VSTOL Thrust Vectoring and Balancing: Degradation Mitigation Strategies

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1-ABSTRACT

This paper describes an investigation into two hypothetical VSTOL aircraft engine configurations with different means of balancing the thrust to remedy the effect of degradation. Fouling of the fan was evaluated at constant thrust at standard inlet ambient conditions. The degradation of the fan resulted in a modification of the front to rear thrust balance. In the first configuration two fine-tuning options are explored, bleed air balancing and core nozzle area change. In the second configuration changes in core nozzle area are the fine-tuning method. The study was carried out with TURBOMATCH, the Cranfield performance code; it shows that to rebalance the thrust by adjusting the bleed air, for a fan degradation of 12%, the mitigation actions require increases in the turbine inlet temperature of 100 K+. SFC is worse by about 10%. While in the other configuration a similar degradation results in much smaller changes.

2-NOMENCLATURE

Ai	- Inlet area
A_{NH}	- Hot or core nozzle area
Ao	- Outlet area
Pi	- Inlet total pressure
Po	- Outlet total pressure
Ti	- Inlet total temperature
To	- Outlet total temperature
SFC	- Specific Fuel Consumption
VSTOL	- Vertical/Short Take-off and Landing

3-INTRODUCTION AND ANALYSIS METHOD

VSTOL applications require a careful balance between the different thrust vectors produced by the propulsion system. This balance is based primarily on a careful disposition of the propulsion system within the airframe, to minimise fine-tuning requirements. This fine-tuning can be achieved by different mechanisms and it can change with the operating conditions of the power plant and aircraft.

This paper describes an investigation into two hypothetical aircraft engine configurations with different means of balancing the thrust. In the first configuration two fine-tuning options are explored, bleed air balancing and core nozzle area change. In the second configuration changes in core nozzle area are the fine-tuning method.

The operational condition explored here is the degradation of the fan producing the front or cold thrust vector of the propulsion system. The degradation of this component, for two engine configurations, was evaluated at constant thrust to match the requirement of the aircraft at standard inlet ambient conditions (288 K and 101 kPa). The degradation of the fan resulted in a modification of the front to rear thrust balance. This imbalance was addressed using the fine tuning methods indicated above to ensure that the net thrust and the moment of thrust on the aircraft centre of gravity did not change.

To carry out the engine performance evaluations the Cranfield Gas Turbine Performance System TURBOMATCH was employed. TURBOMATCH incorporates algorithms to carry out steady state, degraded and transient performance evaluations. It is based on component performance maps and iterative procedures to match mass and energy balances for the whole plant. It can produce a detailed analysis of a very wide range of gas turbine engines for land, sea and air applications. TURBOMATCH has been validated repeatedly against a range of gas turbines; to assist users a large library of engines has been produced based on public information. Many engine features have been incorporated, the focus here is on the use of bleed air and changing propelling nozzle areas to balance the front and rear thrust vectors of VSTOL propulsion systems.

The authors were intrigued that they could not find any public analysis of the type outlined here. Therefore a reference list has not been produced, instead a bibliography that may be helpful to the reader is provided.

4-ENGINE CHARACTERISTICS

There is a wide range of propulsion systems that can be employed to provide the thrust vectors needed for the vertical and horizontal operating models for VSTOL. These include separate engines, multiple exhausts and tilting powerplants. Here the analysis for two hypothetical configurations is shared: a separate exhaust turbofan and a remote lift fan propulsion system. These two machines have been conceived to provide a suitable balance between the different thrust legs they produce. A detailed cycle optimisation has not been carried out here because it would not have changed the nature of the message of the research.

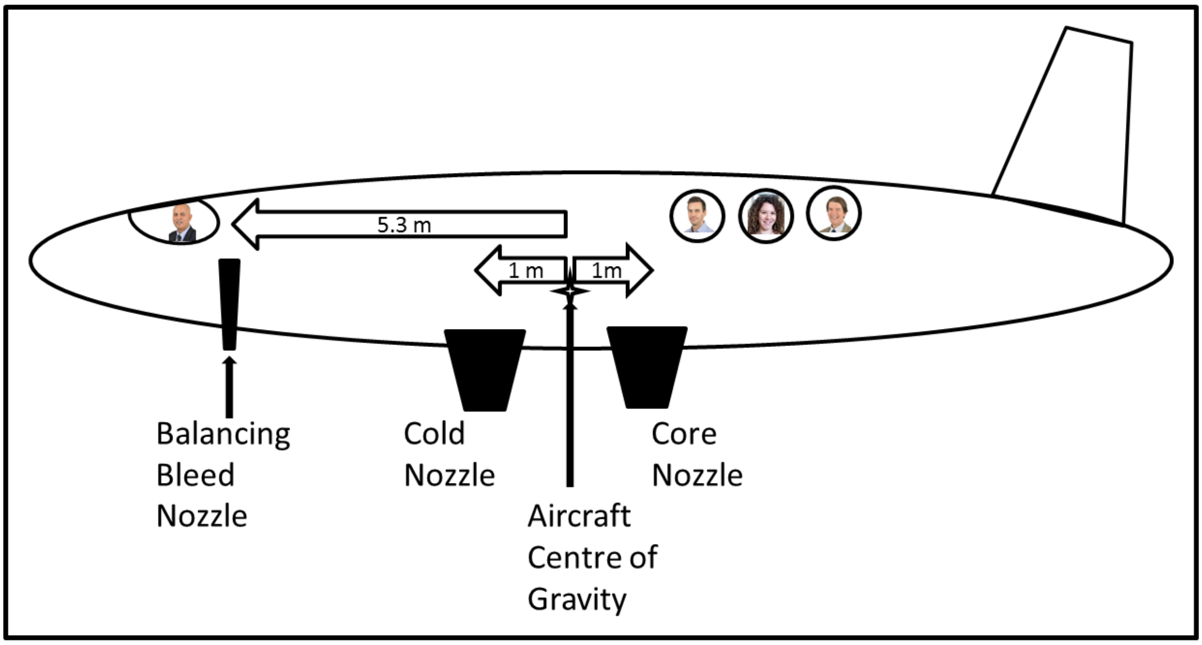

Fig 1 – Configuration 1 showing the location of the nozzles relevant to the investigation.

4.1-Configuration 1 – Separate Exhaust Turbofan

Configuration 1 consists of a turbofan engine that comprises a fan, a high pressure compressor, combustor, high pressure turbine and low pressure turbine. Two exhaust nozzles are used in this jet engine; one is for the bypass flow to deliver the cold thrust vector. The second nozzle is the core exhaust that produces the hot or core thrust vector. The cycle is designed so that the cold (front) and core (rear) thrust vectors are the same, at 53 kN each. Table 1 shows the main thermodynamic performance parameters of the cycle of the turbofan. The column labelled ‘clean’ shows the baseline parameters with the thrust required and balanced between the front and rear thrust vectors.

The main power plant nozzles are located 1m from the centre of gravity of the aircraft, one to the front, the other to the rear. In a configuration like this, several bleed air nozzles would be placed in several positions in the airframe to fine-tune the total thrust and moment of thrust ensuring satisfactory balance. In this investigation only one such auxiliary nozzle is considered, located at the front of the aircraft at 5.3 meters from the centre of gravity of the vehicle. This nozzle produces thrust through the discharge of a bleed from the high pressure compressor delivery. This nozzle is one of the two balancing mechanisms deployed for this configuration. The second is the variation of the core nozzle area. These are deployed separately and constitute the two examples explored for this configuration.

CONFIGURATION 1	Clean	Degraded (max) Unbalanced	Degraded (max) Bleed balanced	Degraded (max) A_{NH} balanced
Thrust [kN]	106.5			
Front Thrust [kN] Bypass	53.20	50.39	50.16	53.26
Rear Thrust [kN] Core	53.31	56.12	56.37	53.26
Bleed Thrust [kN]	0	0	0.98	0
Turbine Entry Temperature [K]	1600	1728	1750	1696
Exhaust Gas Temperature [K]	1069	1162	1178	1118
Fan Pressure Ratio	2.14	2.07	2.06	2.14
Compressor Pressure Ratio	7.61	8.11	8.04	7.82
Overall Pressure Ratio	16.29	16.78	16.58	16.75
Bypass Ratio	1.94	1.87	1.87	1.91
Airflow [kg/s]	213	206	206	210
Balancing bleed [%]	0	0	1.91	0
A_{NH} [m^2]	0.2272	0.2272	0.2272	0.2463

Table 1 – Configuration 1: performance parameters, clean and degraded

4.2-Configuration 2 – Turbofan with remote lift fan

Configuration 2 consists of a main propulsion engine that comprises a fan, a high pressure compressor, combustor, high pressure turbine and low pressure turbine. For VSTOL operations there is a remote fan that is engaged via a clutch to the low pressure shaft, the shaft that incorporates the main engine fan and the low pressure turbine. Four exhaust nozzles are used in this jet engine; one is for the remote fan to deliver the cold thrust vector. The second nozzle is the core exhaust that produces the hot or core thrust vector. This core nozzle discharges the core flow of the main engine. It was assumed that the main engine bypass air is ejected through two wing nozzles, assumed to be located to each side of the centre of gravity of the aircraft. So in this analysis where only VSTOL operations were considered, these wing nozzles contribute to the thrust but not to the balancing of the aircraft, so the focus is on the remote fan and the core nozzles. The cycle analysed here is designed so that the cold (front) and core (rear) thrust vectors are the same, 84 kN each when the engine is clean.

Table 2 shows the main thermodynamic performance parameters of the cycle of the whole system. The column labelled ‘clean’ shows the baseline parameters with the thrust required and balanced between the front and rear thrust vectors. For this configuration, one balancing mechanism is used to ensure the correct distribution of front and rear thrust: the variation of the core nozzle area.

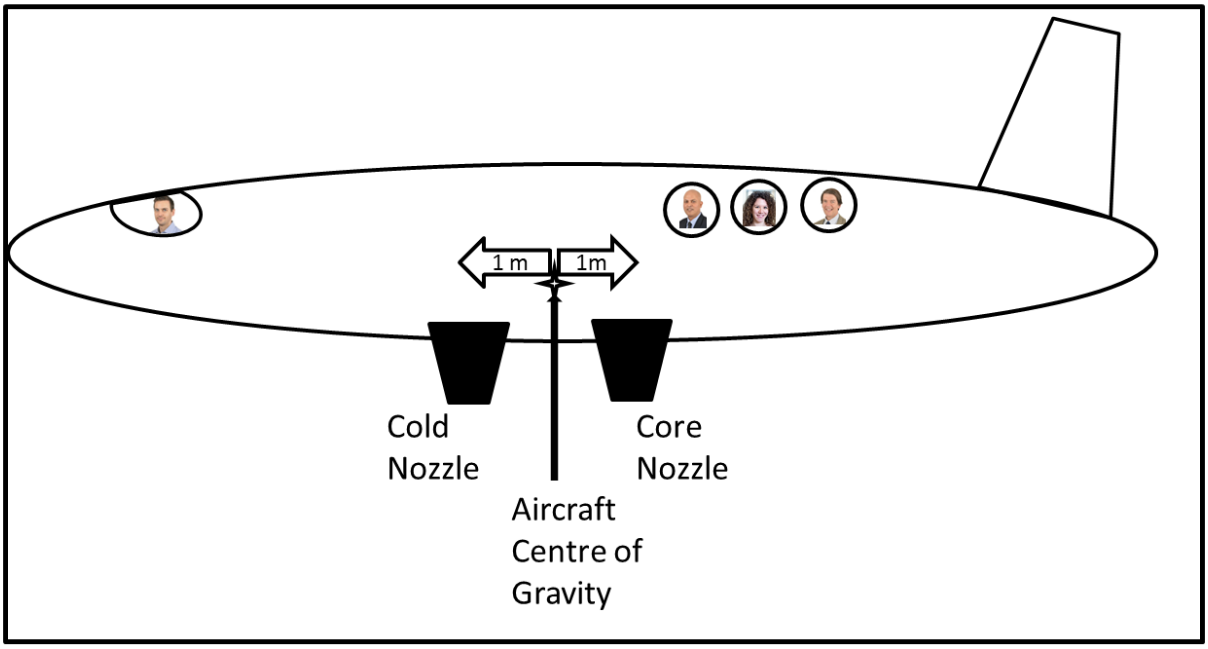

Fig 2 – Configuration 2 - Turbofan with remote lift fan, auxiliary wing nozzles not shown

CONFIGURATION 2	Clean	Degraded (max) Unbalanced	Degraded (max) ANH balanced
Total Thrust [kN]	190.36		
Front thrust [kN] Remote Fan	*84.01*	*78.38*	*82.59*
Rear Thrust [kN] core	84.17	88.63	82.59
Wing nozzle thrust [kN]	22.18	23.35	25.17
Turbine Entry Temperature [K]	2000	2026	1981
Exhaust Gas Temperature [K]	1280	1298	1234
Remote Fan Pressure Ratio	*2.11*	*2.02*	*2.09*
Fan Pressure Ratio	3.07	3.19	3.39
Compressor Pressure Ratio	9.44	9.46	8.77
Overall Pressure Ratio	28.98	30.22	29.71
Bypass Ratio	0.51	0.51	0.54
Remote Fan flow [kg/s]	*225*	*214*	*220*
Main Engine Airflow [kg/s]	140	145	147
Core Nozzle Area [m^2]	0.2262	0.2262	0.2563

Table 2 – Engine model parameters, including remote lift fan.

5-CONFIGURATION 1: FAN DEGRADATION AND MITIGATION

When the engine is in the 'clean' condition, there is an exact thrust balance between the front and the rear thrust vectors. With the passage of time and for many reasons, power plants will exhibit performance degradation. In this investigation the degradation was limited to one component, the fan of the engine. A degradation of up to 12% was examined for this component. 1% of fan degradation means a reduction of 1% of the fan efficiency plus 1% degradation of the fan airflow capacity. In this context, at a given pressure ratio the fan needs 1% more power per unit of mass flow and at a given corrected speed the fan will deliver 1% less corrected airflow. This type of degradation could be the result of fouling of the fan. Of course the degradation of many components, alone or in combination will affect the front to rear thrust balance. These will be the subject of subsequent assessments.

In the present investigation five cases were examined, the clean one plus degradations of 3, 6, 9 and 12%. Naturally, degradation changed the performance of the engine and upset the front to rear thrust balance. Figure 3 and Table 1 show that in the extreme case the hot nozzle thrust was more than 10% larger. This imbalance is clearly not acceptable and remedial action is necessary.

The thrust was maintained constant to match the aircraft requirements through an increase in the Turbine Entry Temperature. This increase in turbine temperature resulted in increased core pressure ratio and temperatures. This in turn delivered higher pressure ratio and exhaust gas temperature for the core nozzle that resulted in a higher specific thrust from the core nozzle. The overall mass flow and bypass ratio have fallen as a result of the fan degradation. The outcome is the change of the balance between the cold and hot thrust vectors, the hot one being significantly larger.

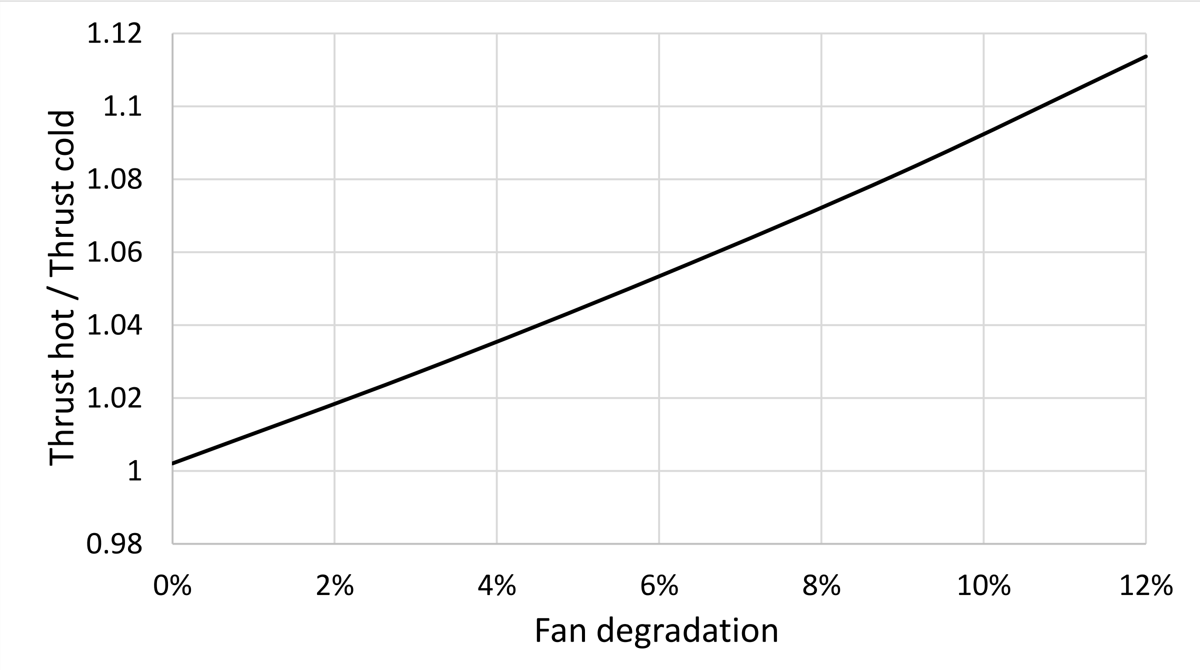

Fig 3 – Effect of Fan degradation on Configuration 1 at constant thrust

Two mitigation strategies were employed: thrust balancing using a bleed extraction discharged through the balancing bleed nozzle and thrust balancing adjusting the core nozzle area, assuming the core nozzle is a variable area nozzle.

In the first instance the thrust is balanced using an air bleed from the exit of the high pressure compressor. This stream of air is ducted to the balancing bleed nozzle located at the front of the aircraft, 5.3m from the centre of gravity of the vehicle. In the extreme case of fan degradation examined here a balancing thrust of nearly 1kN is needed (Fig 4). This thrust is delivered by an air bleed, in the extreme degradation case, of nearly 2% of the high pressure compressor air flow (Fig 5).

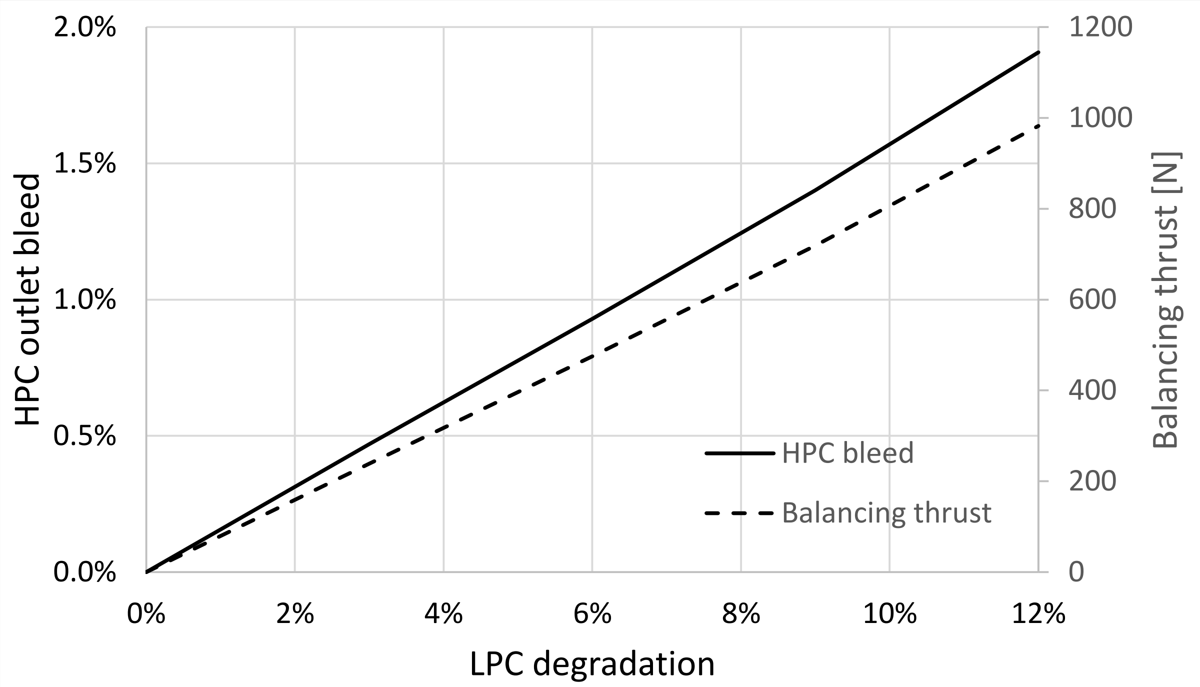

Fig 4 – Thrust from bleed nozzle and bleed fraction at constant engine thrust

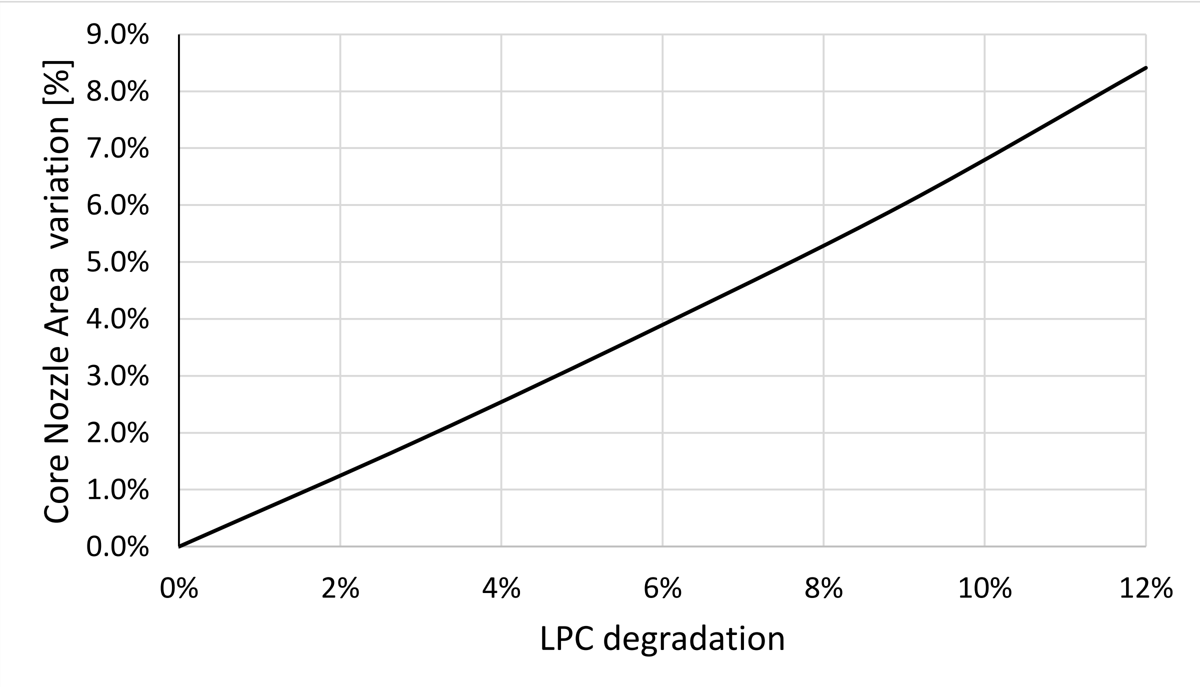

Fig 6 – Core nozzle area increase at constant thrust

The other thrust balancing mechanism explored for Configuration 1 is the variation of the core nozzle area. For a modern gas turbine where the nozzle guide vanes and the propelling nozzles are choked it can be shown that, for the turbine upstream, approximately:

$$Pi/Po = (Ao/Ai)^{0.9} \quad \text{and} \quad Ti/To = (Ao/Ai)^{4}$$

Ai is the throat area of the nozzle guide vanes at inlet to the turbine. So the effect of the increased core nozzle area (turbine Ao above) is an increase in the pressure ratio and temperature ratio of the low pressure turbine that delivers an increase in the specific work of the turbine. Figure 6 shows how much the nozzle area needs to change to compensate for the thrust imbalance. The resulting increase in low pressure turbine specific work enables an increase in the fan corrected speed, mass flow and fan pressure ratio, compared with the unbalanced case. Furthermore the increased pressure ratio of the low pressure turbine reduces the core nozzle pressure and temperature, reducing the specific thrust from the core. These effects combined balance the thrust.

Table 1 and Fig. 7 show that the Turbine Entry Temperature needs to increase in all degraded cases to balance the thrust. This increase is in the range of 100K or more, depending on the case. Within the context of this exercise it is assumed that the increase in Turbine Entry Temperature is tolerated. However these increases could give rise to concerns regarding the turbine life. In the unbalanced case, the Turbine Entry Temperature increase is the result from the requirement to meet the prescribed thrust.

An even larger increase in Turbine Entry Temperature is necessary when the thrust balancing bleed is extracted from the high pressure compressor exit. Bleed extractions cause increases in turbine inlet temperature because the turbine needs to produce the compressor work with a lower airflow than when a bleed is not extracted.

When the core nozzle area change is used as a mitigation strategy there is also an increase in the turbine inlet temperature. In this case the increase is smaller than in the unbalanced case because much of the mass flow reduction has been restored via the increased specific power of the core. The slightly lower mass flow in the bypass stream is compensated with a slightly higher temperature of the fan exit arising from the degradation. The low pressure shaft is now operating at a higher corrected rotational speed because the nozzle area change delivers an increase in the low pressure turbine pressure ratio. In the core, the airflow is also lower and compensated by the higher temperature resulting from the increased Turbine Entry Temperature compared to the clean case.

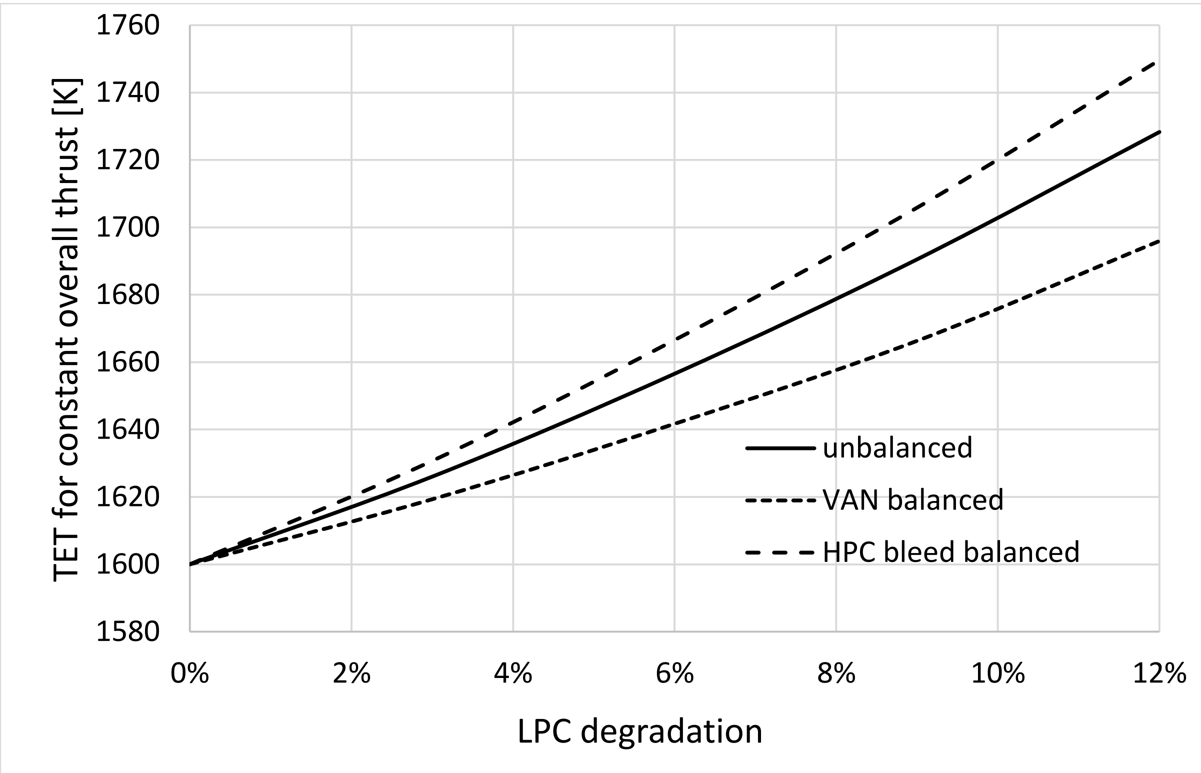

Fig 7 – TET variation at constant thrust

Figure 8 shows the SFC penalties of the degradations in the three scenarios. As the fan degrades, the conventional SFC penalty is shown for the unbalanced case. This is, as expected, of the order of 10%. Apart from the increased fan losses, a key reason for this is the reduced bypass ratio and mass flow that require an increase in specific thrust. Furthermore due to the reduced fan pressure ratio there is a reduction in bypass specific thrust. Due to the increased core nozzle temperature and pressure ratio there is, as explained earlier, an increase in the core specific thrust. This change also affects the SFC. When the bleed is deployed to produce the balancing thrust, the SFC is slightly worse. This is because the pressure ratio of the bleed nozzle is very high due to the position of the bleed extraction. When the remedial action used is through the core variable area nozzle, the SFC penalty is somewhat smaller than the other two degradation scenarios. This is because the mass flow and bypass ratio are nearly restored. The main reason for SFC degradation here is the losses within the power plant resulting from the fan degradation.

6-CONFIGURATION 2: REMOTE FAN DEGRADATION AND MITIGATION

As for Configuration 1, five cases were examined, the clean case plus degradations of 3, 6, 9 and 12%. As expected again, the degradation changed the performance of the engine and upset the front to rear thrust balance. Figure 9 and Table 2 show that in the extreme case the hot nozzle thrust was more than 10% larger. This imbalance is clearly not acceptable and remedial action is necessary.

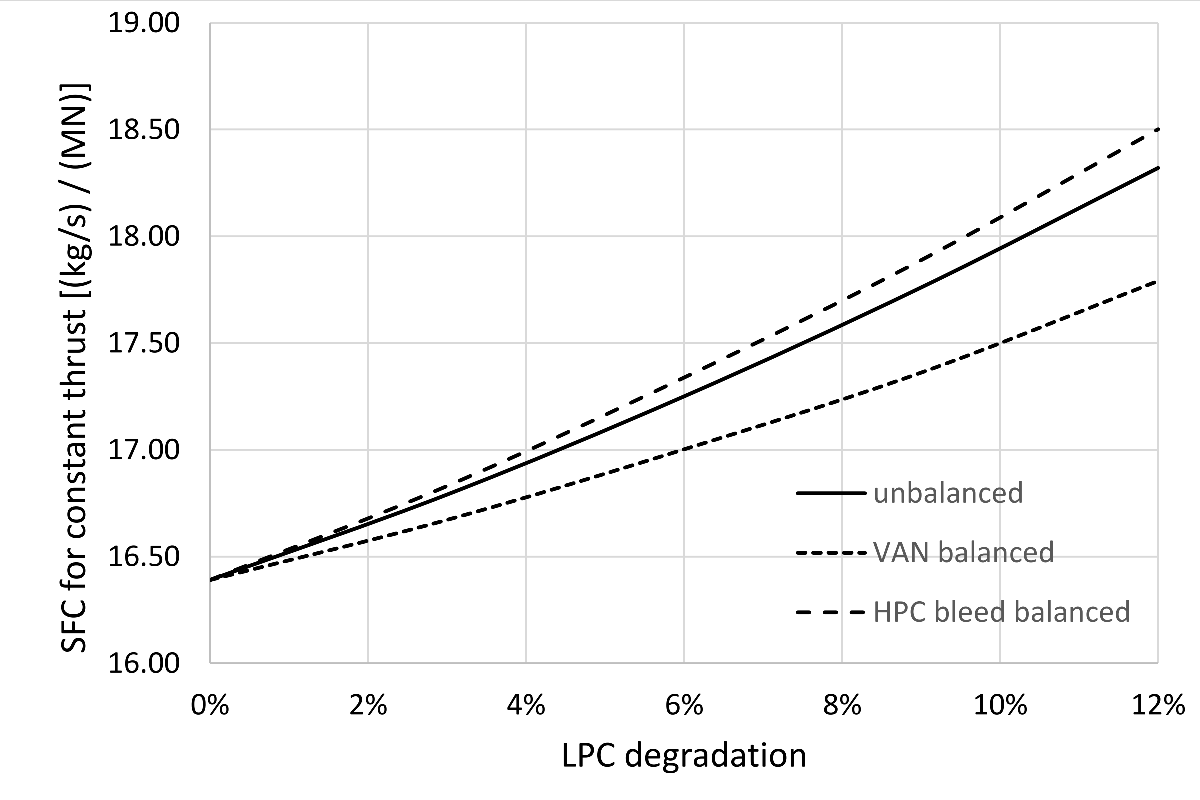

Fig 8 – SFC variation for Configuration 1 cases

The thrust was maintained constant to match the aircraft requirements through an increase in the Turbine Entry Temperature. This increase in turbine temperature resulted in increased core pressure ratio and temperatures. This in turn delivered higher pressure ratio and exhaust gas temperature for the core nozzle that resulted in a higher specific thrust from the core. The remote fan mass flow has fallen as a result of the fan degradation. The outcome is the change of the balance between the cold and hot thrust vectors, the hot one being significantly larger.

To balance the thrust, the core nozzle area was increased by 13% in the extreme degradation case. For this configuration the results are somewhat different to those of Configuration 1. It can be observed that the proportional change in nozzle area is significantly larger (13% vs 8%). This increase results in an increased rotational speed and power output of the low pressure shaft that drives the remote fan and the main engine fan. This induces a larger airflow and bypass ratio of the main engine plus a restoration (compared to the unbalanced case) of the airflow of the remote fan. In Configuration 2, part of the thrust balancing arises from the reduction of the core thrust and an increase of about 10% of the wing nozzle thrust that, given their position alongside the centre of gravity of the aircraft, do not affect the front/rear thrust balance.

The Turbine Entry Temperature changes of Configuration 2 are much smaller than those of the earlier case. This is because the relative severity of the degradation is much smaller for Configuration 2. Two reasons underpin this result. Firstly, only one of three compressors, the remote lift fan, is degraded. In configuration 1 one compressor out of two was fouled. Furthermore the core of Configuration 2 operates with a much higher baseline Turbine Entry Temperature, making the degradation less important in relation to the total power transfers within the engine. So, for the extreme degradation scenario, the change in Turbine Entry Temperature needed to restore the thrust in the unbalanced case for Configuration 2 is of the order of 25K rather than the 100+K needed in configuration 1 (Tables 1 and 2). When the core nozzle area is opened to balance the thrust, the Turbine Entry Temperature falls slightly because of the increased bypass ratio of the main engine. This makes the core cycle more efficient from a propulsive efficiency perspective. As expected, Fig 13 shows that SFC rises by about 5% in the extreme degradation case examined for configuration 2 when the thrust is not balanced. In Configuration 1 the changes are of the order of 10% (Fig. 8). When the thrust is balanced, the lower Turbine Entry Temperature and the higher bypass ratio result in very small change in SFC. The trend shown in Fig 3 is mainly influenced by small changes in the efficiencies of the components that result from the re-matching that arises from the change in operating points in compressors and turbines. The authors expect that if the severity of the degradation were increased beyond the levels shown here, the Turbine Entry Temperature and the SFC will rise. Of course the specific thrust of the engine is now lower.

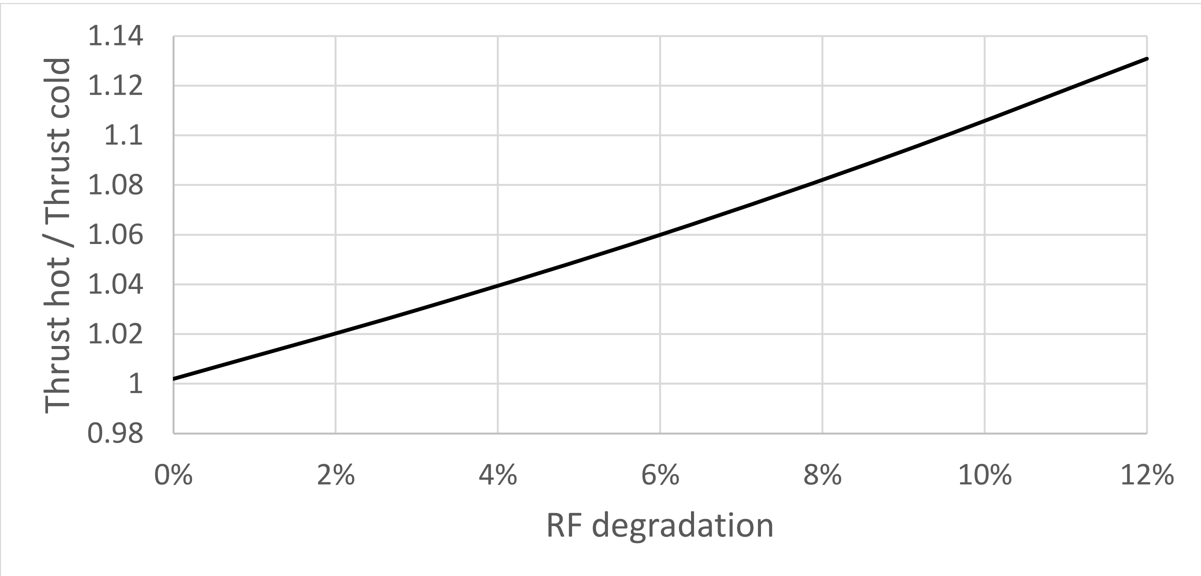

Fig 9 – Thrust imbalance arising from Remote Fan degradation

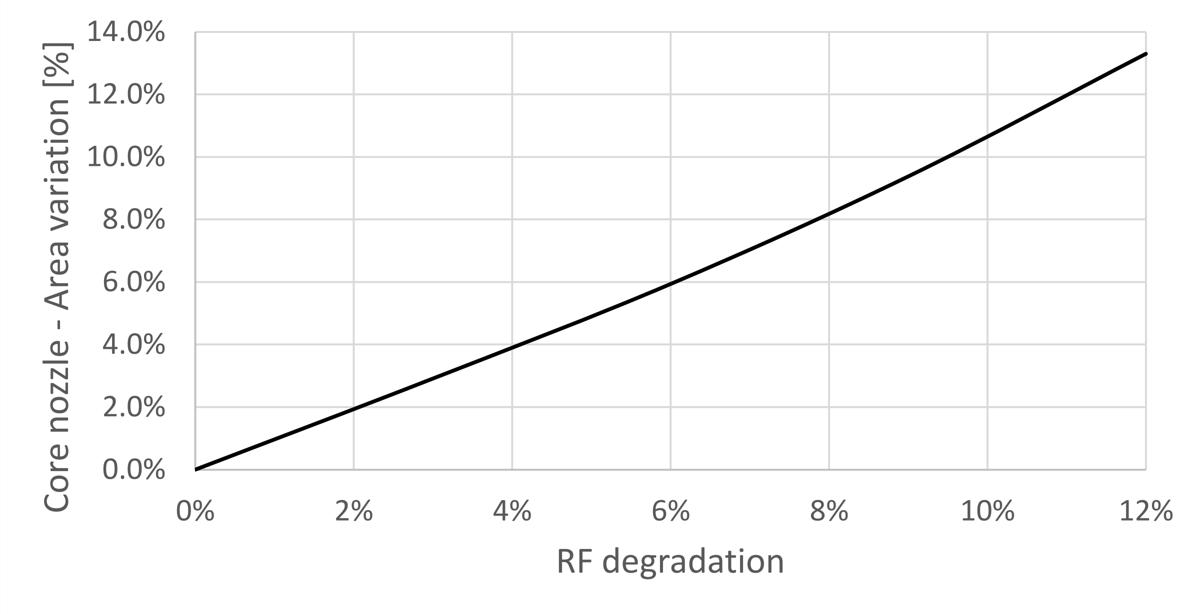

Fig 10 – Core nozzle area variation required to re-balance Remote Fan degradation.

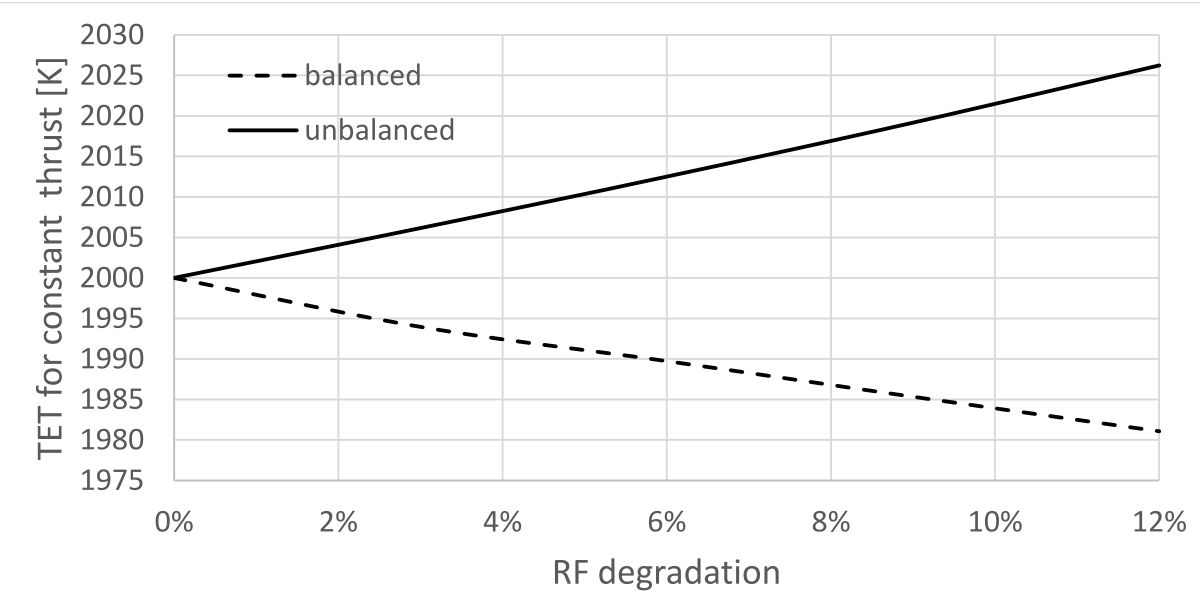

Fig 12 – TET variation with RF degradation.

7-CONCLUSION

This paper describes an investigation into two hypothetical aircraft engine configurations with different means of balancing the thrust. In the first configuration, two fine-tuning options are explored, bleed air balancing and core nozzle area change. In the second configuration, changes in core nozzle area are the fine-tuning method.

A thermodynamic performance model of each engine was produced using TURBOMATCH, to deliver an analysis that the authors have not seen in the public domain. This study shows the significant insights that can be obtained through the judicious use of a reliable gas turbine performance model.

In the first configuration, two methods were used to balance the thrust following the fouling of the fan. The degradation results in a higher turbine inlet temperature. However, balancing the thrust with a variation of the core nozzle area requires a smaller increase in turbine inlet temperature. This is beneficial in terms of lifing considerations of the engine. In

the second configuration, a variation in core nozzle area is used to balance the thrust. In the second case, due to the lower relative severity of the degradation the impact of the change in operating conditions is smaller.
A parallel conclusion is the value of examining turbofan operating scenarios with a reliable and comprehensive performance simulation code. Realistic outputs can be obtained that add great value to design, operating and maintenance considerations.

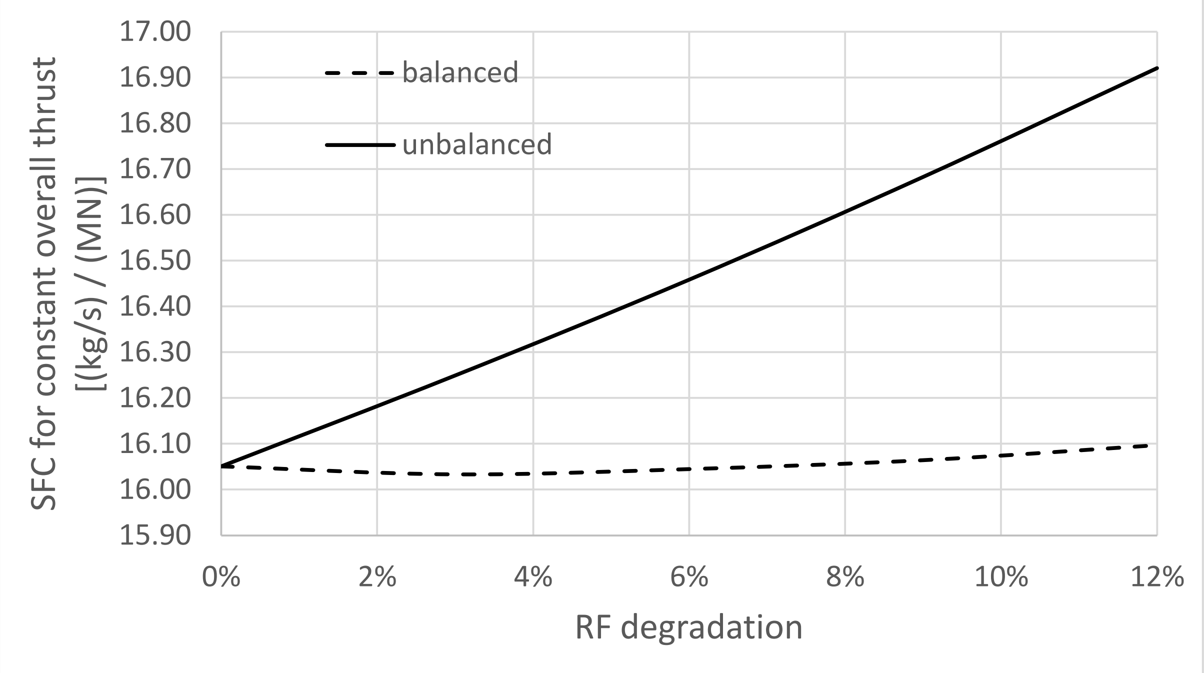

Fig 13 – SFC variation with Remote Fan degradation.

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