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A Study on variable geometries and component matching of variable cycle engine for aircraft with super cruise capability

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The main aim of this work is to investigate variable cycle concept for combat aircraft with super cruise capability. In particular, this study investigates impact of different variable geometry mechanisms and components of aero-gas turbine engine on variable cycle characteristics. This work essentially involves engine cycle modeling and variable geometry control study in order to identify the performance benefits of variable cycle concept. Extensive literature survey is carried out before establishing investigation method and analysis procedure for this research.

Single bypass architecture is adopted for this research as it offers easier implementation and yet represents variable cycle concept in complete sense. Hence, conventional mixed flow turbofan engine with bypass ratio of 0.5 is modeled with TURBOMATCH as a baseline configuration for this study. After design point calculation to estimate design point size data and key performance parameters, simulation model is modified in order to investigate the effect of different variable geometries such as bypass mixer, core mixer, nozzle throat and low pressure turbine separately as well as in combination in some cases. A further study is also performed to minimize component losses in order to gain full benefits of cycle effect.

From this study, it is found that opening of nozzle is having the largest effect on expanding bypass ratio (2.54 times) and therefore results in lowest fuel consumption. Partial closure of bypass mixer with partial opening of nozzle is turned out be best control schedule for achieving maximum specific thrust. Low pressure turbine NGV variability has a potential to vary the bypass ratio in the range of 0.3-0.75 from design point BPR of 0.5,while modulation of flow capacity in vane-less LPT only results in around 6-7% change in BPR.

I. Nomenclature

A13	=	core mixer area (sq.m)
A14	=	area at mixing plane(sq.m)

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A16	=	nozzle throat area (sq.m)
A22	=	bypass mixer area (sq.m)
CN	=	corrected speed relative to design speed
DP	=	design point
ETA	=	isentropic efficiency (%)
FN	=	thrust (N)
HPC	=	high pressure compressor
HPRS	=	high pressure rotor speed
HPT	=	high pressure turbine
LPC	=	low pressure compressor
LPRS	=	low pressure rotor speed
LPT	=	low pressure turbine
NDMF	=	non dimensional mass flow
OD	=	off design point
OL	=	operating line
OPR	=	overall pressure ratio
PCN	=	mechanical spool speed relative to design speed
SF	=	specific thrust (N/Kg/s)
SFC	=	specific fuel consumption (g/kN.s)
TF	=	flow capacity relative to design flow capacity
W1	=	engine inlet mass flow (kg/s)
W5	=	core mass flow (kg/s)
W22	=	bypass mass flow (kg/s)
Z	=	surge margin parameter

II. Introduction

The next generation combat aircraft as well as supersonic commercial aircraft are expected to possess long range and mixed mission capability. Combat aircrafts in particular are expected to operate in variety of different mission to enhance its survivability and combat power. The variable cycle concept will be able to provide these capabilities for both next generation military and commercial supersonic aircraft to augment their combat capability and fuel economy respectively. At present, military aircraft employs low bypass ratio turban engine with afterburners for combat missions as low bypass turbofan at dry mode is suitable for mission warranting low fuel consumption, while afterburner mode is selected for mission requiring high specific thrust. However, augmentation of thrust using afterburner is highly uneconomical in terms of fuel burn which in turn reduces the mission range of combat aircraft. In addition, supersonic cruise capability is an inevitable trait that new generation combat aircraft needs in order to increase the target coverage. Hence, variable cycle concept was conceived to meet these new requirements. This paper is extract of author's MSc thesis from Cranfield University,UK on variable cycle concept [1].

III. Aim and Objectives

The main aim of this work is to investigate the variable cycle concept for combat aircraft with supersonic cruise capability. This work in particular, aims to investigate the influence of different variable geometry mechanisms and components on variable cycle parameters and their capability to minimize the fuel consumption for subsonic cruise operation and to maximize the specific thrust for supersonic cruise mission of combat aircraft. This study also involves cycle optimization in order to mitigate component losses so that full advantage of cycle benefits is achieved.

IV. Methodology

The idea of the work is to investigate different variable geometry mechanisms and components of military aero gas turbine engine on their ability to impact variable cycle characteristics. According to variable cycle concept's definition, typical twin spool turbofan engine is called single bypass engine which is one of the simplest form of variable cycle engine [2]. Considering the simplicity of single bypass engine architecture, conventional mixed flow twin spool low bypass turbofan engine is selected for this investigation.

This approach makes implementation of this investigation simple in terms of simulation model development and matching of component during simulation as single bypass version has fewer components. However, single bypass configuration consists of all the important elements of typical variable cycle engine such as variable bypass mixer, variable nozzle, variable compressors and turbines. Hence, outcome of this investigation is very much applicable to other VCE architectures and this investigation method can very well be extended to double bypass or triple bypass engine. Extensive literature survey is carried out before establishing investigation method and analysis procedure for this research [3][4][5][6][7][8][9][10][11][12].

The following methodology has been adopted in this research.

1. Selection of engine cycle for investigation
2. Modeling of conventional mixed flow turbofan engine(MFTF) using TURBOMATCH[13]
3. Carrying out design point simulation of MFTF engine and estimating size data such as bypass mixer area, core mixer area, nozzle throat area and key performance parameters such as BPR, thrust and SFC.
4. Investigation of effect of different variable geometries on variable cycle benefit (BPR)
5. Study on vane-less low pressure turbine and its capacity to alter bypass ratio
6. Investigation on mitigation of component losses and recovering cycle benefits at off design conditions.

In this investigation, TURBOMATCH gas turbine performance tool from Cranfield University, United Kingdom is being used innovatively to carry out some special investigation. For example, in case of LPT NGV closing flow capacity degradation factor (TF) feature in TURBOMATCH is used to reflect LPT NGV closing. Scaling of compressor maps using surge margin parameter and PCN are used to reflect the changes in component design to minimize or eliminate the component losses [13].

V. Simulation Process

A. Thermodynamic Cycle Selection

Variable cycle concept is beneficial for supersonic combat aircraft as well as supersonic commercial transport aircraft. Engine cycles for these two applications will be vastly different from each other as they have different mission requirements. The main aim of this study is to investigate the variable cycle concept for combat aircraft with super-cruise capability. Hence, typical twin spool mixed flow turbofan engine with the BPR of 0.5 used in combat aircraft with supersonic cruise capability is selected as a baseline configuration for this investigation. It is loosely based EJ200 engine, though design parameters and component maps do not match EJ200. Table 1 summarizes key design point cycle parameters.

Table 1 Key cycle and component parameters at design point

Sl.No	Parameters	Value	Sl.No	Parameters	Value
1	Mass flow (kg/s)	73	9	HPC efficiency (%)	87
2	Bypass ratio	0.5	10	HPC surge margin parameter	0.85
3	Overall pressure ratio	25	11	Combustor efficiency (%)	99
4	Turbine entry temperature(K)	1755	12	HPT efficiency (%)	90
5	LPC pressure ratio	4.2	13	LPT efficiency (%)	89
6	LPC efficiency (%)	88	14	Tail pipe duct loss (%)	7
7	LPC surge margin parameter	0.85	15	Nozzle coefficient	0.969
8	HPC pressure ratio	5.95	--	---	--

B. Simulation Model Development

Performance model of typical mixed flow turbofan engine is constructed using zero dimensional aero engine performance tool called TURBOMATCH which was developed by Cranfield University[13]. In TURBOMATCH, engine model is developed by set of interconnected gas components. Behaviour of these components is expressed in terms of respective component maps or empirical formulas. Each component is treated as block box whose inlet and outlet sections are defined for simulation. Each components take specific thermodynamic input data and results from proceeding component to calculate output data. In this way performance calculation is carried out numerically for all the gas components successively. More information about TURBOMATCH can be found from the manual attached in thesis as reference [13].

The first component in the engine model is intake followed by low pressure compressor. The next component is mass flow splitter called PREMASS brick in TURBOMATCH which is used to simulate cooling flow bleed circuit from low pressure compressor to low pressure turbine. The fourth component in the model is another PREMASS which models the bypass flow bleed from low pressure compressor. The next component is high pressure compressor followed by another PREMASS brick for high pressure turbine cooling bleed flow path. Next component is combustion chamber followed MIXEES brick which is part of high pressure turbine cooling flow path. Next component is high pressure turbine followed by second MIXEES which represents the low pressure turbine cooling flow line. The next component is low pressure turbine followed by MIXFUL brick which is part of bypass flow path. MIXFUL brick ensures that mixing loss of bypass and core flow mixing is considered in this model. The final component is convergent nozzle. There are two DUCT elements to simulate the ducts such as tail pipe and the duct just after LPT. This model does not include use of afterburner, though afterburner dry loss is taken into account. Table 2 summarizes the inlet and outlet station numbering of gas components. Fig. 1 gives structure of simulation model.

Table 2 Station Numbering of Engine model

Sl.No	Number	Section	Sl.No	Number	Section
1	1	Intake inlet	11	8	Burner outlet
2	2	LPC inlet	12	9	HPT inlet
3	3	LPC outlet	13	10	HPT outlet
4	21	Mass flow split to LPT cooling	14	11	LPT inlet
5	4	Core mass flow split	15	12	LPT outlet
6	22	Bypass inlet (Bypass mixer)	16	13	Duct -1 outlet (Core mixer)
7	5	HPC inlet	17	14	Bypass and core mixing plane
8	6	HPC outlet	18	15	Nozzle inlet
9	23	Mass flow split to HPT cooling	19	16	Nozzle throat
10	7	Burner inlet	--	--	--

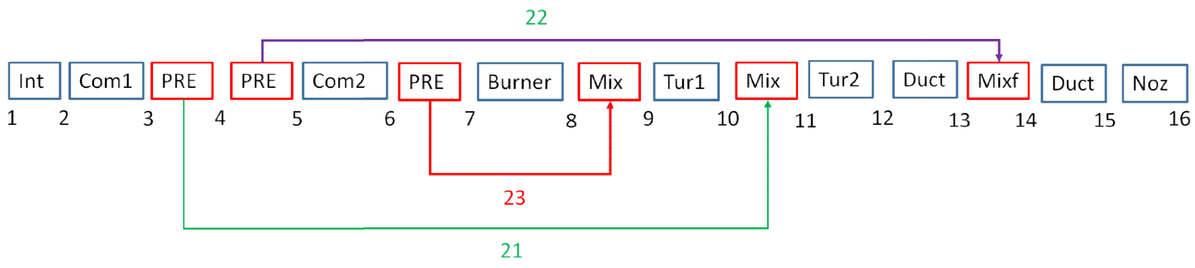

Fig. 1 Simulation model of mixed flow turbofan engine

C. Design Point Calculation

Design point for this study is set as sea level static (take-off) when MFTF engine is operated with its fixed thermodynamic cycle. Design point corrected speed of both compressors is 100%. Design point simulation is carried out with TURBOMATCH to estimate the key overall performance parameters and size data such as bypass mixer area, core mixer area and nozzle throat area. Outcome of design point simulation is summarized Table 3.

Table 3 Design point simulation results

Parameters	Actual value
Thrust (N)	56903
Specific thrust (N/kg/s)	779.5
SFC (g/kN.s)	20.93
Fuel flow (kg)	1.19
Bypass mixer area (sq.m)	0.0809
Core mixer area (sq.m)	0.1351
Nozzle throat area (sq.m)	0.1327

Having completed the design point simulation, off design point simulations are carried out by varying the different variable geometries. Turbine entry temperature has been maintained same throughout this study. These off design simulations are covered in the following chapters.

VI. Variable Geometry Study

A. Mixer Variability

- **Bypass Mixer Area (A22) Closure**

Two different simulations have been carried out with regard to closing bypass mixer area (A22). In the first simulation (simulation 1), bypass mixer area is closed from DP value, while the core mixer area (A13) is kept unchanged which means A14 decreases as it is merely sum of A22 and A13. In the second simulation (simulation 2), while A22 is decreased from its DP value, A13 is increased from its DP value so that A14 is always constant. The bypass mixer area (A22) has been decreased from DP value (100%) to 25% of DP value in both simulations. A22 below 25% of DP value, simulation fails to converge as static pressure balance between bypass and core flows at mixing plane (14) could not be maintained. Only details related to second simulation is presented here due to space constraints. Closing of bypass mixer increases the engine mass flow initially and later it drops. Bypass mixer closure results in reduction of bypass ratio and increase in specific thrust (Table 4).

Table 4 Effect of Bypass mixer closure on Performance parameters

A22 (%)	A13 (%)	W1	W5	W22	BPR	OPR	FN	SFC	SF
100(DP)	100	73.0	44.3	22.1	0.50	25.0	56903	20.9	779
87	108	73.4	44.9	21.9	0.49	25.4	57393	21.0	782
74	115	73.6	45.5	21.5	0.47	25.7	57707	21.0	784
62	123	73.3	45.8	21.0	0.46	25.8	57568	21.1	785
49	130	72.7	46.1	20.0	0.43	26.0	57207	21.3	787
37	138	71.0	46.3	18.3	0.39	26.2	55977	21.6	789
25	145	67.5	46.5	15.0	0.32	26.3	53507	22.3	792

Closing of bypass mixer (with opening core mixer) affects the other components following manner. Closing of bypass mixer (A22) causes outlet back pressure of LPC to increase which leads to reduction in surge margin and bypass mass flow. Meanwhile, opening of core mixer results in increase in LPT expansion ratio which in turn increases LPT output work. The increase in LPT output work makes the LPRS and absolute core mass flow to go up. Fig. 2 shows effect of closing of bypass mixer on the efficiency map of LPC. Effect of bypass mixer closure on HPC, HPT and LPT is insignificant.

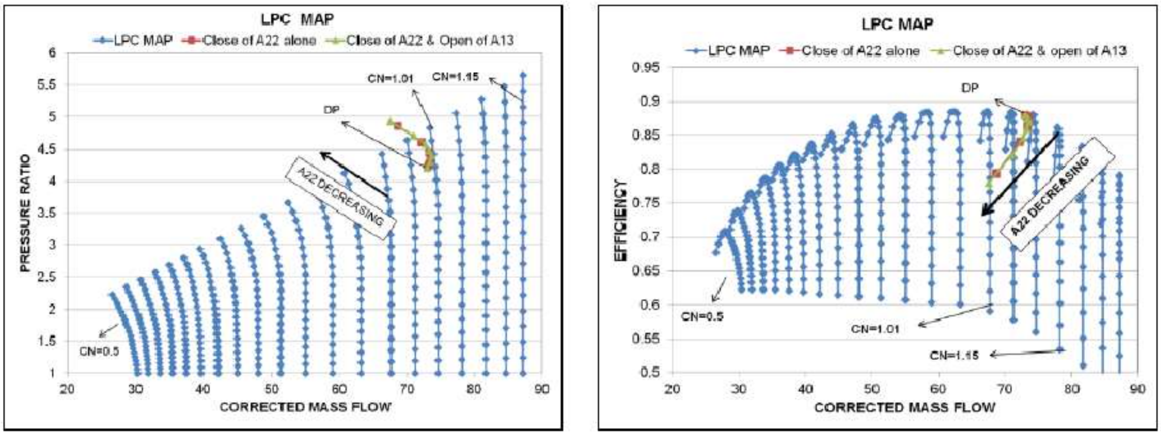

Fig. 2 Effect of bypass mixer closure on LPC pressure ratio map (left) and efficiency map (right)

The effects of bypass mixer closing on cycle benefits (BPR variation), component losses (efficiency degradation) and eventual performance gains (SFC and specific thrust gains) are compared in Fig. 3. It can be seen that bypass ratio drops by 35%. However, it results only in 2% increase in specific thrust. This is because there is 11% degradation in LPC efficiency which negates the cycle benefits. Moreover, there is approximately ~8% drop in absolute mass flow and hence, around 7% reduction in absolute thrust. Recovering LPC efficiency and engine mass flow is essential for gaining full benefit of cycle effect.

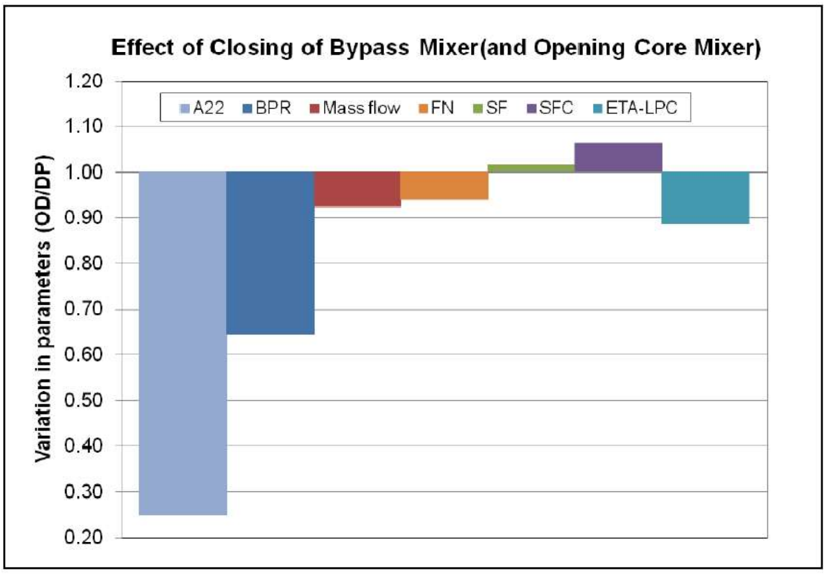

Fig. 3 Comparison of cycle benefits, component loss and performance gain due to bypass mixer closing

- **Core Mixer Area (A13) Closure**

In the case of core mixer closing also two different simulations are carried out similar to bypass mixer closing study. In the simulation, when core mixer area (A13) is closed, bypass mixer area (A22) is increased so that sum of these two mixer areas (A14) is always constant, is only presented here. In both simulations, core mixer area is closed by 33% from its design point area beyond which static pressure equality at mixing plane could not be satisfied.

Table 5 Effect of core mixer closing on performance parameters

A13 (%)	A22 (%)	W1	W5	W22	BPR	OPR	FN	SFC	SF
100	100	73.0	44.3	22.1	0.50	25.0	56903	20.9	779
89	119	71.5	43.0	22.1	0.51	24.2	55461	21.0	775
81	131	70.0	41.8	22.0	0.53	23.5	54019	21.0	771
74	143	67.7	40.1	21.5	0.54	22.6	51838	21.2	766
67	156	64.5	37.9	20.7	0.55	21.4	48861	21.5	758

Closing of core mixer leads to decrease of LPT expansion ratio which decreases LPRS and thereby total mass flow falls. Meanwhile, opening of bypass mixer reduces outlet back pressure of LPC which leads to increase in flow capacity and surge margin of LPC (Fig. 4). As a consequence of LPT expansion ratio drop and LPC flow capacity rise, bypass ratio increases. Though the absolute core mass flow declines and HPRS (mechanical) remain almost constant, corrected core flow and corrected speed of HPC rise as inlet temperature to HPC drops. This leads to reduction in HPC efficiency as corrected speed of HPC increases beyond 100% where efficiency starts to decline (Fig. 6).

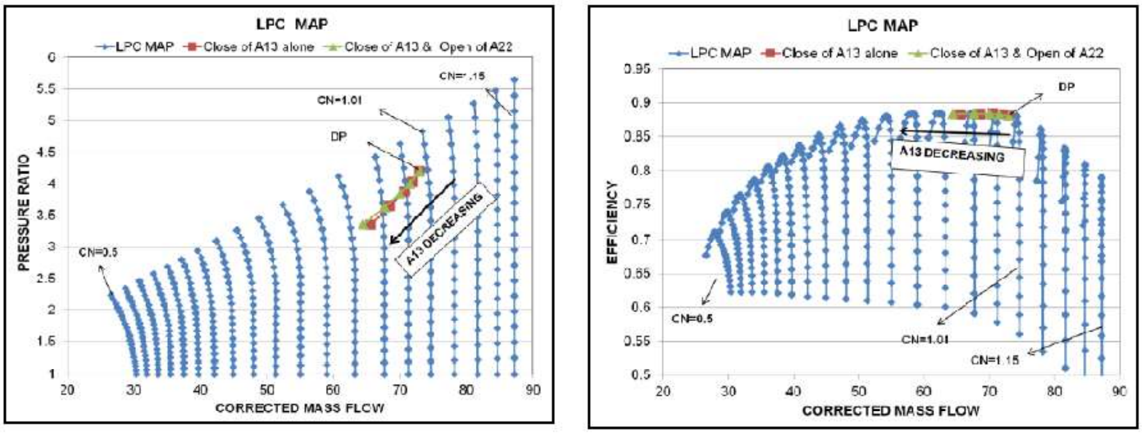

Fig. 4 Effect of core mixer closure on LPC pressure ratio map (left) and efficiency map (right)

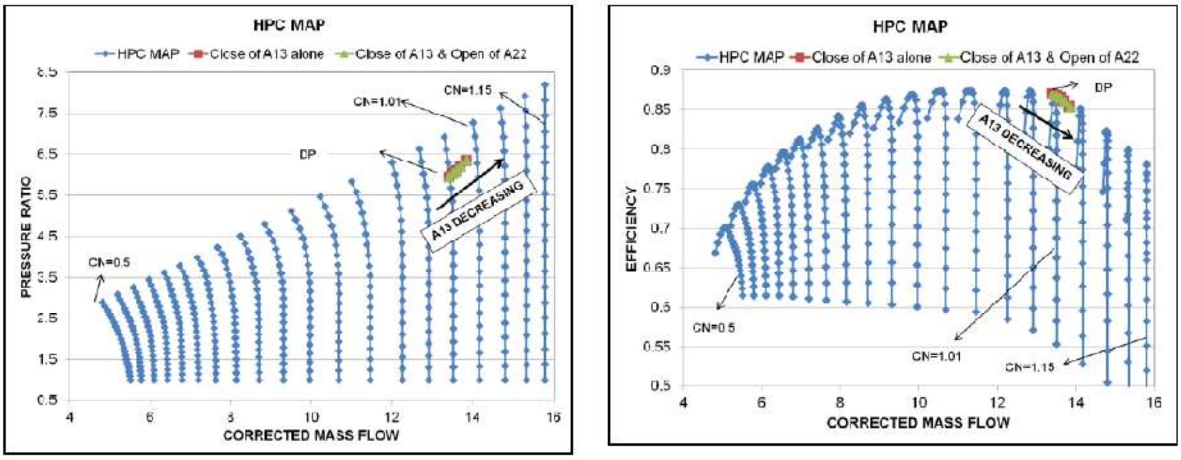

Fig. 5 Effect core mixer closure on HPC pressure ratio map (left) and efficiency map (right)

The below graph (Fig. 6) shows that the main cycle benefit of closing core mixer is 9% increase in bypass ratio from design point BPR. Bypass ratio increase does not result SFC reduction rather SFC raises by 3% from DP. This is due to the fact that effect of component losses (HPC efficiency drop by 2%) outweighs the benefits of cycle effects. Moreover, there is large reduction in total mass flow (12%) which results in similar amount of thrust reduction (14%).

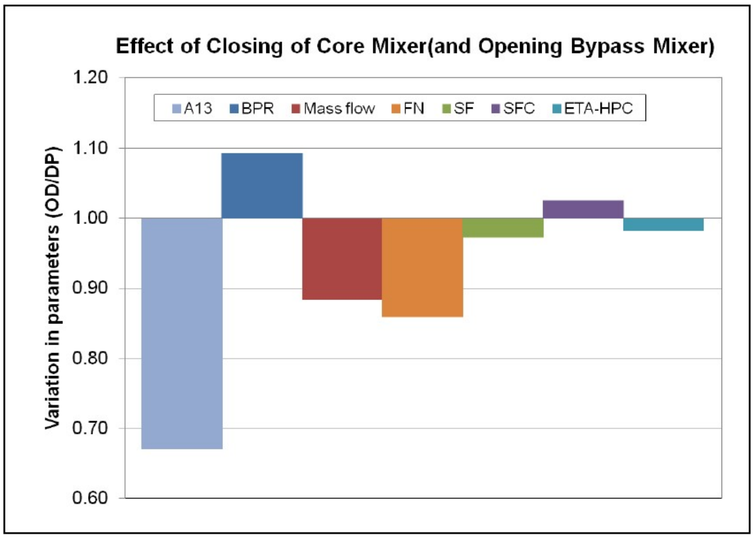

Fig. 6 Comparison of cycle benefits, component losses and performance gain due to core mixer closure

B. Nozzle Variability

- **Propelling Nozzle Opening**

Simulation model developed for nozzle throat area variability study is modeled with convergent nozzle as it is sufficient to carry out variable geometry studies. OD calculations are performed by opening the nozzle throat area from DP area (100%) to 151% of design point area beyond which simulation fails to converge as static pressure balance of bypass and core streams could not be achieved at the mixing plane (station14). it can be observed that opening of propelling nozzle throat area results in increase in inlet mass flow and BPR, while core mass flow decreases.

Table 6 Effect of nozzle opening on performance parameters

A16 (%)	W1	W5	W22	BPR	OPR	FN	SFC	SF
100(DP)	73	44.3	22.1	0.50	25.0	56903	20.9	779
106	74.6	42.7	25.2	0.59	24.1	56628	20.4	759
113	75.3	40.1	28.5	0.71	22.6	54907	19.9	729
121	76.2	37.9	31.5	0.83	21.3	53440	19.5	701
128	77.2	36.1	34.2	0.95	20.3	52198	19.1	676
136	78.2	34.6	36.6	1.06	19.4	51051	18.8	652
143	79.4	33.3	38.9	1.17	18.7	50069	18.6	631
151	80.6	32.3	41.0	1.27	18.2	49280	18.4	611

Opening of nozzle affects the mixed flow turbofan engine in two ways. Firstly, it increases the flow capacity of LPC as outlet back pressure of LPC is reduced. Secondly, it increases the expansion ratio across LPT which makes the LPRS and total mass flow to go up. These two effects can be seen from LPC map shown below (Fig. 7) as the nozzle opens, operating line of LPC moves away from surge line as well as moves towards higher corrected speed.

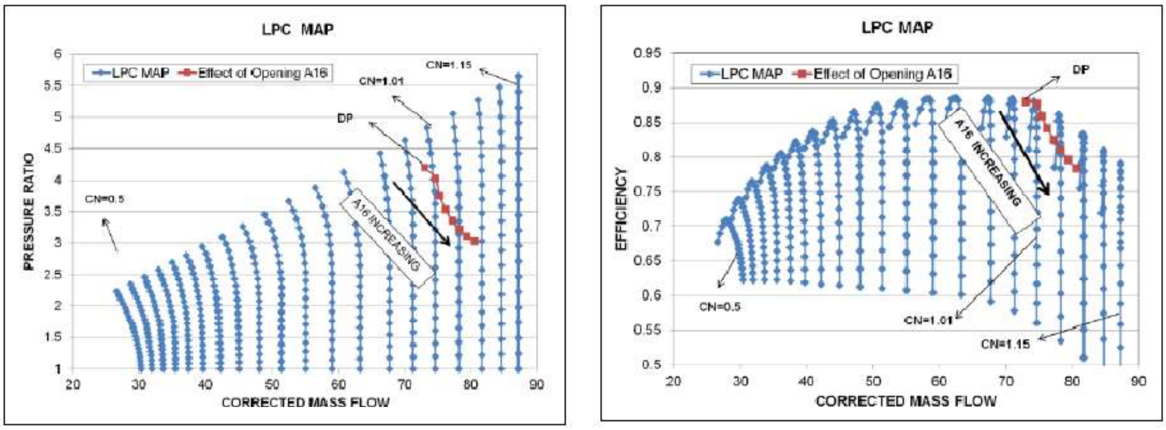

Fig. 7 Effect of nozzle opening on LPC pressure ratio map (left) and efficiency map (right)

Consolidated results (Fig. 8) shows that here is 2.54 times increase in BPR compared to design point BPR of 0.5 and total mass flow has increased by 10%. As far as thrust is concerned, nozzle opening lowers the thrust by 13% as mass flow through the core is reduced .SFC saving is 12% compared to DP SFC at the maximum nozzle throat opening. Here again, component losses (LPC efficiency degradation) offset the cycle effects (BPR rise) and limits the SFC gains. Full benefits of cycle effect can only be achieved if component losses are minimized or eliminated[14].

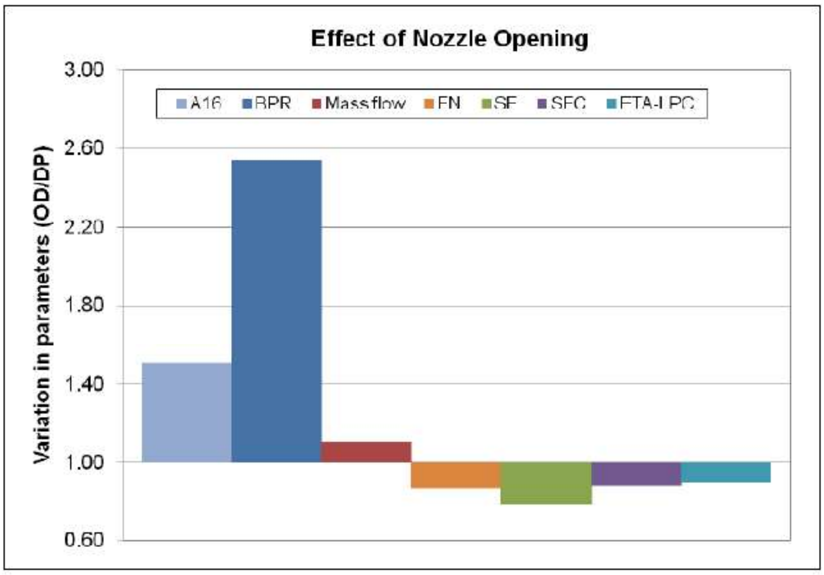

Fig. 8 Effect of nozzle opening on cycle benefits, component loss and performance gain

- **Propelling Nozzle Closing**

Off design calculation are carried out by closing nozzle throat up to 75% of DP throat area after which simulation fails to converge due to static pressure incompatibility at mixing plane. Nozzle area reduction has exactly opposite effect as that of nozzle area increase on engine cycle. As the nozzle closes, total mass flow and bypass mass flow drop, while core mass flow increases slightly and therefore BPR drops (Table 7).

Table 7 Effect of nozzle closure on performance

A16 (%)	W1	W5	W22	BPR	OPR	F	SFC	SF
100(DP)	73.0	44.3	22.1	0.50	25.0	56903	20.9	779
98	72.0	44.7	20.8	0.47	25.2	56615	21.2	787
94	69.8	45.2	18.3	0.40	25.5	55804	21.6	800
90	66.9	45.3	15.5	0.34	25.6	54357	22.1	813
83	60.5	45.0	10.0	0.22	25.4	50697	23.3	839
75	53.8	44.4	4.5	0.10	25.1	46637	24.7	867

Reduction of nozzle throat area also affects the mixed flow turbofan engine in two ways. On one hand, it increases the outlet back pressure of LPC because of which LPC's flow capacity is reduced. On the other hand, it reduces the expansion ratio across LPT which results in reduction low pressure spool corrected speed and therefore total inlet mass flow. It can be observed from that LPC operating line moves towards surge line as the nozzle closes and eventually it migrates to unstable region of compressor map when nozzle throat area is 75% of DP area. This movement of operating line makes LPC efficiency to fall to 77% from 88% at DP (Fig. 9).

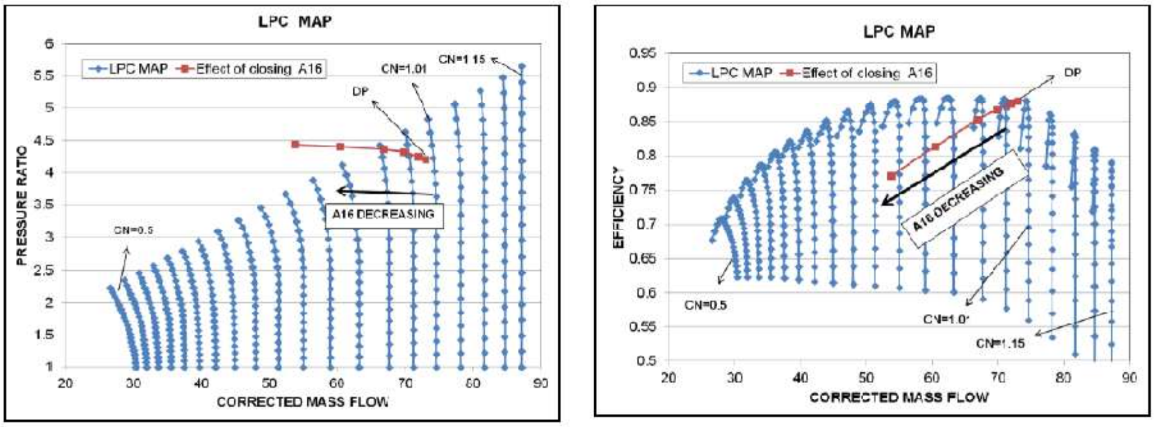

Fig. 9 Effect of nozzle closing on LPC pressure ratio map (left) and efficiency map (right)

The following bar chart (Fig. 10) shows that nozzle throat area reduction reduces the mass flow by 25% and decreases BPR to 20% of DP BPR. Effect of this huge mass flow reduction and BPR drop can be seen in thrust reduction. Coming to fuel economy, there is 15% increase in SFC compared to design point SFC. But here 15% SFC degradation is due to the combined effect of BPR reduction and LPC efficiency degradation.

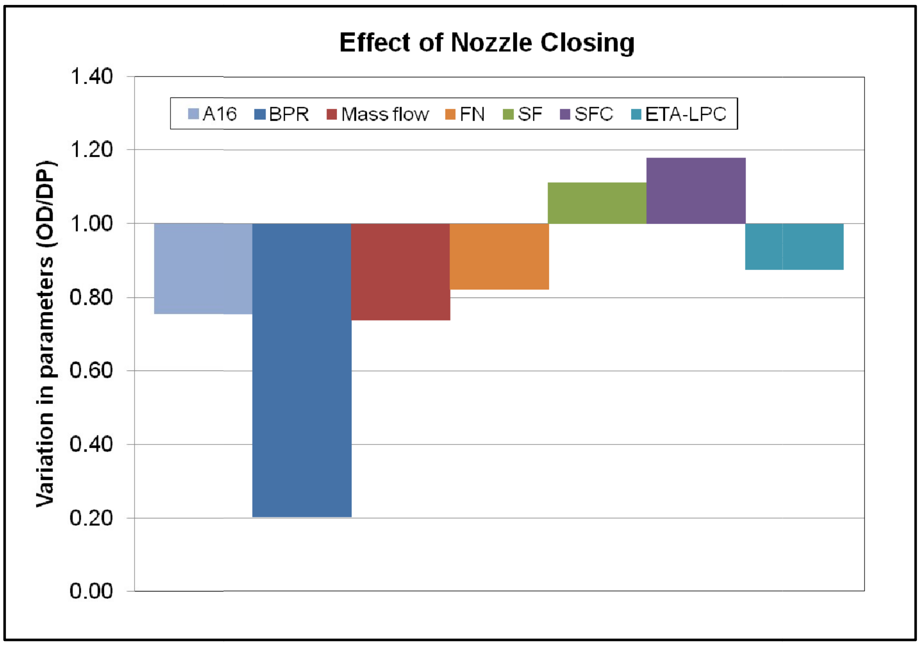

Fig. 10 Effect of nozzle closing on cycle effect, component loss and performance benefit

C. Combined Variability of Mixer and Nozzle

Individual variable geometry study of bypass mixer closure, core mixer closure, nozzle closing result in reduction of engine mass flow, which causes thrust reduction. Only nozzle opening increases the mass flow. From multiple iterations, it is found that combined modulation of bypass mixer closure and nozzle opening gives desirable cycle benefits, while core mixer and nozzle closure do not provide tangible advantage.

It can be observed from Fig. 11 that opening of propelling nozzle (with bypass and core mixer area corresponding to design point) is the best option to increase the BPR and therefore to save SFC and partial closure of bypass mixer with partial opening of nozzle is the best variable geometry scheme to lower the BPR without much reduction in total mass flow and therefore high specific thrust. However, component losses make achieving full potential of cycle variations difficult. LPC efficiency degradation is approximately 3% and10% respectively at maximum thrust and minimum SFC points which negate the cycle benefits.

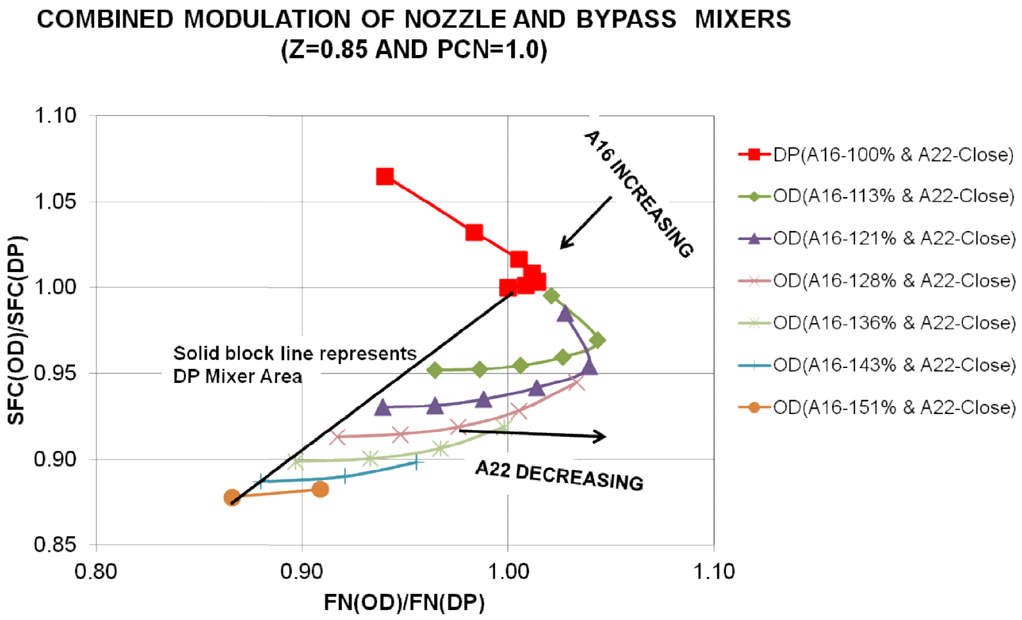

Fig. 11 Effect of combined variability of nozzle and bypass mixer area on SFC and thrust

D. Low Pressure Turbine Throat Area Variability

- **Low pressure turbine nozzle guide vane (LPT NGV) opening**

Provision is available in TURBOMATCH to increase the flow capacity of LPT by varying LPT NGV angle. In this simulation, LPT NGV angle is varied from 0 deg (DP) to 6 deg. Effect of NGV opening on major engine parameters are provided in Table 8.

Table 8 Effect of LPT NGV opening on performance

NGV Angle	W1	W5	W22	BPR	OPR	FN	SFC	SF
0(DP)	73.0	44.3	22.1	0.50	25.0	56903	20.9	779
1	73.8	46.3	20.8	0.45	26.2	58089	21.2	788
2	73.8	47.7	19.5	0.41	27.0	58567	21.4	793
3	73.3	48.5	18.2	0.37	27.4	58422	21.6	797
4	72.6	49.1	17.0	0.35	27.8	58055	21.8	799
5	71.6	49.4	15.8	0.32	27.9	57319	22.0	801
6	70.4	49.4	14.6	0.30	28.0	56420	22.2	802

Opening of LPT NGV increases flow capacity and decreases the expansion ratio across LPT. Comprehensive effect of increasing mass flow and decreasing expansion ratio initially (for NGV angle 0-3 deg) increase the LPT power output and therefore LPRS and total inlet mass flow increases. After NGV angle 4 deg and above, LPT power output, LPRS and total inlet mass flow drops as reduction in expansion ratio has dominant effect over increase in flow capacity across LPT. Effect of opening of LPT NGV on LPC operating line can be seen in Fig. 12. LPT NGV opening increases the expansion ratio across HPT, though flow capacity of HPT remains same [7]. This makes HPT power output to go up which results in HPRS and corrected mass flow of HPC to increase (Fig. 13).

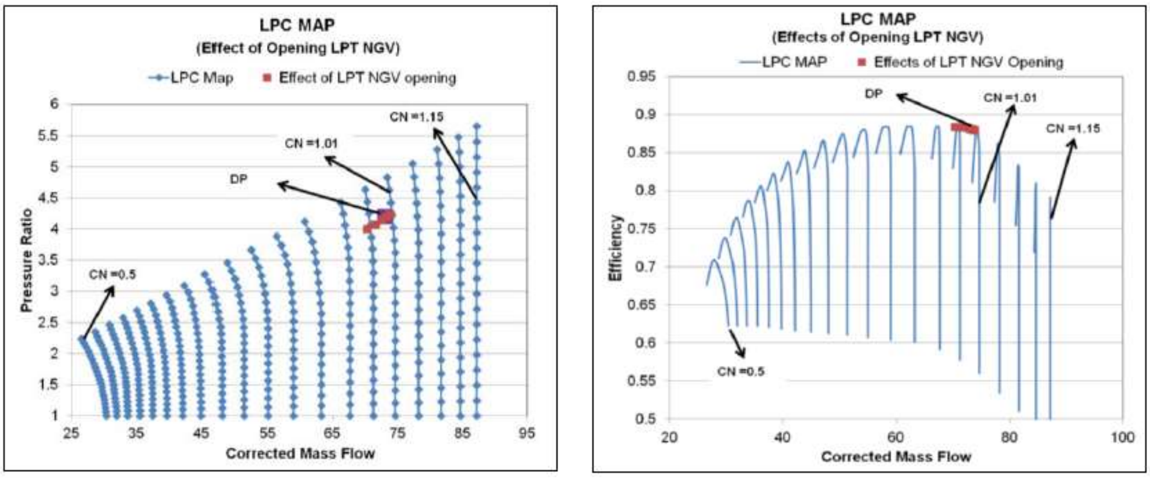

Fig. 12 Effect of LPT NGV opening on LPC pressure ratio map (left) and efficiency map (right)

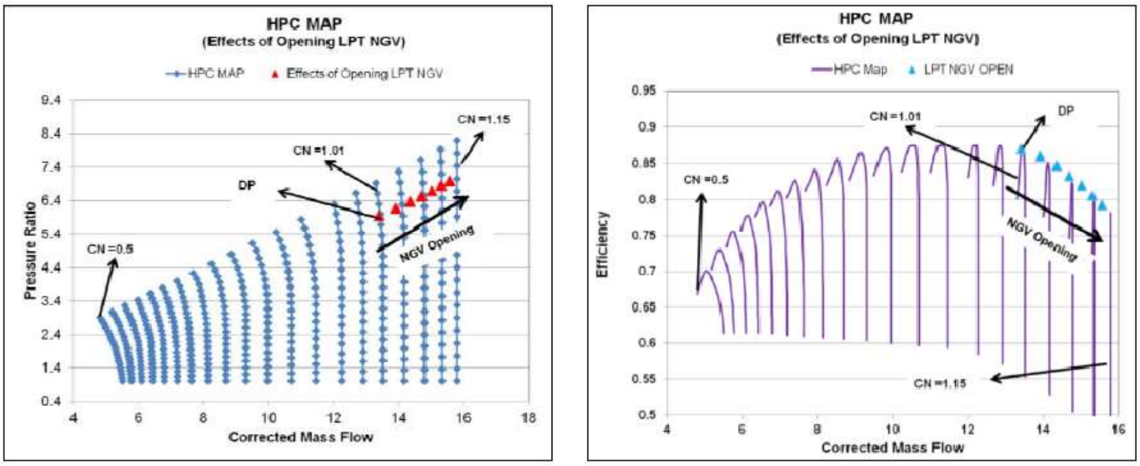

Fig. 13 Effect of LPT NGV opening on HPC pressure ratio map (left) and efficiency map (right)

The following observation can be made from Fig. 14. When LPT NGV is opened by 6 deg, BPR reduces to 60% of its design point BPR, specific thrust improvement is around 3% from its design point. As far as fuel economy is concerned, there is 6% increase in SFC for NGV opening of 6 deg compared to 0 deg. Though BPR reduction will always increase the fuel consumption, component loss in the form of HPC efficiency reduction has additional implications on fuel consumption. Hence, HPC efficiency degradation is to be minimized if complete variable cycle benefit of LPT NGV opening is to be achieved. Study on recovering cycle benefits LPT NGV opening is covered next.

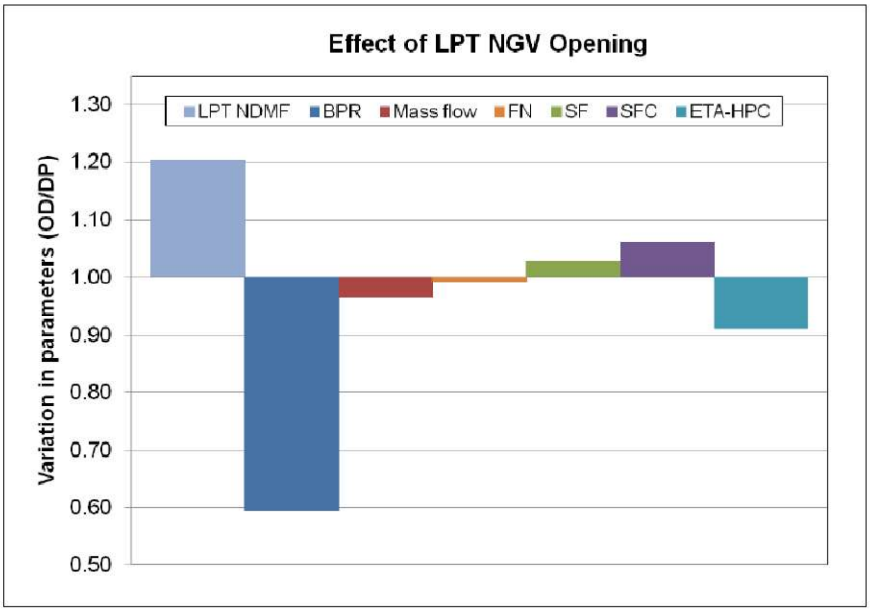

Fig. 14 Effect of LPT NGV opening on cycle benefits, component efficiency and performance gain

By scaling HPC map (Fig. 15) such that design point is positioned at PCN value of 0.88, HPC efficiency degradation during LPT NGV opening can be avoided (Fig. 16). By doing this, HPC efficiency migration stays within the flatter region of the efficiency map as HPC corrected speed at maximum LPT NGV opening is close to 100%.

Downside of scaling of components to recover cycle benefits is increased size of the components. Another drawback is that though scaling of map helps in mitigating components losses under some conditions (in this case LPT NGV opening), it worsen the situation under some other conditions (in this case LPT NGV closing).

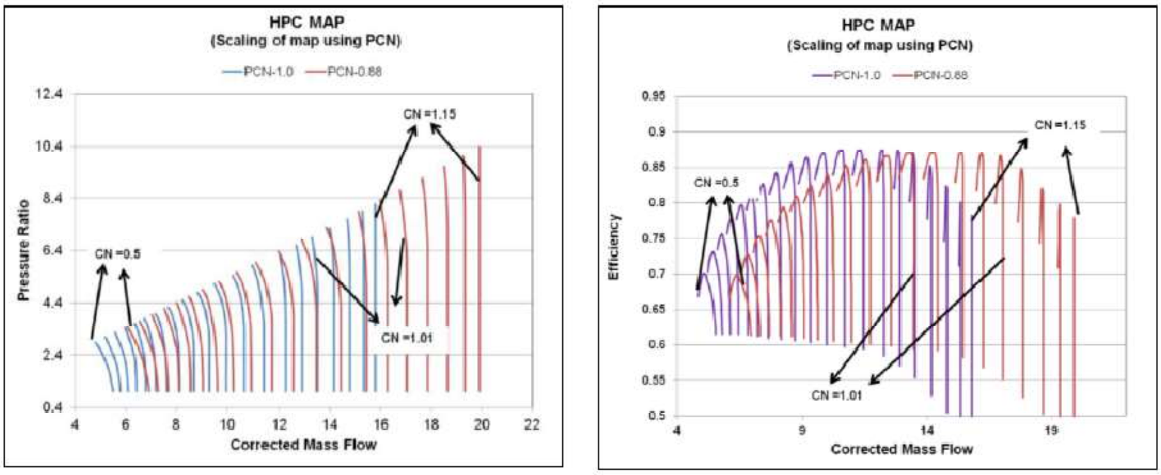

Fig. 15 Scaling of HPC pressure ratio map (left) efficiency map (right)

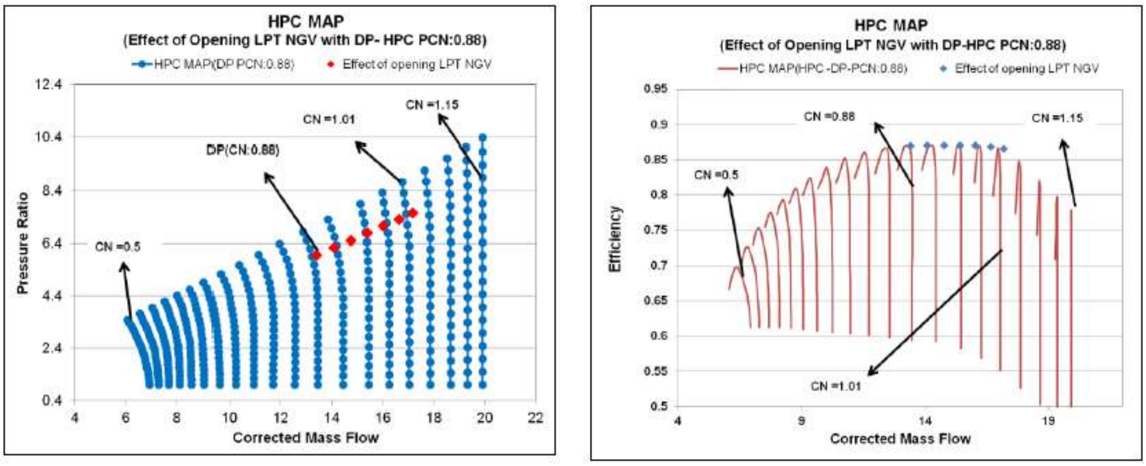

Fig. 16 Effect of LPT NGV opening on HPC pressure ratio map (left) and efficiency map (right) after scaling of map

- **LPT NGV Closing**

TURBOMATCH has provision to reduce the flow capacity (TF) of LPT from design point flow capacity. In this simulation, flow capacity of LPT NGV is reduced by 10% from DP (with 2% interval) and its effect on variable cycle characteristics are investigated. Table 9 tabulates the effect of flow capacity reduction of LPT (LPT NGV closing) on key engine cycle and performance parameters. Effect LPT NGV closing on LPC and HPC matching can be seen Fig. 17 and Fig. 18 respectively.

Table 9 Effect of LPT NGV closing on performance

TF	W1	W5	W22	BPR	OPR	FN	SFC	SF
1(DP)	73.0	44.3	22.1	0.50	25.0	56903	20.9	779
0.98	71.9	42.5	22.9	0.54	24.0	55524	20.8	772
0.96	70.5	40.5	23.6	0.58	22.8	53789	20.7	763
0.94	68.8	38.3	24.3	0.63	21.6	51818	20.5	754
0.92	66.9	36.1	24.8	0.69	20.3	49663	20.4	743
0.9	65.0	33.8	25.3	0.75	19.0	47439	20.3	730

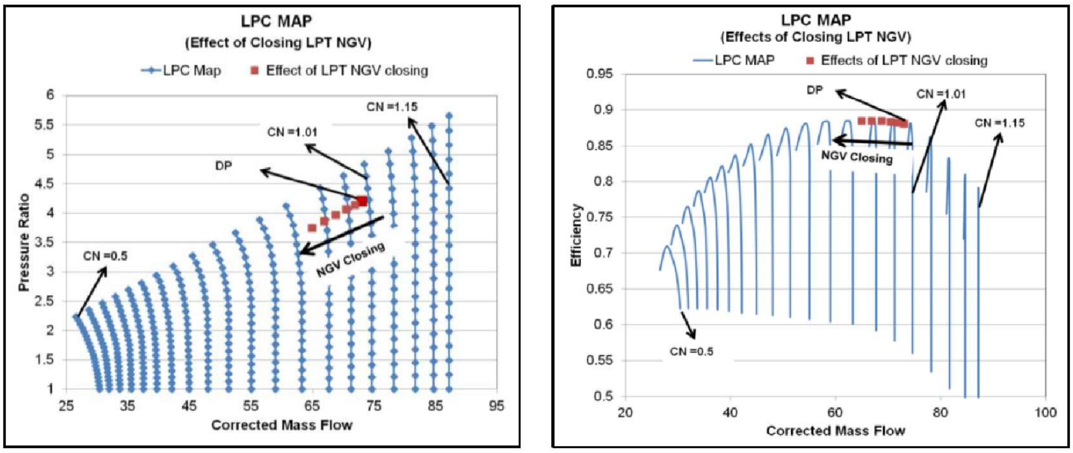

Fig. 17 Effect of LPT NGV closing on low pressure compressor pressure ratio map (left) and Efficiency map (right)

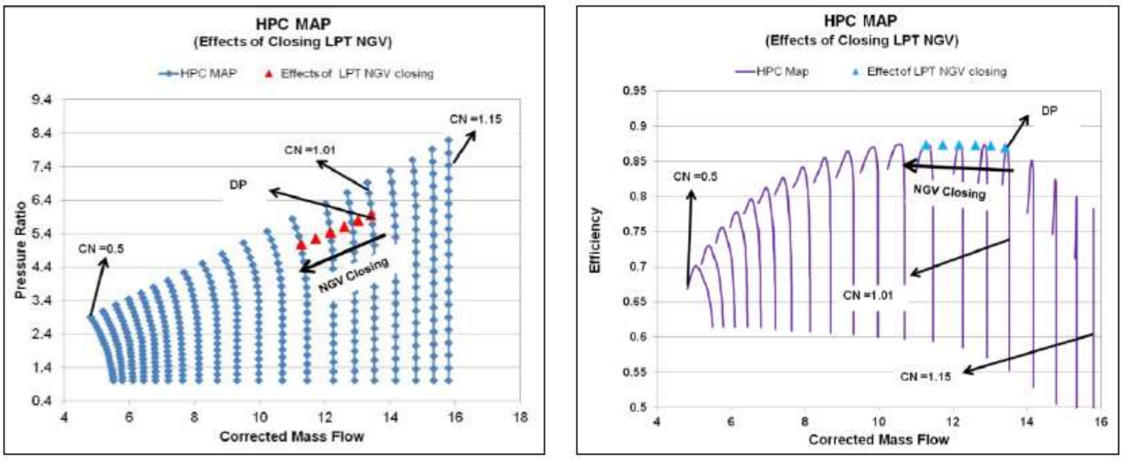

Fig. 18 Effect of LPT NGV closing on high pressure compressor pressure ratio map (left) and Efficiency map (right)

From Fig. 19, it can be observed that there is almost 50% increase in BPR when LPT flow capacity declines by 10%. Reduction in thrust is more than 15% due to 12% reduction in total mass flow. There is 3% reduction in SFC due to 50% increase in BPR .Similar SFC improvement for LPT NGV closing has been reported in open literature[15]. Unlike LPT NGV opening, component losses are negligible for LPT NGV closing as both rotor speeds drop and move towards constant efficiency zone of respective component map. Therefore, cycle benefits are not affected by component losses.

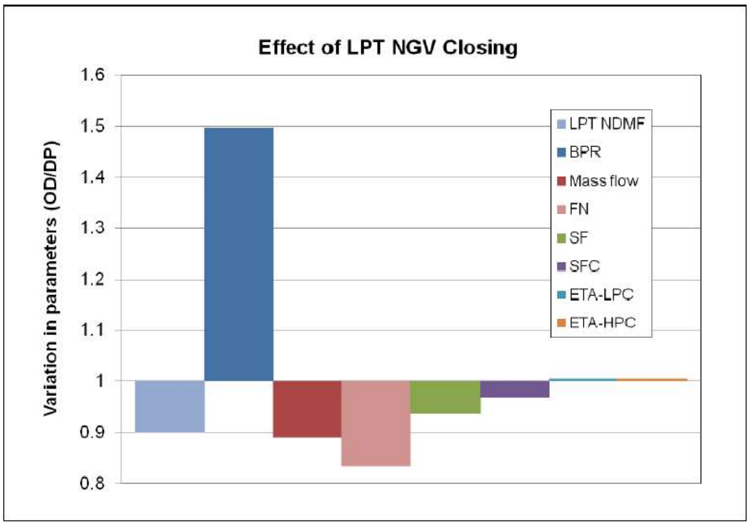

Fig. 19 Effect of LPT NGV closing on cycle effect, component loss and performance gains

E. Variation of LPT Rotor Choking Capacity (Vane-less LPT)

As there are no stators in counter-rotating turbine [8][9][10], choking of flow invariably will occur at LPT rotor passage. In TURBOMATCH, provision is available to analyze vane-less turbine by using different turbine map which represents rotor choking[13]. TURBOMATCH uses turbine maps for rotor choking which are similar to turbine characteristics (rotor choking) reported by Walsh and Fletcher [11]. Choking capacity of vane-less low pressure turbine can be varied by low pressure compressor variable stator vanes (LPC VSV) which in turn varies the corrected speed of low pressure spool.

- **Effect of Closing of LPC VSV on LPT Rotor Choking Capacity**

In this study, LPC VSV has been closed up to maximum possible in TURBOMATCH (40 deg) as this tool only have in built standard compressor maps for compressor variable geometry closing up to 40 deg. Closing of LPC VSV leads to 14% increase in LPRS and 2 % decline in HPRS. As there is 1.75% reduction in LPT flow capacity, there is around 6% increase in bypass ratio. However, there is large reduction in engine mass flow and LPC efficiency (Fig. 20).

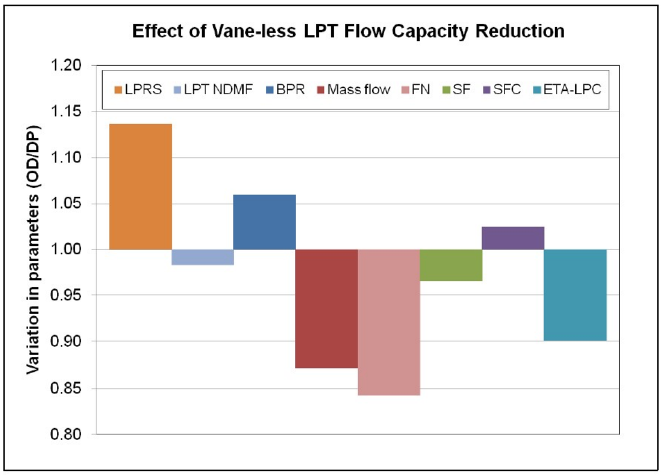

Fig. 20 Effect of vane-less LPT flow capacity reduction on cycle effect, component loss and performance gain parameters.

- **Effect of Opening of LPC VSV on LPT Rotor Choking Capacity**

TURBOMATCH has capability to model LPC VSV opening up to -10 deg. In contrast to LPC VSV closing, opening of LPC VSV results in reduction in LPRS (15%) and increase in HPRS (1.5%). There is 1.5% increase in NDMF of LPT. Main cycle effect is ~6% reduction in bypass ratio. However, there is there is a large reduction in engine mass flow as well as in LPC efficiency as LPC corrected speed drops by 15% (Fig. 21).

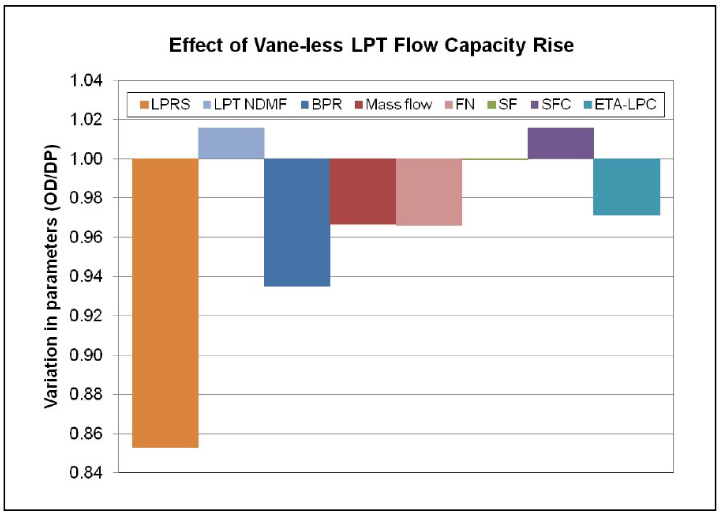

Fig. 21 Effect of vane-less LPT flow capacity rise on cycle effect, component loss and performance gain parameters

VII. Conclusion, Contribution and Future Work

- **Conclusions**

The following conclusions can be drawn from this investigation:

- Among various variable geometries investigated in this study, nozzle variability has the greatest impacts on variable cycle characteristics. Opening of nozzle gives greatest increase in BPR (2.54 times), which is requirement for subsonic cruise mission where SFC should be lowest.

- Partial closing of bypass mixer in combination with partial opening of propelling nozzle enables to reduce bypass ratio without affecting the total mass flow of the engine. This combination of control scheme gives maximum specific thrust, which meets the super cruise requirements.

- Low pressure turbine variability (conventional turbine) has the capacity to vary BPR of conventional mixed flow low bypass ratio turbofan engine (BPR=0.5) to the range of 0.3 – 0.75.

- In case of vane-less LPT, maximum BPR expansion achievable is 6-7% on either side of design point BPR, while components losses associated with the flow capacity variation is around 10%.

- It can be concluded from this investigation that individual components of variable cycle engine need to be designed for certain design range rather than one design point and also different component needs to designed for different design point or design range rather than common design point considering variability, performance and component matching requirements.

- **Contributions**

The following outcomes can be considered unique and original contributions of this investigation.

- Developed new component matching method (by scaling component maps) to mitigate the component losses in order to recover cycle benefits completely. However, this method has its own drawbacks in terms weight and stability margin penalty.
- Investigated effect of vane-less LPT choking flow capacity modulation on variable cycle characteristics and quantified cycle benefits, component losses and explored component matching issues for the first time.
- In this investigation, TURBOMATCH scheme is used innovatively to examine vane-less LPT flow capacity variation and conventional LPT NGV closing for variable cycle benefits. Study on mitigation of component losses also involves ingenious implementation of TURBOMATCH.

- **Future Work**
  - More work needs to be done to find a robust method to eliminate or minimize the component losses, while obtaining complete benefit of cycle effect.
  - Extension of this analysis procedure to double bypass and triple bypass engine configuration
  - More research is required to be done on characteristics of vane-less LPT and its variable cycle benefits.
  - Besides advantages of VCE, drawbacks such as weight penalty, technological risk and economic aspects are also to be studied in detail.

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