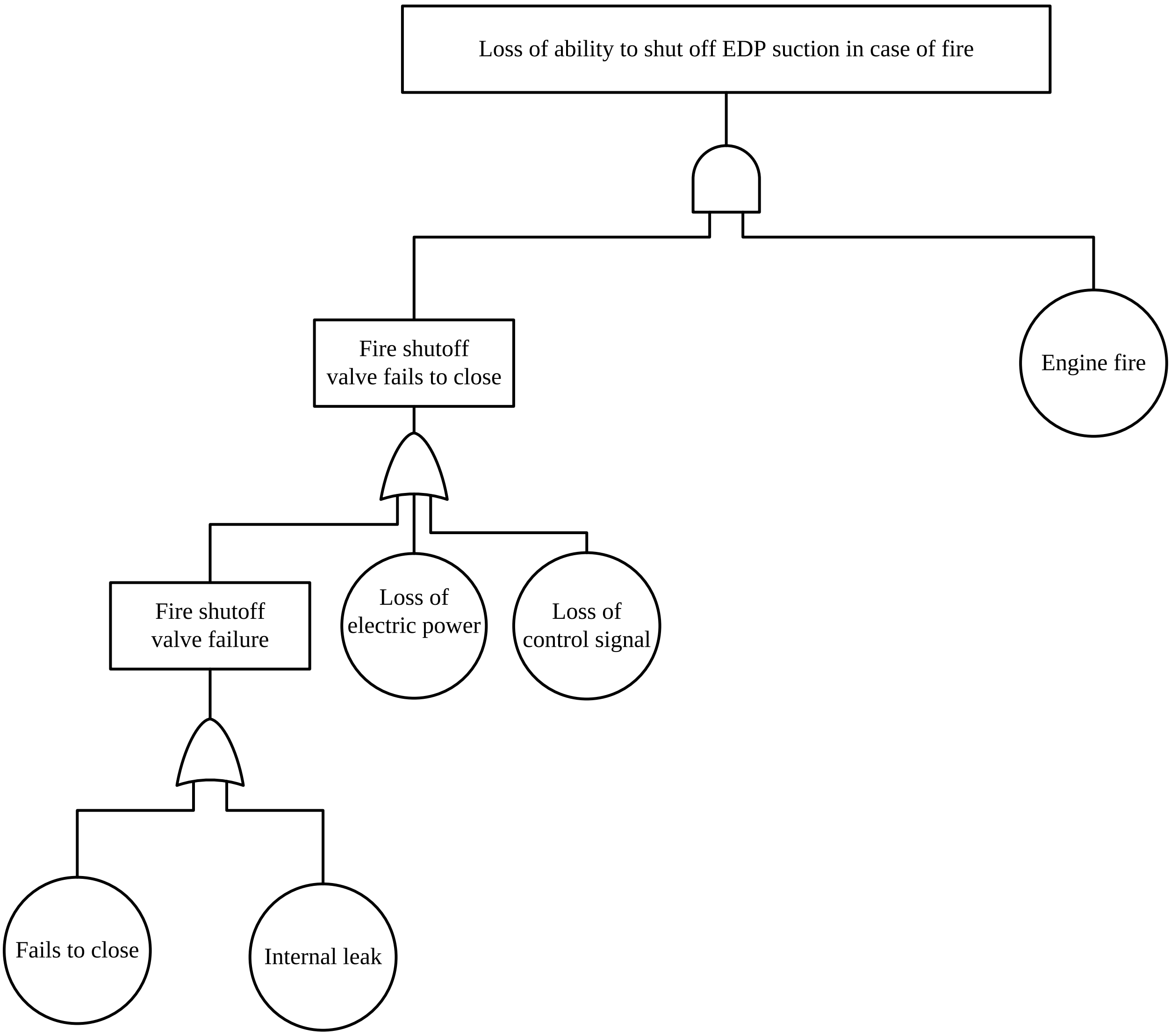
Loss of all hydraulic power supply (1)



Loss of all hydraulic power supply (2)



Loss of low-Pressure warning when LEFT, RIGHT and CENTRE hydraulic power subsystems failure



Loss of ability to shut off EDP suction flow in case of fire