PERFORMANCE IMPROVEMENT OF THE CFM56-3 AIRCRAFT ENGINE BY ELECTRIC POWER TRANSFER

H. Balaghi Enalou, S. Bozhko

University of Nottingham, Nottingham, the UK
hbalaghienalou@gmail.com, Serhiy.bozhko@nottingham.ac.uk

ABSTRACT

With the design trends towards the More Electric Engine (MEE) for the More Electric Aircraft (MEA), areas for novel technologies can be pinpointed for multi-spool engines, introducing remarkable improvements to push the boundaries of propulsion technology as it strives to create quieter and more efficient engine. Provided that a multi-spool engine is equipped with electrical machines connected to each of its shafts, using power electronics within a single high-voltage DC bus configuration, it is possible to circulate desired amount of power between the engine shafts independent of their speeds. This paper presents an engine model which has also considered Variable Stator Vanes (VSVs) and Variable Bleed Valves (VBVs) for bleeding in order to investigate the idea of power transfer at low speed settings. Validation with test results from the CFM56-3 engine highlights acceptable level of accuracy of the engine model. Moreover, preliminary results show that the idea of power circulation is highly desirable for low speed settings for the CFM56-3 aircraft engine. The electrical power transfer from the Low Pressure (LP) to the High Pressure (HP) shaft at engine’s low speed settings such as taxi and flight idle, helps to decrease the fuel rate and increase the available surge margin of compressors.

KEYWORDS

AIRCRAFT ENGINE, ELECTRIC POWER TRANSFER, MORE ELECTRIC ENGINE (MEE), VARIABLE BLEED VALVES (VBVs), VARIABLE STATOR VANES (VSVs)

NOMENCLATURE

<table>
<thead>
<tr>
<th>CC</th>
<th>Combustion Chamber</th>
<th>PEC</th>
<th>Power electronic Convertor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>Control Volume</td>
<td>SFC</td>
<td>Specific Fuel Consumption (g.kN⁻¹.s⁻¹)</td>
</tr>
<tr>
<td>ECS</td>
<td>Environmental Control System</td>
<td>SLS</td>
<td>Sea-Level-Static</td>
</tr>
<tr>
<td>EEC</td>
<td>Electronic Engine Control</td>
<td>SM</td>
<td>Surge Margin</td>
</tr>
<tr>
<td>EOM</td>
<td>Engine Operation Mode</td>
<td>VBV</td>
<td>Variable Bleed Valves</td>
</tr>
<tr>
<td>EPS</td>
<td>Electrical Power System</td>
<td>VSV</td>
<td>Variable Stator Vanes</td>
</tr>
<tr>
<td>EPT</td>
<td>Electric Power Transfer</td>
<td>J</td>
<td>Shaft inertia (kg.m²)</td>
</tr>
<tr>
<td>HP</td>
<td>High Pressure</td>
<td>P</td>
<td>Power (Watt)</td>
</tr>
<tr>
<td>HPC</td>
<td>High Pressure Compressor</td>
<td>R</td>
<td>specific gas constant (J.kg⁻¹.K⁻¹)</td>
</tr>
<tr>
<td>HPT</td>
<td>High Pressure Turbine</td>
<td>T</td>
<td>Temperature (°K)</td>
</tr>
<tr>
<td>ICV</td>
<td>Intermediate Control Volume</td>
<td>V</td>
<td>Volume (m³)</td>
</tr>
<tr>
<td>LP</td>
<td>Low Pressure</td>
<td>m</td>
<td>Mass (kg)</td>
</tr>
<tr>
<td>LPC</td>
<td>Low Pressure Compressor</td>
<td>p</td>
<td>Pressure (pa)</td>
</tr>
<tr>
<td>LPT</td>
<td>Low Pressure Turbine</td>
<td>t</td>
<td>Time (s)</td>
</tr>
<tr>
<td>MEA</td>
<td>More Electric Aircraft</td>
<td>ω</td>
<td>Speed (rad.s⁻¹)</td>
</tr>
<tr>
<td>MEE</td>
<td>More Electric Engine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
INTRODUCTION

Conventional multi-spool gas turbines can operate within a wide speed range for industrial, propulsion or power generation purposes. Among them, high bypass ratio turbofans are considered as the dominant sources of propulsion for most of civil aircrafts. Recently, the MEE has encouraged the use of high-power, high-efficiency, lightweight motor/generators connected to both the Low Pressure (LP) and High Pressure (HP) of the engine to augment electric power to the airframe of the MEA and reduce the effects of large load transients (Provost, 2002, Pluijms et al., 2008, Kloos et al., 2018). Having parallel sources of power with alternating speed on various engine shafts has resulted in introduction of innovative power system architectures with Power Electronic Convertors (PECs) controlling the generation. Engine designers have a great opportunity to take advantage of these architectures, introducing new integrated systems within the MEE concept.

However, the off-design efficiency of multi-spool engines such as aircraft engines is very low, irrespective of the engine size, in part because of the particular manner in which the engine operates at these conditions. Typically, for gas turbines, higher engine pressure ratio leads to higher efficiency, while at part loads, the engine pressure ratio drops due to the decrease in the speed of compressors. The engine components (compressors and turbines) are thermodynamically coupled since the Low Pressure Compressor (LPC) delivers airflow to the High Pressure Compressor (HPC) and the High Pressure Turbine (HPT) delivers the hot combustion products to the Low Pressure Turbine (LPT). This makes an approximately fixed power split ratio between the HPT and the LPT which, as a result, forces the shaft speed variations to bind to each other thermodynamically from part to full power settings, although there is no mechanical link between the shafts. The inflexibility of shaft speeds causes mismatches in the performance of compressors at off-design conditions which is dealt with by handling bleed systems such as Variable Bleed Valves (VBVs) between the compressors. As a consequence, the engine operates in a sub-optimal condition at low compressor speeds, thereby being fuel inefficient.

In this case, any system which can help to decouple the shaft speeds is highly desirable. Power transfer has been highly desirable since 1990 for engineers, suggesting various methods such as implementation of a hydraulic transmission system with hydraulic pumps and motors, multi speed transmission systems with clutch assemblies, auxiliary air turbines, electric heaters and magnetic gearboxes (Hield et al., 1993, Eick et al., 2005, Anghel et al., 2012). Among all, provided that there is at least one electrical machine on each shaft, there is the ability to transfer power between the shafts with Power Electronic Convertors (PECs) with high efficiency and reliability.

This idea can be applied broadly for applications which include, but are not limited to, aircraft engines, ship engines and ground-based power generations. The main expectations from this configuration are:

• fuel burn reduction at off-optimum conditions
• increase in engine stability margins
• dynamic response improvement

Moreover, this configuration will decouple shaft speeds to some degree, depending on the amount of power transfer to shaft powers, in order to:

• improve engine starting and relighting
• optimize compressors’ performance at higher efficiency with adequate Surge Margin (SM)
• remove Variable Stator Vanes (VSVs) and Variable Bleed Valves (VBVs)
• help faster acceleration and deceleration of the engine;
• help the engine core withstand severe transients
• increase the engine’s thermodynamic cycle efficiency
• manage engine start-up and performance at very high or low ambient temperature

Prior control schemes, mainly suggested for turbofans, have elaborated on multi-spool offtake for the More Electric Aircraft (MEA), attempting to optimize engine performance by splitting the electrical loads on the two spools (Pluijms et al., 2008) or circulation of power between them to further optimize and enhance the engine performance (Enalou et al., 2018, Phillips et al., 2013).
(Belokon et al., 2003) has also considered power exchange with a LP shaft through an auxiliary generator/motor to maintain a high peak temperature to optimize engine efficiency at part-load conditions in a multi-spool turbo-generator for a distributed power generation system.

This paper investigates fuel burn and SM of the engine by implementing the concept of power exchange for the CFM56-3 engine model which has considered the effect of VBV and VSV. For this purpose, a brief overview on multi-spool engine performance will be provided. Then the electric power transfer system will be introduced. Afterwards, the engine model will be elaborated followed by performance results at different operation scenarios.

**MULTI-SPOOL ENGINE**

Figure 1 shows the schematic diagram of a typical high bypass turbofan where the LP spool is colored as blue and the HP spool is colored as dark brown. The common components of these engines can be named as: fan, LPC, inter-compressor bleeds, HPC and cooling bleeds, fuel metering system, combustion chamber, HPT, LPT and discharge nozzles. The HPT drives the HPC on the HP shaft and the LPT drives the fan and LPC on the LP shaft.

For the multi-spool engine, corrected speed of the HPC determines the outlet conditions of the LPC. The HPC will swallow and pass flow delivered by the LPC, provided that the HPC speed is properly matched with that of the LPC. However, if the HPC speed is less than its desired matched value with that of the LPC, the HPC demands less mass flow. Hence, it acts as a blockage for the rear side of the LPC, pushing it to decrease its mass flow on the same speed line as shown in Figure 2. As a result, the pressure ratio of the LPC increases and the operation point of the LPC gets closer to the surge line.

Therefore, the operating line of the LPC is determined by the flow requirement of the HPC which is determined by the HPC corrected speed. LPC and HPC speeds are normally matched for the high speed setting at design condition while, due to the HPT/LPT power split ratio at lower speed settings, the HPC speed is lower than the desired matched value. For this reason, there is a risk of LPC surge at low speed settings.

To prevent this, the VBV are located between the LPC and HPC with the function of regulating the primary flow entering the HPC. VBV act primarily at low speeds due to lower LPC SM. However, bleeding of
compressed air is a loss of energy, for which VBVs positions are normally scheduled with the HPC speed to avoid considerable drop in efficiency. The HPC operation point also moves closer to the surge line with reduction in its speed due to considerable power offtake (Enalou et al., 2016). By power offtake from the LP shaft and feeding it to the HP shaft the speed reduction will be compensated. Moreover, with higher HP speeds HPC can afford more massflow which is accordingly provided by scheduled VBVs. The decrease in bleeding will also increase the engine efficiency. This highlights the fact that power transfer to HP shaft in order to increase its speed is highly desirable.

The Variable Stator Vanes (VSVs) are also located in the first three stages of the HPC. They form the stators of these stages. Their objective is to optimize the HPC performance for each combined state of HP spool speed and air density.

**ELECTRIC POWER TRANSFER BETWEEN SHAFTS**

Already offered in the MEE (Provost, 2002, Newman, 2004, Hirst et al., 2011, Kreuzer and Niehuis, 2017), electrical machines are connected to both LP and HP shafts through fixed speed ratio gearboxes shown in Figure 1. (Gao et al., 2015, Gao and Bozhko, 2016, Gao et al., 2016) have also elaborated on the single DC bus architecture to handle variable frequency power generation. Figure 3 shows a single DC bus with two electrical machines connected to it through bidirectional converters.

This provides the opportunity to circulate power between the shafts, having the privilege of dynamically controlling it. While one of the electrical machines is controlling the DC link voltage, the other one can be in current control mode to manage the amount of power which is circulated between the engine shafts. This configuration accommodates an engine with flexible power split ratios at different operational speeds depending on the amount of power transfer as described:

\[
P_{HPT} + P_{EHP} = J_{HP} \dot{\omega}_{HP} + P_{HPC} \quad (1)
\]

\[
P_{LPT} - P_{ELP} = J_{LP} \dot{\omega}_{LP} + P_{FAN} + P_{LPC} \quad (2)
\]

\[
P_{ELP} + P_{EHP} + P_{EPS} = 0 \quad (3)
\]

where; \(P_{ELP}\) and \(P_{EHP}\) are electric power transfer for LP and HP shafts, \(P_{EPS}\) is the onboard MEA electrical power system load on the DC link. It should be noted that with increasing power demand for the MEA, the impact of MEA load on the DC link and electric power transfer should be analyzed together.

**MODELLING**

A zero-dimensional (0-D) multiple spool engine model has been developed in the MATLAB-SIMULINK environment by using the ICV method (Enalou et al., 2016) which has been verified in (Enalou et al., 2017).

In the ICV method, the model includes component, Control Volume (CV), inertia and combustor modules. It is important to maintain mass/momentum/energy conservation through these modules. Within each component module, the inputs are inlet and back pressure, inlet temperature and shaft speed (shown in Figure 4). This data is then used to find the performance point of each respective component. Components including fan, compressors and turbines are represented by maps in which corrected mass flow and adiabatic efficiency are indexed by corrected shaft speed and pressure ratio. Outlet temperature and power can be obtained by having inlet mass flow and efficiency and implementing thermodynamic laws for open systems including conservation of mass and energy. Once mass flow and efficiency of every component has been interpolated using component maps, the outlet temperature is calculated.
CV modules consider the flow transient between each two consecutive components. The change in mass inside the CV is calculated using:

\[
\frac{dm_{CV}}{dt} = \dot{m}_{in} - \dot{m}_{out}
\]  

where; \( m_{CV} \) is the current mass of the CV. Pressure, Temperature and volume of the mass inside the CV are related by using the ideal gas law as below:

\[
pV = m_{CV}RT
\]

Pressures and temperatures are total amounts including the kinetic energy of the gas. Assuming no temperature gradient in the control volume (Rahman and Whidborne, 2009), by using (3) and (4), the outlet pressure can be determined as:

\[
\frac{dp}{dt} = \frac{\dot{m}_{in} - \dot{m}_{out}}{V/RT}
\]

The imbalanced torque by components on engine shafts leads to acceleration or deceleration which after integrating over time gives up the shaft speeds. The shaft inertia modules in Simulink, shown in Figure 5, use Newton’s second law, where; \( P_{GT} \) is power produced by the turbine and \( P_{Load} \) is power consumed by compressors and other loads on the shaft and \( J \) is the shaft inertia.

For the studied engine in this paper, VBVs and VSVs have been scheduled against HP speed as it is shown in Figure 6. The deviations of the VSVs from nominal schedule have a secondary relevance. The effect of closing the VSVs relative to the nominal schedule will shift the whole compressor map as shown in Figure 7. Corrected massflow, pressure ratio of the HPC map are modified in the model to make it match with the operation line of correlated test results on the HPC map. Efficiency values are also modified in order to make the simulation results match with the specific fuel consumption of the correlated test results.
MODEL VALIDATION

The engine model has already been validated for a multi-spool turbo-generator in (Enalou et al., 2017). This section presents the performance validation for the CFM56-3 engine for which generic component maps from (GASTURB), that are selected from similar turbomachines and with similar design, have been implemented for the Off-Design simulation. They are all from axial flow machines, therefore they are scaled in such a way that they fit to the cycle design point of the CFM56-3 engine. In order to validate the simulation results of the engine model, compressor operating lines are compared with the ones from the correlation test report data for the CFM56-3 presented in (Ridaura, 2014, Martins, 2015). Figure 8, 9, 10 and 11 show acceptable agreement between the simulation results with the test data for the fan, LPC and HPC operating lines for steady-state test at Sea-Level-Static (SIS) condition from idle to full throttle setting. However, part load SFC (shown in Figure 11) depends primarily on compressors’ efficiency for which, the operating points from the CFM56-3 correlation test report do not match with the model due to the use of generic component maps. In order to make the model match with test results slight modifications have been done on HPC’s efficiency map. Results for SFC are illustrated in Figure 11. The SFC starts decreases from 100 kN to 75kN due to the increase in HPC efficiency. While between 75kN to 65kN of thrust, the HPC operation point hits its maximum efficiency which is 87 % on the HPC map. Below 65kN of thrust, the VBVs and VSVs start to act which affect the SFC severely, decreasing the SFC for 65kN to 55kN of thrust and increasing it below 55kN of thrust.
In this section, performance improvements due to power transfer between shafts for a turbofan at taxiing and flight idle maneuver are presented. In order to investigate the idea of power exchange between shafts, considering losses in gearboxes, electrical machines and converters, overall efficiency of the Electric Power Transfer (EPT) is assumed to be 90%.

Results for ground and flight idle scenarios are presented for a CFM56-3 engine with 100 kN of thrust at SLS condition. The derived values of $P_{\text{fan}}$, $P_{\text{LPC}}$, $P_{\text{HPC}}$, $P_{\text{HPT}}$ and $P_{\text{LPT}}$ from the engine model are fed to the LP and HP shaft modules together with the amount of electric power transfer between them in accordance with the dynamics given in equations 1 to 2.

**Taxiing**

For taxi maneuver, a 10% of engine thrust is required based on ICAO values in (Chati and Balakrishnan, 2013). For the purpose of comparison a controller keeps the thrust at its minimum value as it is shown in Figure 12. Since the fan provides most of the thrust, by electric power transfer, LP speed remains unchanged, while HP speed increases. Plotted in Figure 13, the compressors’ SM also increases as expected by increase in HPC speed by 5% and 2.5% for the LPC and HPC respectively. Moreover, the fuel rate at taxi reduces by approximately 3%.

**Flight Idle**

During descent, flight idle mode is selected where the engine needs to operate at a high enough power to keep the bleeding pressure higher than a minimum for its application in the ECS. In order to keep the engine operation within its limits while allowing immediate recovery of thrust during power transfer, the controller must maintain HP speed at its default minimum idle setting which has
also been assumed to be 70% of its nominal value. $p_{30}$ limit controller protects against the supply pressure for ECS (Linke-Diesinger, 2010) which has been assumed to be 210kPa for this engine. Results for flight idle at 10kft and 30kft are presented in Figure 14 to 17.

At 10kft, up to 190kW power transfer, by keeping the HP speed at its minimum permissible value the fuel rate decreases by 26%, (shown in Figure 14 and 15). Since the power is extracted from the LP shaft its speed decreases by 25% which reduces the thrust more or less by the same value. The $p_{30}$ level is more than its minimum value at 10kft and the minimum controller switches from the HP shaft speed to the LP one at 190 kW. Indicated in Figure 15, SM for the LPC and HPC increase by 13% and 10% respectively.

At 30kft, $p_{30}$ limit controller is acting within 200kW of power transfer. Results over 200kW of electric power transfer is not valid since LPT cannot provide enough power for electric power transfer. The small deviation from 210kPa shown in Figure 16 is due to the transient of the p30 controller during increasing the amount of electric power transfer. By 200kW electric power transfer, LP speed drops by 30% while HP speed remains at its existing level to ensure the pressure of 210kPa at HPC exit. Shown in Figure 17, available SM for the LPC and HPC increases by 13% and 14% respectively, and the fuel rate decreases by almost 31%.

**Cruise condition**

In order to have a proper assessment of electric power transfer for cruise condition, a controller has been implemented to keep the thrust at its existing value without the electric power transfer system. Shown in Figure 18, the assumed value of thrust is 26kN for CFMS56-3 (Chati and Balakrishnan, 2013) which is aligned with propulsive efficiency for the aircraft at cruise condition.

The engine efficiency is at its maximum level with the existing configuration for cruise condition with 26kN of thrust. Therefore, electric power transfer is not expected to reduce the fuel rate, however, it can increase SM of compressors. Figure 19 highlights the fact that any power transfer increases the
fuel rate around the existing design point. For ±300kW electric power transfer, the amount of increase in fuel rate is around 4.5% and the amount of increase in SM for the LPC and HPC are approximately 5% and 8% respectively. Therefore, electric power transfer at cruise condition is not beneficial unless for increasing SM.

Figure 18. Thrust and shaft speeds (cruise)

Figure 19. Available SM and fuel rate (cruise)

CONCLUSIONS
This paper presented a model for the CFM56-3 engine with VBVs and VSVs involved. Validation with test results indicated acceptable level of accuracy for the engine model although with slightly modified generic engine maps from GASTURB. Furthermore, the paper provided preliminary results for the impact of electrical power transfer for the CFM56-3 engine. Power was proposed to be circulated between the electrical machines, connected to the engine shafts, through the single DC bus architecture with the assumed efficiency of 90%. Results showed that, power transfer from the LP to the HP shaft at low compressor speeds is highly desirable both in terms of available SM and efficiency. These are the outcomes of increased HPC speed operating at higher efficiency and away from surge line. For Taxi 3% and for flight idle more than 25% of fuel rate reductions are achieved by the electric power transfer system. However, electric power transfer at cruise condition increases the fuel rate which makes this idea futile for cruise unless for increasing SM by positive electric power transfer. The results in this paper motivate further analysis into the idea of electric power transfer for turbofans in future.

ACKNOWLEDGEMENTS
This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 807081.

REFERENCES


Kurzke J. 2008. The importance of component maps for gas turbine performance simulations. 12th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC-12), Honolulu, HI.


