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INVESTIGATION OF VARIABLE GEOMETRIES ON THE OPERABILITY AND AIRCRAFT LEVEL PERFORMANCE OF A THREE-SHAFT TURBOFAN ENGINE FOR ENTRY INTO SERVICE 2050

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Abstract

The development of advanced propulsion systems has entailed complex and accurate fuel control strategy during transient operations. The application of variable geometry has proved to be an effective and practical approach for safety, energy, noise and emission reduction. This paper aims at exploring the influences of implementing variable geometry on a three-shaft turbofan engine performance, including variable inlet guide vanes (VIGV), blow-off valve (BOV) and bypass variable area nozzle (VAN). A dynamic model was established in Simcenter Amesim to provide the ability to assess the operability and aircraft level performance. The fan and compressor map, shaft speed, net thrust, specific fuel consumption (SFC), T4 as well as other critical parameters were investigated to observe the benefits of incorporating the mentioned devices. Results show that BOV opening would significantly mitigate the IPC surge issues by increasing the surge margin (SM) from 10% to 15%. However, the resulted loss in net thrust (FN) and SFC would reach 1.38% and 1.35% at take-off condition. The mission analysis also reveals that the over-open of BOV would consume 2.7% additional fuel. By contrast, a 10% of VAN expansion could better the SFC at take-off and block fuel by 8.62% and 2.41% respectively. Furthermore, T4 dropped by at least 26K if the bypass VAN went up by 10%. Meanwhile, the introduction of VIGV would not bother the engine performance but enlarge the core fan surge margin. Finally, exploiting the potential advantages of VIGV, BOV and VAN, a comprehensive control schedule was established to improve stability and save mission fuel.

Keywords: three-shaft engine, transient assessment, operability, bypasses VAN, flight mission

1. Introduction

The strict environment request on the civil aircraft, combined with the increasing operating cost, has promoted the evolution of clean, quiet and fuel-efficient aero engines[1]. Engines are innovated to adopt giant fans and high bypass ratios to improve propulsive efficiency and decrease SFC[2]. As one of the promising engine architectures, the three-shaft turbofan engine employs an intermediate pressure shaft to boost the turbine component efficiency, cutting down the turbine stages and engine weight. Meanwhile, the noise emission would be somewhat relieved due to the lowered fan tip speed[3]. Therefore, the advantages of employing a large fan for the three-shaft engine are rather prominent since the enlarged bypass ratio could save fuel burn without relatively high noise production. However, a well-designed three-shaft turbofan engine should have superb aerothermal performance and function properly. The aerodynamic instabilities of compressors have drawn continuous concerns for aero engines at low corrected speed, which might result in flow reversal and blade vibration and even flame-out and blade failure[4][5][6]. Several measures are widely utilized to prevent these severe issues, such as VIGV, BOV, variable stator vane (VSV), bypass VAN, variable pitch fan (VPF). Numerous researchers have studied the effects of the above devices. Lopez-Dfez[7] conducted research on three kinds of airplanes and presented the impacts of bypass VAN on engine performance at different power settings. The results showed that the application of VAN would affect the design of aircraft and engine and modify the drag polar due to the changed nacelle geometry. It was also useful for extending the flight range and balancing the aircraft without changing the fuel flow. Michel[8] found that besides providing sufficient SM, VAN employment was beneficial for saving block fuel and reducing noise for a turbofan engine. Fan would be allowed to apply lighter blade and operate at the optimum efficiency with a slight improvement during the whole flight mission. Halliwell[9] demonstrated that although the installation of VPF would cause a 3.8% of extra fuel consumption, the betterment of propulsive efficiency would compensate for the penalty.

Furthermore, engines always experience transient operations and instability issues, correspondingly, concentrating on component maps is mandatory to ensure fan and intermediate pressure compressor (IPC) stability at low power settings. Wang[10] investigated the manoeuvre effects on the performance of a three-shaft engine Trent 1000, including fuel schedule, shaft inertia, volume packing. The transient working characteristics of Fan, IPC and high-pressure compressor (HPC) were achieved, and the overshoot of turbine inlet temperature (T4) was uncovered. Mears[11] studied the impacts of turbine degradation on a three-shaft gas turbine performance at take-off and top of climb operating points. The degradation of the high-temperature turbine (HPT) was discovered to be most influential in engine performance. In terms of the research on other types of engine, Roumeliotis[12] launched a recuperated model using Simcenter Amesim and carried out a comparison between it with a simple cycle engine. The findings revealed that the transient activities of the former are more reluctant to respond and would delay about 10s to reach another equilibrium state.

Overall, these studies highlight the need for the investigation of the variable geometries on the engine operability and aircraft level performance. This paper focuses on exploring the effects of BOV, VIGV, bypass VAN on the performance of a three-shaft turbofan engine enter into service (EIS) in 2050. The boundaries of the engine performance have been approached by utilizing the technology limits in 2050, such as ceramic matrix composites (CMC), Resin matrix composites(RMC), ultra-high bypass ratio and overall pressure ratio. The equilibrium matching among the components would be more complex for a three-shaft engine compared to other architectures. Dynamic simulation during take-off operating condition was performed based in Simcenter Amesim model environment. Net thrust, T4, SM and SFC were analyzed by introducing the variable geometry individually. Afterwards, flight mission analysis would be finally conducted to seek the potential benefits of using variable geometries. The outcome of this research would provide a deep insight into the influences and the effectiveness of the utilization of BOV, VIGV, and VAN on the three-shaft turbofan engine.

2. Methodology

2.1 Engine Parameters

The studied three-shaft turbofan engine was assumed to power A350-900 aircraft for EIS2050. A series of three-shaft turbofan engines with different fan diameters were designed and optimized according to the method[13] to pursue the optimum engine. The technology level in 2050 was fully exploited by approaching the boundary limitations and applying advanced materials. The temperature at the HPC outlet and HPT inlet at take-off was reached the highest allowable values by tuning the pressure ratio and T4 at the design point. Bypass ratio (BPR) and fan pressure ratio (FPR) was looped at cruise until the optimum SFC was achieved. Moreover, CMC was applied on turbine vanes and blades to lower the weight and elevate the T4. Furthermore, the burden on demand for the cooling air was significantly relieved by comparison with Inconel 718 material. The adoption of Resin matrix composites on fan blades could also cut down the engine weight and decrease the fan shaft inertia. Consequently, component matching would be more consistent during transient operations. The critical parameters of the optimum engine are listed in Table1.

Table 1 Critical parameters of the engine

Parameters	Value
Fan diameter/m	3.26
Intake mass flow/(kg/s)	567.7
BPR	21.39
T4/K	1766
OPR	69.5

Specific thrust/(N/(kg/s))	105.7
Propulsive efficiency	0.822
Thermal efficiency	0.594
SFC/((g/s)/kN)	11.42
Overall efficiency	0.488
Engine weight/kg	5761

2.2 Transient Assessment Model

Simcenter Amesim is commercial software developed by Siemens that is capable of building multiple physical systems, such as mechanical, thermal, electronic, electrical and control systems. A wide selection of components such as mission envelopes, compressors, fans, turbines, combustion chambers and nozzles could be used to simulate the transient performance of gas turbines. In the flight mission envelope module, the parameters such as flight Mach number, altitude and duration could be defined. The transition state performance of the engine or the whole flight mission can be simulated. In addition, designers can quickly access Amesim to build the basic architecture of the engine through the critical parameters obtained by the steady-state cycle design, as shown in Figure 1.

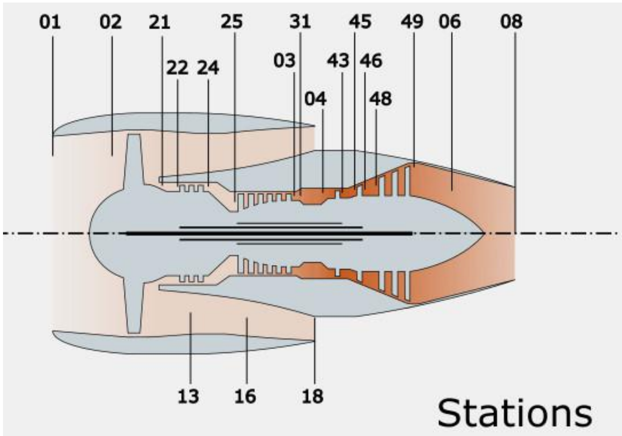


Figure 1 - A three-shaft turbofan engine architecture

Transient modelling and simulation were undertaken after the preliminary engine design. The transient performance modelling is a great necessity to validate a good design especially when advanced 2050 technology application is employed. The transient performance evaluation model of a three-shaft turbofan engine is shown in Figure 2. It includes the key components, such as Fan, IPC and HPC, HPT, LPT, combustion chamber, core nozzle and bypass nozzle. Variable geometries such as VAN, BOV, VIGV are also presented. Meanwhile, control modules were added to accommodate flight envelope, cooling air distribution, fuel flow and BOV schedule. In addition, the calculation module can also obtain NO_x, CO_2, H_2O emission and fuel burn. To accurately tune the fuel, the PID controller module was applied, which requires the input of ideal fuel and thrust schedule. The thrust differences would be transmitted to the fuel management system as a fuel adjustment signal. The tuning process would be repeated until the net thrust difference equals zero. Consequently, a new fuel flow schedule would be fed into the combustor.

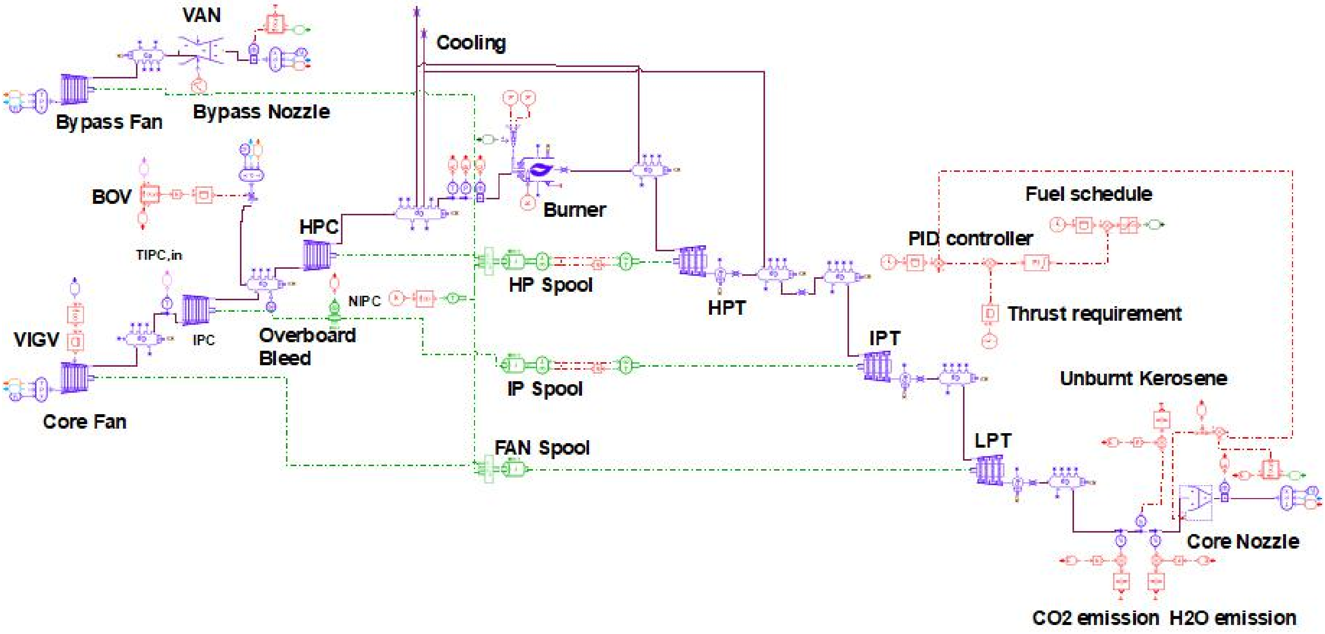


Figure 2 - Dynamic model of the three-shaft turbofan engine

2.3 Transient Assessment Method

The engine operability and performance during transient situations are essential to check whether the components would work stably and satisfactorily with respect to aero-thermal and mechanical characteristics. The following aspects are the most concerns: SM, rotational speed, flow capacity and temperature levels. The undesirable instability must be avoided as it might endanger the engine or even flight safety. BOV, VIGV, bypass VAN are always the need when the judgment of components stability is made. This paper investigated the three devices individually with regard to the effects on the transient behaviour, engine performance and fuel burn of an 8100nm flight range.

2.3.1 BOV investigation

BOV or handling bleed performs to release excessive air to drop the compressor working lines at low power settings. This study set a BOV at the IPC delivery without affecting the compressor characteristic maps but the operating points. The blow-off air is usually programmed at a specific fraction of the mass flow at the IPC outlet. Four cases of BOV control area were investigated, zero (without BOV), a designed area and a 10% enlarged area. Finally, the schedule is varied with the corrected rotational speed of the IP shaft.

2.3.2 VIGV investigation

The implementation of VIGV would not affect the operating points. It is always modelled at the design angle position shown in Figure 3, so the gas path flow would be reduced to move the surge line to the left. There would be an appropriate SM for the component to work in a stable situation. This study installed a VIGV in front of the fan and set the VIGV angle with four cases: design angle, closed 3 and 6 degrees, and varied angles during the flight mission.

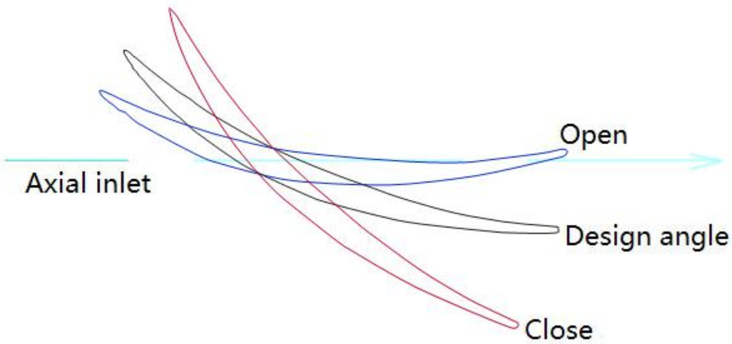


Figure 3 – VIGV angle close indication

2.3.3 Bypass VAN investigation

Bypass VAN is particularly appropriate for the ultra-high bypass turbofan engine to avoid Fan surge issues. The area of bypass VAN is relatively large for take-off operations to ensure that back-pressure does not induce the fan flutter conditions. On the contrary, smaller bypass VAN is desired for reduced power operations at cruise to slow the flow through the engine. For a whole flight mission, the bypass VAN would provide additional benefits for saving fuel due to increased thrust from bypass. The bypass VAN was scheduled for three fixed values, such as design area, increased 5% and 10% area. Finally, the exit area of the bypass nozzle was programmed according to power ratings. The fuel burnt would be calculated and compared with the case with a fixed nozzle area to dig out the potential benefits of using VAN.

2.3.4 Fuel schedule

The engine accelerates when the throttle lever is pulled, causing more fuel to be injected into the combustor. Then the shaft speed responds to increase with more air mass flow being swallowed. The turbine expansion work would exceed the compression work, resulting in engine acceleration. A typical aero engine is able to accelerate from idle to maximum speed within 2 seconds to 8 seconds[5][14]. In this scenario, the over-fueling time from idle to take-off is set as 6 seconds, then stable for 50 seconds until reaching a steady state. A deceleration is scheduled similarly, present in Figure 4. Regarding the scheduling during the flight envelope, fuel was accurately metered and pumped by application of the PID controller. The required fuel for the whole mission was derived from the engine cycle design and optimization process, which could be seen in Figure 5. Apparently, take-off is the most fuel demanding point to produce adequate thrust, while the fuel flow at the cruise segment linearly and slightly declines due to the consumed onboard fuel weight.

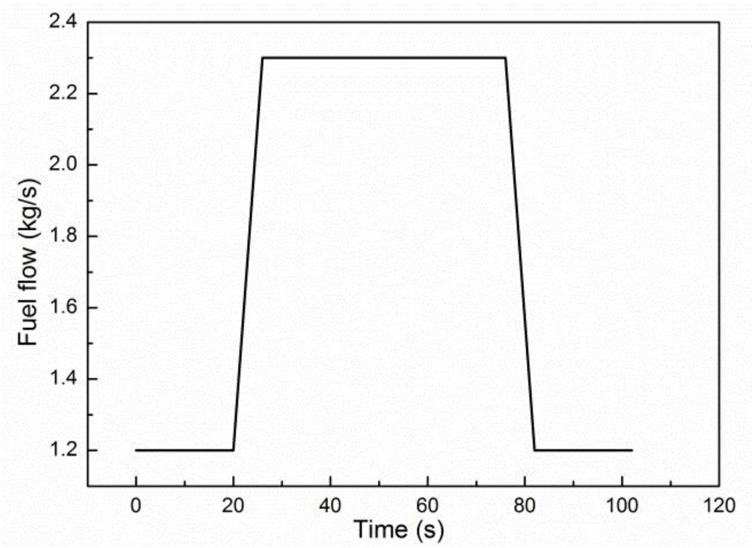


Figure 4 – Fuel schedule at take-off segment

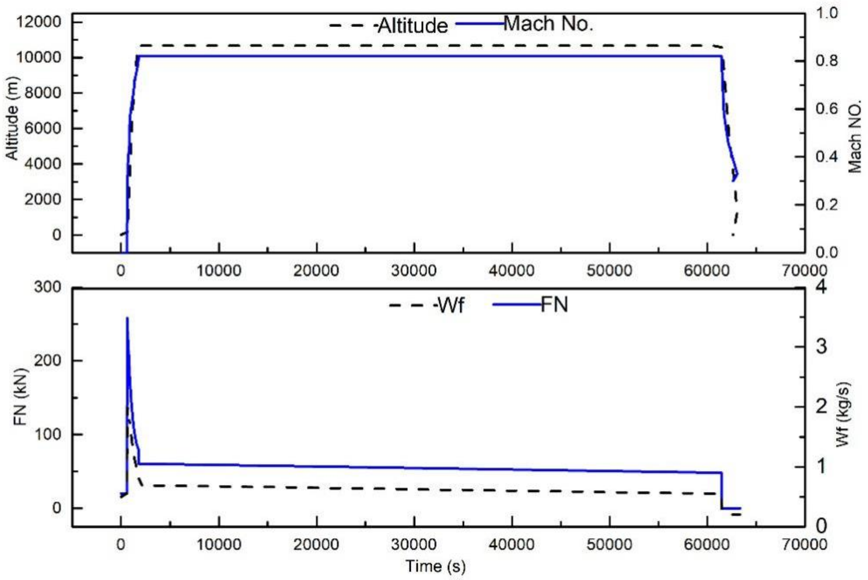


Figure 5– Mission profile and thrust, fuel demand

3. Results and Analysis

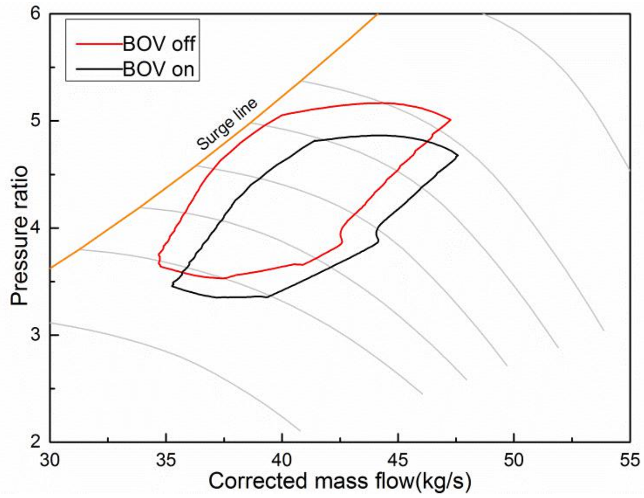
3.1 BOV effects

3.1.1 Transient behaviour

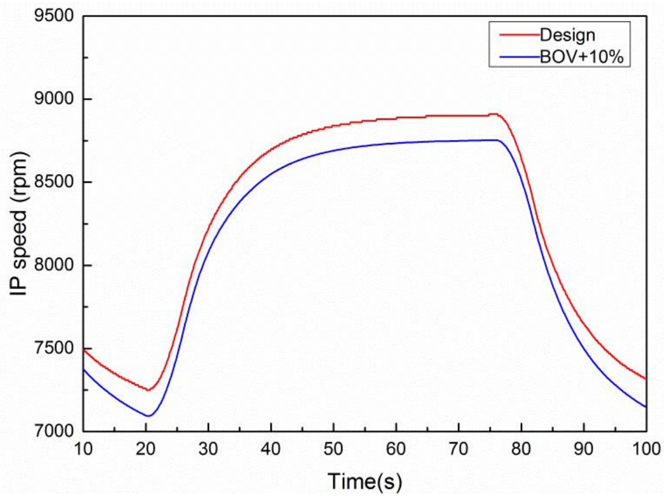
BOV is assumed to be a primary approach to protect the IPC from surge since the working line would step downwards to maintain an acceptable SM. During deceleration, the excursion of the IPC working point was above the steady-state line, whereas the acceleration trajectory is the opposite. As depicted in Figure 6 a), the IPC was inherently to surge during deceleration, especially for a slam throttle back operation. However, as BOV was switched on, there was a noticeable increase in mass flow, whereas an obvious reduction in IPC pressure ratio, which would dramatically ease the IPC surge issue and guarantee a safe manoeuvre. When the blow-off valve opens 10% larger than the designed schedule during the deceleration process, more wasted turbine work was triggered by the dumped air from the mainstream. Therefore, the reduced IPT power could not retain the initial output work and has to slow down the IP shaft speed, almost by 1.7%, as shown in Figure 6 b).

Furthermore, the rise of blow-off air would lead to a worsened net thrust and SFC, as shown in Figure 7. To be specific, implementing a 10% of over-opened BOV would incur a 1.38% decline in net thrust and a 1.35% rise in SFC at the take-off segment. In addition, an apparent elevated turbine inlet temperature during the whole transient operation could also be observed in Figure 8. The higher fuel-air ratio resulting from the restricted air flowing into the combustor was responsible for the temperature rise. Besides, the T4 overshooting phenomenon was severer when the BOV was over-opened during the high power setting condition. The corresponding 53.5 K increase in T4 overshooting would dramatically shorten the turbine blade life.

Therefore, an opened BOV is not desired in the high power setting condition since discharging airflow with work input would be a waste and the resulted overshooting is unacceptable. From the fuel economy perspective, BOV is only used at low corrected speed during deceleration or drop load condition to avoid IPC surge. In contrast, the blow-off valve is kept closed during acceleration.

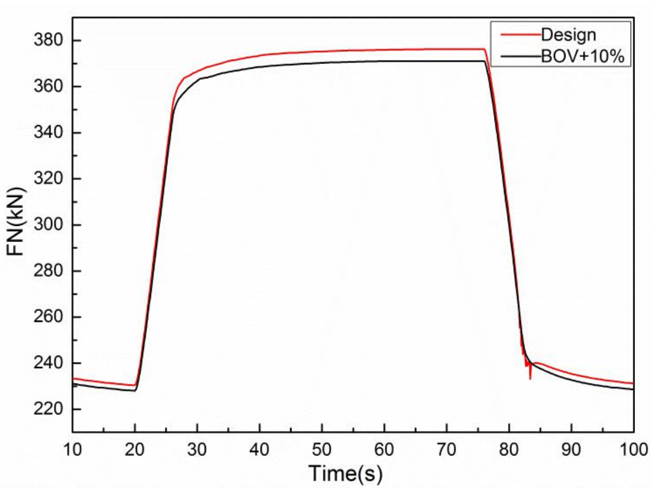


a) IPC map

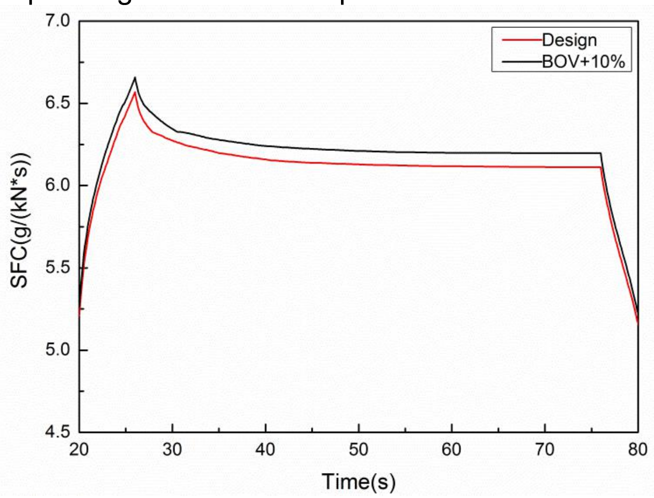


b) IP shaft speed

Figure 6 – Effects of BOV on IPC operating line and shaft speed



a) FN



b) SFC

Figure 7 – Effects of BOV on net thrust and SFC

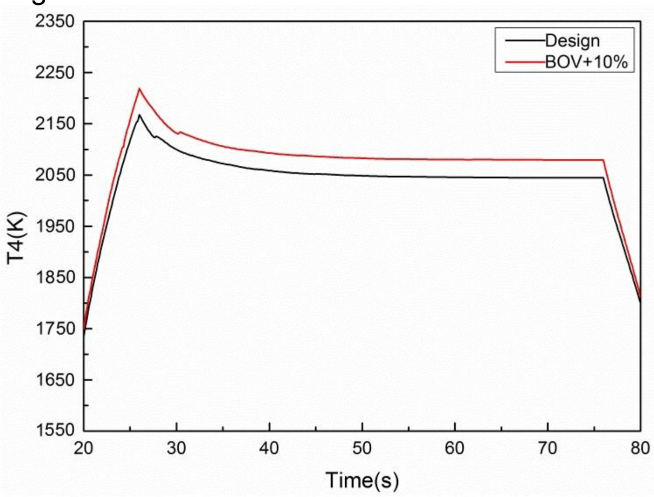


Figure 8 – Effects of BOV on T4

3.1.2 Flight mission performance

A comprehensive BOV profile was incorporated to analyze the flight mission performance for the three-shaft turbofan engine.

As can be seen in Figure 9, over opening the blow-off valve consumed another 2.77% block fuel and produced more H_2O, CO_2, NO_x emissions. The additional block fuel mainly came from dumping a certain quantity of useful main path airflow. Meanwhile, the production of NO_x, CO_2 and H_2O, has increased by 1.63%, 2.77% and 2.83%, respectively. The fundamental reason is that the HPC mass flow dropped while the fuel flow remained the required value during a slam operation, resulting in a higher T4 and more emissions. The mission analysis results highlighted the importance of incorporating a well-scheduled BOV to curb the additional fuel consumption and emission products.

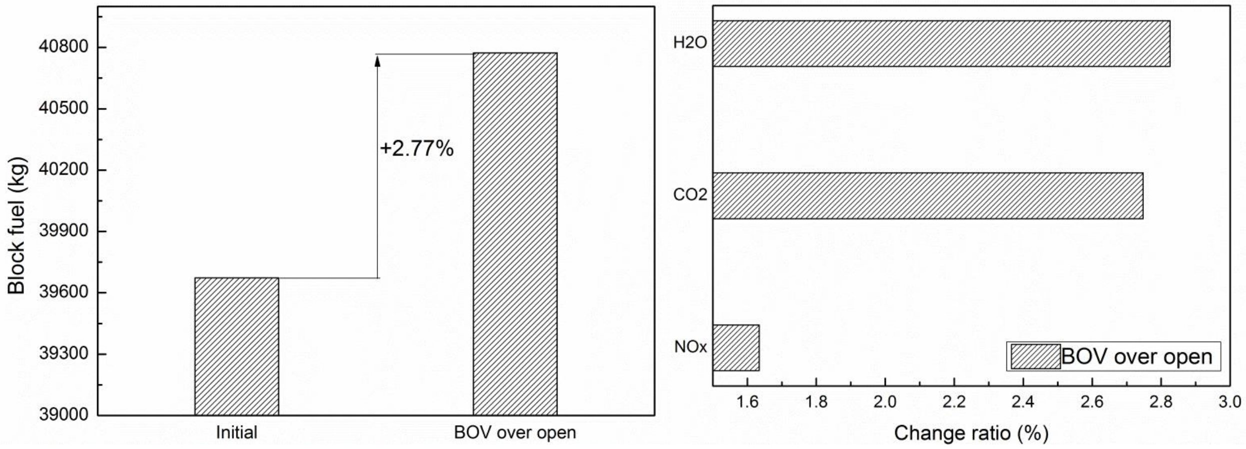


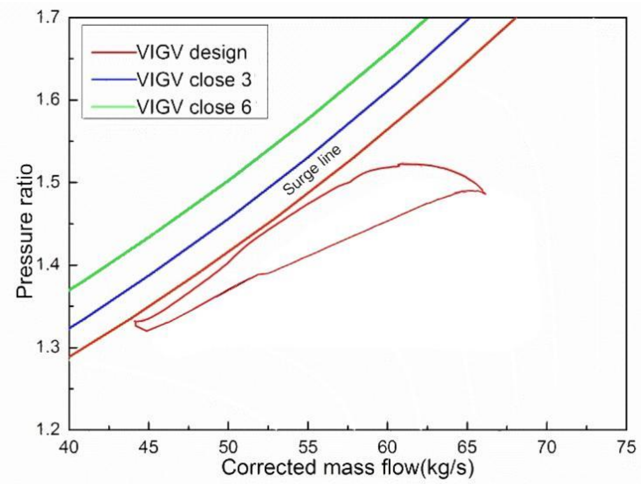
Figure 9 – Effects of BOV on mission block fuel and emissions

3.2 VIGV effects

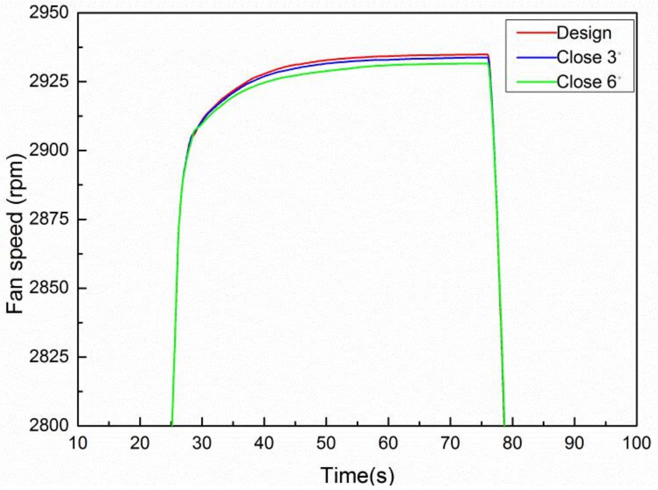
3.2.1 Transient behaviour

The VIGV plays a crucial role in deciding the core fan operating line, especially during transient operations[15][16]. The influences of VIGV with the design angle and close 3 degrees and 6 degrees are depicted in Figure 10. It should be noted that for the VIGV closed cases, the close continued until the maximum rotational speed. An obvious observation is that the close of VIGV was an effective method to protect the fan from surge, and change the angle of VIGV would alleviate the operating line of the core fan away from the surge line to a different extent. The core fan was approaching the sure line when the VIGV was at design position, whereas it was promoted to 12.3% and 13.7% when VIGV close 3 degrees and 6 degrees respectively. The magnificent improvement originated from the decreased core mass flow coming from the dropped fan shaft speed. Meanwhile, the fan pressure ratio fell and the fan map was altered, indicating betterment in SM.

However, the adverse effects of VIGV angle close were negligible. The shifted fan shaft speed due to VIGV close led to a reduction in fan power, while the decreased mass flow would contribute to the increase in fan shaft torque and power. Consequently, the fan net thrust was slightly lower than the required value, revealing a worsened SFC. Close inspection on Figure 10 indicates that the FN fell by 0.56% while SFC rose by 0.54% when VIGV close 6 degrees. Though the T4 overshooting phenomenon has not deteriorated, the T4 at maximum working condition was higher than the desired temperature level, as shown in Figure 12. Finally, the VIGV angle close operation would be limited at low corrected speed to prevent fan surge while fully open at high power settings to achieve desired engine performance.

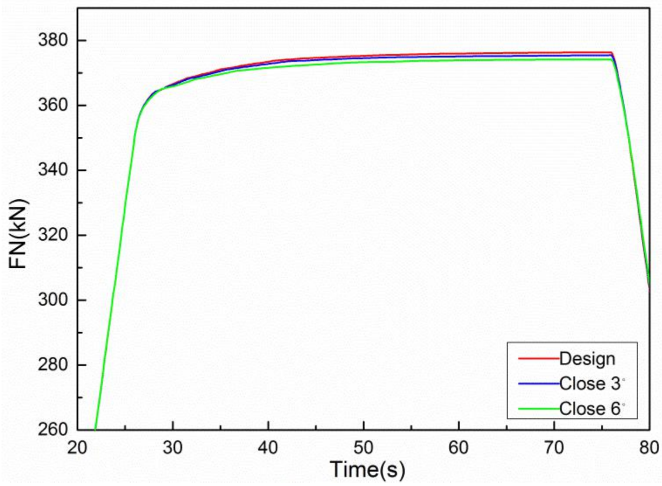


a) Fan map

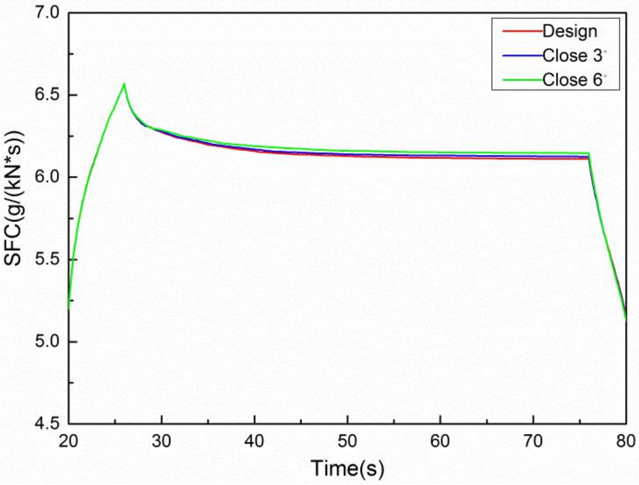


b) Fan shaft speed

Figure 10 – Effects of VIGV on core fan operating line and fan shaft speed



a) FN



b) SFC

Figure 11 – Effects of VIGV on net thrust and SFC

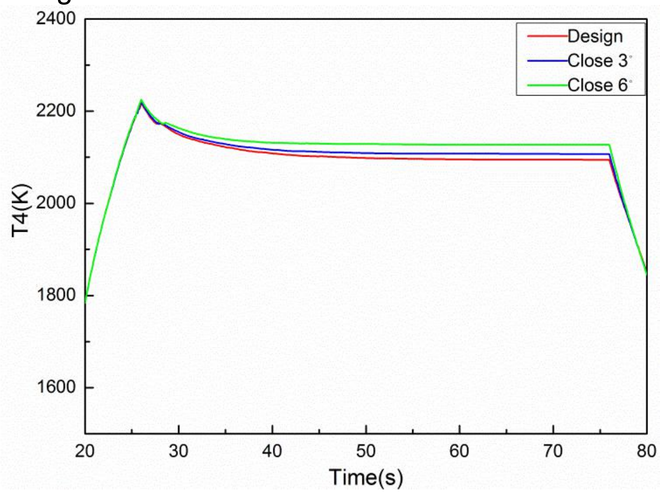


Figure 12 – Effects of VIGV on T4

3.2.2 Flight mission performance

Similar to the open of BOV, the VIGV close would also generate an added block fuel for the design range mission, as shown in Figure 13. The increase in block fuel consumption was 7.7kg and 28.7kg when VIGV close 3 degrees and 6 degrees, respectively. The relatively small penalty in block fuel reveals that the VIGV has negligible effects on the mission performance. However, scheduling the VIGV according to the fan corrected speed would be more economically. VIGV was closed at low corrected speed to ensure a sufficient SM and opened at high power settings to produce adequate thrust. Finally, the resulted fuel burnt of the mission kept the same level as the initial schedule case.

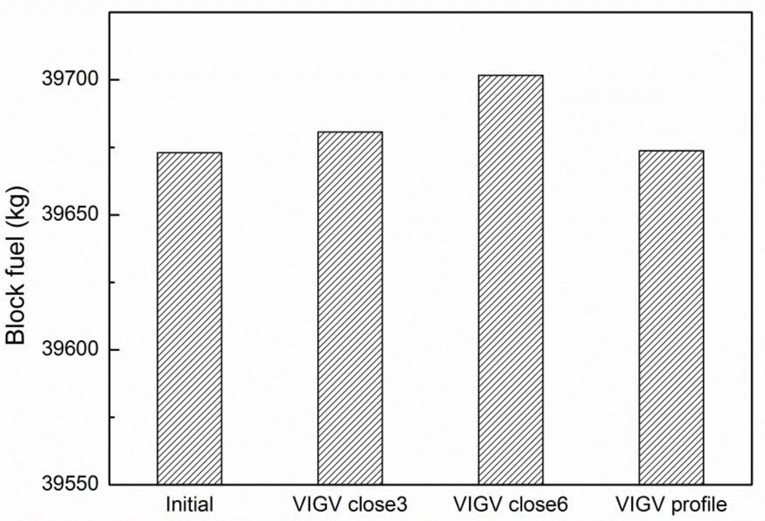
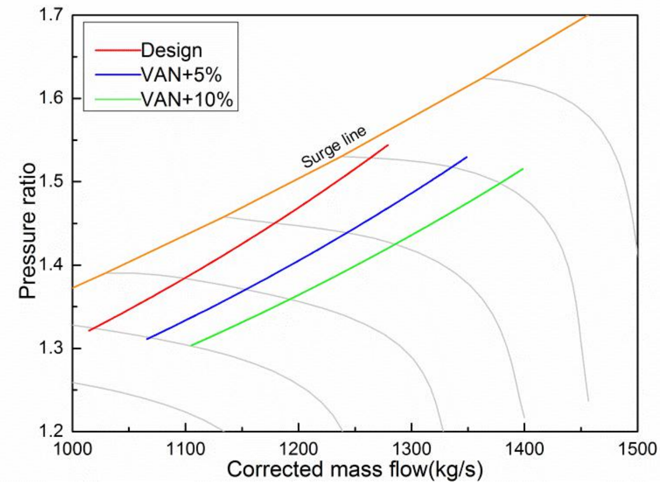


Figure 13 – Effects of VIGV on mission block fuel

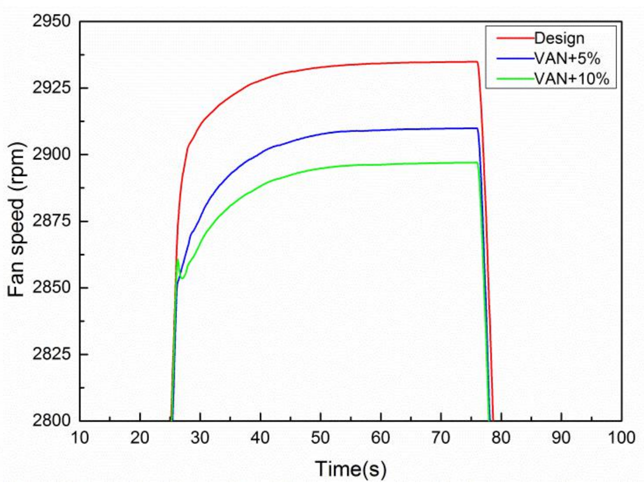
3.3 Bypass VAN effects

3.3.1 Transient behaviour

It is well-established that VAN has evolved into a fundamental and mature solution for the thrust augmentation of the combat fighter[17][18]. However, the application of VAN in the civil engine has been a great challenge due to the consideration of complexity and cost. In this scenario, the bypass nozzle was investigated to explore the benefits and possibility of utilizing VAN. As shown in Figure 14 a), enlarging the bypass nozzle area has demonstrated tremendous advantages in relieving the bypass fan surge issue. Specifically, the SM at high corrected speed has risen from 4% to 12.4% when the bypass nozzle area increases by 10%. Apparently, the open of VAN would result in a slow fan shaft speed and hence a relatively low-pressure ratio. However, due to the expanded bypass mass flow, The FN would grow larger than the expected thrust. In this scenario, the PID controller was utilized to attain the desired FN when the nozzle area enlarged. As a result, SFC reveals a sharp drop of 6.45% and 8.62%, respectively, as presented in Figure 15. Furthermore, T4 is slightly down when the VAN is utilized due to the fact that the cold flow produces higher thrust leading to less fuel requirement, as depicted in Figure 16.

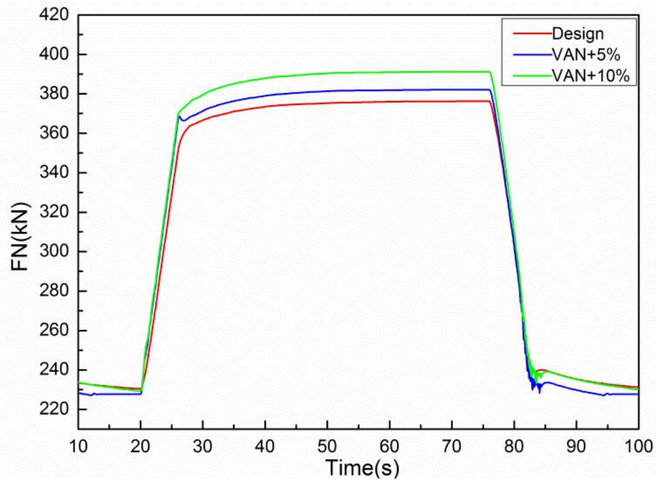


a) Bypass fan map

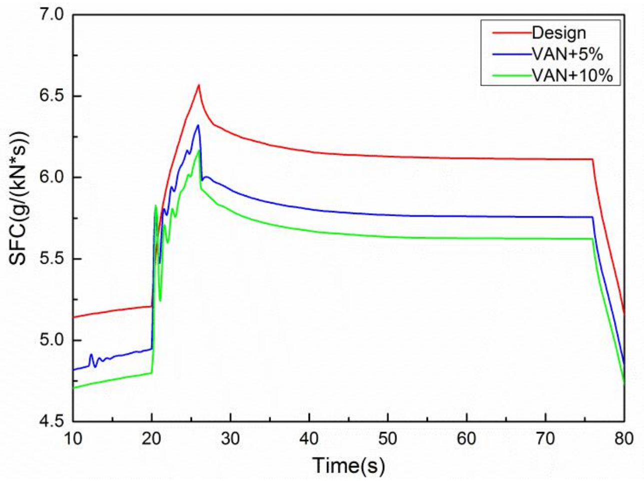


b) Fan shaft speed

Figure 14 – Effects of VAN on bypass fan operating line and fan shaft speed



a) FN



b) SFC

Figure 15 – Effects of VAN on net thrust and SFC

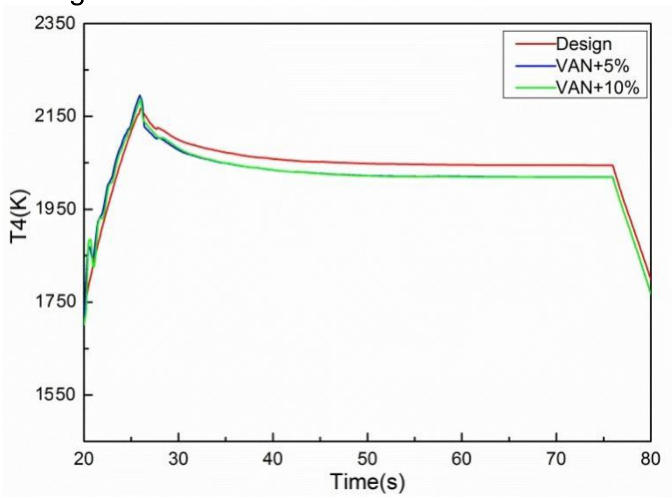


Figure 16 – Effects of VAN on T4

3.3.2 Flight mission performance

The increase of VAN also offers block fuel reduction during the flight mission, as shown in Figure 17. It could be seen that the reduction in block fuel was 2.15% and 2.41%, while the T4 was slightly alleviated. It indicates that the reasonable bypass nozzle area adjustment would be a preferred option during the mission operation.

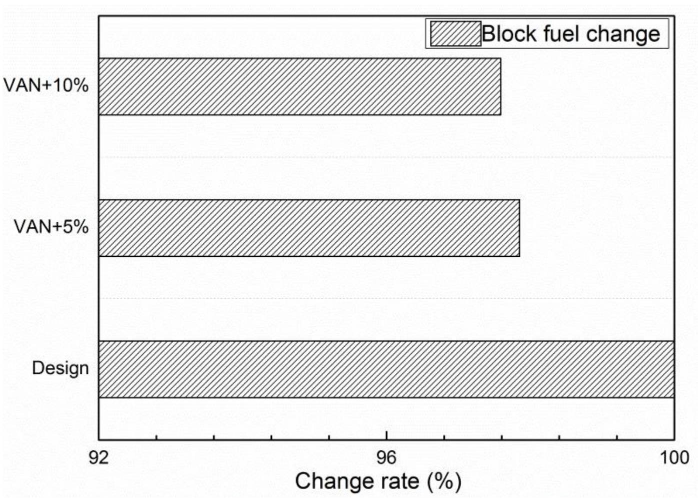


Figure 17 – Effects of VAN on mission block fuel

3.4 Comprehensive control schedule

By comparing the engine performance and shaft speed variation at take-off, the influences of adopting variable geometry were thoroughly explored, as shown in Figure 18. It could be seen that the utilization of BOV shows dramatically negative impacts on engine performance and should be avoided at high power settings. On the contrary, the application of VAN would result in a modified SFC and lower T4 when net thrust was fixed, whereas the VIGV has relatively slight effects on the engine performance except for T4. The results indicate that a comprehensive control schedule should be incorporated into the system to guarantee a surge-free engine as well as promoted performance.

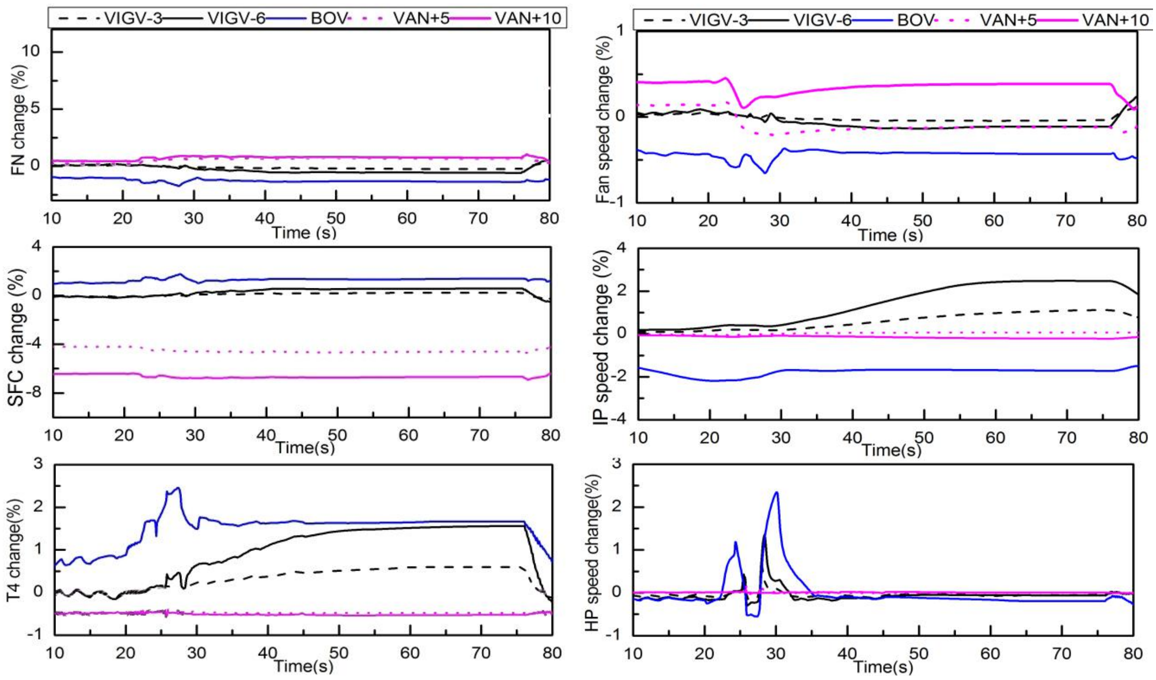


Figure 18 – Effects of variable geometry on engine performance

In this scenario, the VIGV, BOV and VAN were all implemented in the flight mission investigation. The proposed schedule for the variable geometry is depicted in Figure 19. The VIGV and BOV were both opened until approaching the cruise segment, while the VAN was opened above 1.0 corrected speed. More importantly, T4 was slightly lowered at take-off condition when maintained the same thrust level, indicating an extended turbine cycle life. By comparing the SM and performance data for the mission, the proposed strategy has effectively mitigated the surge issue and reduced fuel consumption, as depicted in Figure 20. The minimum SM for the core fan, bypass fan and IPC occurs at the climb phase, with the SM reaching 12.04%, 12.02% and 15.15%, respectively. The above values have satisfied the typical SM requirements for civil aircraft[5]. Meanwhile, the reduction in block fuel, NOx, CO_2 and H_2O was 3.36%, 5.55%, 2.47% and 2.53 %, respectively.

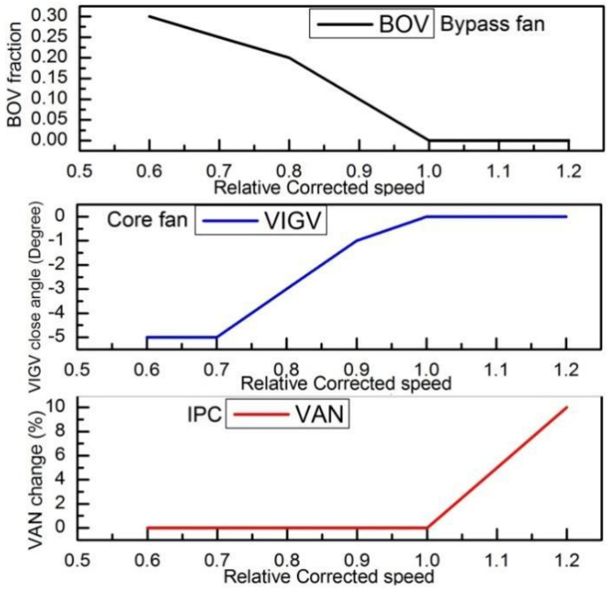
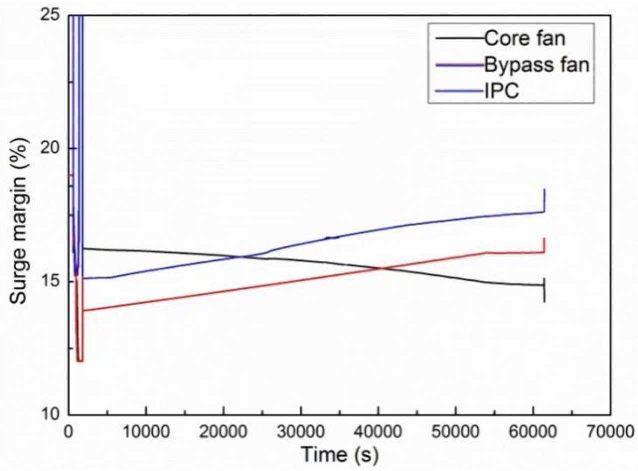
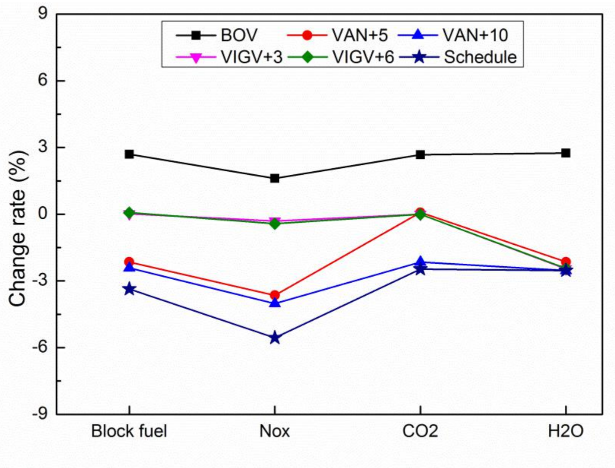


Figure 19 – Variable geometry schedule for the mission





a) Surge margin b) Fuel and emission

Figure 20 – Mission performance results

4. Conclusions

This paper carried out systematic research to investigate the benefits of implementing the variable geometry scheme in the three-shaft turbofan engine for EIS2050. The VIGV, BOV and VAN were the nominated applications that would enlarge the SM of the low-pressure compression system and promote engine performance. The outcomes could be summarized as below:

1. The incorporation of BOV would dramatically mitigate the IPC surge issue but at the expense of engine performance. The over-open of the BOV would result in a 1.38% reduction in net thrust and a 1.35% increase in SFC. Nevertheless, the application of VIGV has tremendous advantages in preventing the core fan from the surge. Besides, the close of VIGV has negligible impacts on engine performance, especially at low corrected speed.

2. The bypass VAN proved to be a profound application in boosting the engine performance and bypass fan operating line. Enlarging the bypass nozzle area by 5% and 10%, the SFC has significantly dropped by 6.45% and 8.62%, respectively. Meanwhile, the lowered T4 at take-off would extend the turbine blade life.

3. The proposed control strategy for a combination of VIGV, BOV and VAN has ensured a safe and economical flight mission. The corresponding reduction in block fuel, NO_x, CO_2 and H_2O reached 3.36%, 5.55%, 2.47% and 2.53 %, respectively.

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6. Copyright Statement

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Nomenclature

BOV	Blow-off valve
BPR	Bypass ratio
CMC	Ceramic matrix composite
EIS	Entry-into-service
FN	Net thrust
FPR	Fan pressure ratio
HPC	High pressure compressor
HPT	High pressure turbine
IPC	Intermediate pressure compressor
LPT	Low pressure turbine
PID	Proportional integral differential
RMS	Resin matrix composites
SFC	Specific fuel consumption
SM	Surge margin
T4	Turbine inlet temperature
VAN	Variable area nozzle
VIGV	Variable inlet guide vane
VPF	Variable pitch Fan

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