Potential Improvements in Turbofan Idle Steady State and Transient Performance

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Abstract

Once the engine is designed, imbalanced air massflow between LP and HP compressors at low speed settings is inevitable which enforces implementing of bleeding. However, by emerging More Electric Aircraft (MEA) with electrical machines on both HP and LP shafts and the advancements in power electronics, it is possible to transfer power electrically from one spool to another. This will result in enabling the engine core components to operate closer to their optimum design point and balancing the air massflow between compressors. At lower power setting of the engine, HPC speed can be increased by taking power from LP shaft and feeding it to HP shaft which can lead to removal of bleeding system which in turn reduces weight and fuel consumption and help overcoming engine stability issues. Fuel consumption can be decreased by decreasing inconsistent thrust with the aircraft mission for flight and ground idle settings. This paper investigates the novel idea of power circulation between shafts using turbofan model developed by ICV method. Results show considerable improvement in efficiency while transient response for severe transient maneuvers is also improved considerably with the new configuration.

Introduction

Efficiency improvement, lower emissions, reduced maintenance and possibly lower costs are possible outcomes of the more electric aircraft (MEA) [1] which has resulted in an increase in power demand of the aircraft through advancements of on-board electrification. The propulsion thrust for A330/B777 size engines are approximately 40MW and the non-thrust power is almost 1.7MW where only 200kW of this power used to be produced by electrical generator on HP shaft for existing electrical loads [2]. By the concept of more electric aircraft the amount of electrical system power has boosted (up to 1MW for Boeing 787 Dreamliner [3].

Electrical generators have been normally mounted on high pressure (HP) engine spool due to its high and relatively constant operating speed, compared to that of the low-pressure (LP) engine spool [4]. However, at low speed settings of the engine compressors are more susceptible to surge which put a limit for the amount of power offtake from HP spool.

For instance, during descent due to increased electrical load at low engine power setting the engine may need to be operated at a higher power level to maintain in a stable, causing inconsistent thrust with the aircraft mission which decreases the efficiency. In addition to this, if engine power is maintained higher than normal to prevent the engine instability, the aircraft would not descend quickly enough, lengthening the descent phase (which is a fuel inefficient operational combination) or result in a significantly higher than normal airspeed during descent (steeper pitch angle) [5].

Thus, the high spool is typically limited to supplying low power, steady state loads. In this case in order to power larger loads from engine, a generator is provided on LP spool. LP Generator can be physically attached to the low spool in locations such as fan drive nosecone or LPT tail cone [6].

In literature, so far a lot of researches have been done on machines and control architecture for the concept of LP spool generator for more electric aircraft [7-10]. Engine performance has also been investigated for power offtake from different shafts for a three spool engine in [11]. Shown in [12], it is always favorable to extract more power from LP shaft than HP shaft at engine low speed settings both in terms of fuel efficiency and surge.

On the other side, [13] has considered power exchange with LP shaft through an auxiliary generator/motor to maintain a high peak temperature to optimize engine efficiency at part-load condition in a multi spool turbo-generator. This fact triggers the novel idea of electric power transfer from LP shaft to HP shaft through bidirectional converters within the single DC bus architecture. Advancements in power electronics have made it possible to transfer power electrically from one spool to another while providing the ability to have flexible speed ratios at various engine speed settings. This novel configuration is expected to:

- provide optimized operation depending on engine operation mode (EOM)
- make the engine provide compatible thrust with flight mission
- increase the stability margin of the engine, Overall efficiency, reliability, availability and maintainability
- reduce the effects of large load transients
- augment the available power from the engine
- help immediate recovery of thrust at extreme transient conditions such as go around

In order to study this idea a modulated multi-spool turbofan model has been developed in [14] and verified in [15]. This paper will investigate the implication of this idea on engine performance at different low speed settings. The authors of this paper have already shown the benefits of power circulation between shafts at cruise, flight and ground idle modes in [16].

In this paper a brief introduction is given into the multi-spool engine performance, followed by description of the idea of electrical power transfer. Then, the engine model and its interaction with single dc bus architecture and simulation results at different flight scenarios are presented, to confirm the implications of the idea.

Multi-Spool Engine Performance

For multi-spool engine, LP and HP spools are not connected mechanically, while engine components including LPC, HPC, combustion chamber (CC), HP turbine (HPT) and LP turbine (LPT) are coupled aero-thermodynamically within the engine. As a result any change in speed of LP or HP spool will affect the whole engine performance which is the case during power exchange between shafts. This fact suggests studying engine components matching to investigate the impact of power exchange between shafts on engine performance.

Figure 1 shows a two-spool unmixed flow turbofan for which LPT drives fan and LPC and HPT drives HPC. LP and HP shaft speeds are thermodynamically coupled throughout range of operation from low to high shaft speeds.

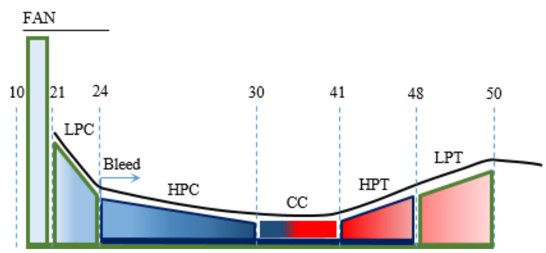

Figure 1. Illustration of turbofan components with denoted their engine positions from 10 to 50

The engine configuration is optimized for cruise, but during other flight phases, such as flight and ground idle modes, it operates in a sub-optimal condition, thereby increasing fuel burn. This happens mainly due to unmatched speed between LP and HP shafts at low speed settings which is inevitable because of thermodynamic coupling of shaft speeds. The main consequence of unmatched shafts speeds is LPC surge which is lifted by implementing bleeding between LPC and HPC.

Since HPC receives the airflow from LPC, it is always favourable if HPC operates at higher speeds. At idle setting, HPC speed can be increased by taking power from LP shaft and feeding it to HP shaft. If the speed of HPC is properly matched with LPC value at low speed settings, HPC can swallow more massflow, thus, there will be no need for air bleeding. Therefore, VBVs can be removed without any concern regarding airflow limits. Besides, normally, core pressure ratio is mainly produced by HPC where power of HPC is more than two times of LPC power, so keeping HPC operation point close to its design point increases the engine efficiency. Removing bleeding will also increase the core massflow therefore enabling HPC, CC, HPT and LPT to operate closer to their optimum design point. Higher core massflow can also help for faster recovery of thrust during severe flight scenarios such as go around.

Unmatched shaft speeds could have been solved by decoupling shaft speeds by using a gearbox between LP and HP shafts to transfer power. However, this idea have been disregarded due to its imposed constraints such as complexity for variable speed ratio while more importantly incapable of transferring controlled amount of power in the favorable direction. This means once the gearbox between shafts is used LP and HP shafts will act as a single shaft train which brings up a lot of complexity and unwanted engine performance issues.

Electric Power Transfer

As discussed in previous section, there will be a great interest in controllable power transfer between shafts specifically at low speed. On the other hand, in MEA electrical machines are connected to both LP and HP shafts through fixed speed ratio gearboxes. Single dc bus architecture is widely elaborated in the literature [17-19]. For this configuration within which the machine outputs are connected to the dc bus through bidirectional convertors. This provides the opportunity to circulate dynamically controllable power between shafts through electrical machines by power electronics privilege. Figure 1 shows a single dc bus with two electrical machines connected to it through bidirectional converters.

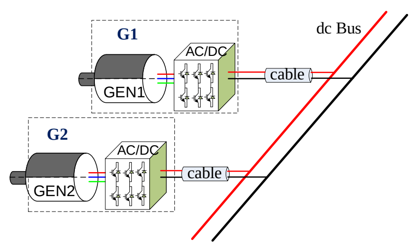

Figure 1 Configuration of single dc bus multi-source EPS

This configuration accommodates an engine with flexible power split ratios at different operational speeds depending on the amount of power transfer as described:

$$P_{HPT} + P_{EHP} = J_{HP}\omega_{HP}\dot{\omega}_{HP} + P_{HPC} \quad (5)$$

$$P_{LPT} + P_{ELP} = J_{LP}\omega_{LP}\dot{\omega}_{LP} + P_{FAN} + P_{LPC} \quad (6)$$

$$P_{ELP} + P_{EHP} + P_{EPS} = 0 \quad (7)$$

where; P_{ELP} and P_{EHP} are electrical power transfer for LP and HP shafts respectively.

It should be noted that with increasing power demand for more MEA, the impact of P_{EPS} will be as important as P_{EHP} and P_{ELP} on the engine performance. Minimizing losses in gearboxes, electrical machines, convertors, etc. is also quite significant for this configuration.

Modeling

Intermediate Control Volume (ICV) method has been implemented in MATLAB/SIMULINK environment to model a zero-dimensional (0-D) model of multi-spool engine. Thermodynamic rules together with compressor and turbine maps from GASTURB has been employed to drive P_{FAN}, P_{LPC}, P_{HPC}, P_{HPT} and P_{LPT} for LP and HP shaft dynamics given in equations 5 to 7. Figure 2 shows the interaction between the engine model and single dc bus model. For electrical machines and converters, dq frame and functional models have been implemented respectively.

However, the main focus in this study is on the impact of electric power transfer on engine performance so EPS dynamics has been ignored. This is acceptable due to EPS much faster dynamic compared to engine dynamics at transient modes.

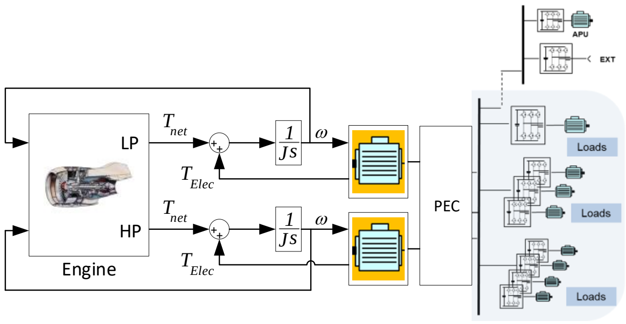

Figure 2 Schematic diagram of engine-electrical system interaction

A bump-less override control structure has been implemented for the turbofan with limit controllers for over-temperature, surge and bleeding pressure for Environmental Control System (ECS).

Idle setting's control system

The engine control idling system is designed to produce three levels of variable idling speeds identified as:

- minimum idle (during taxing and most of descent phase)
- ps30 idle range (during initial phase of descent)
- approach idle (during approach phase)

Minimum idle, having rating HP shaft speed at its lowest possible to minimize the generated thrust, is employed unless the supply pressure for the aircraft pneumatic system and environmental control system is too low.

In this case the idle setting switches to ps30 idle range to meet the required pressure calculated by Electronic Engine Control (EEC) where HP shaft speeds are between minimum idle and approach idle. "Approach Idle" is applied only when "Anti-Icing" is selected or the aircraft has flaps configured for an imminent landing. The reason for higher HP shaft speed is immediate availability of engine high power setting for anti-icing system or thrust demand [20].

Regarding variable idle speeds in engine control system the criteria to determine them can be:

- rapid recovery of thrust during a balked landing manuevour (approach idle)
- Ps30 level to supply pressure for environmental control system
- core massflow should be maintained higher than a minimum level for sustainability of the engine
- enough surge margin for compressors

Results

In this section, performance results with power transfer for ground idle, flight idle and go-around maneuver is provided for the engine with the bleeding system still in use with the existing scheduled values against HP speed.

Results for removal of bleeding system is also presented to asses the amount of power transfer required and also its impact on the engine performance.

Ground idle

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. Consequently, by transferring power from LP to HP shaft, LP speed drops up to a minimum permissible speed where the LP speed controller overrides HP speed controller.

With higher HP speeds HPC can afford more massflow which is accordingly provided by scheduled VBVs. Figure 3 shows transferring power from LP to HP shaft, while maintaining minimum HP speed at idle ground, decreases fuel consumption up to 33% at 350 kW power transfer. For this configuration a minimum LP speed controller at idle should also be implemented since LP speed drops when LPT cannot provide enough power at lower speeds.

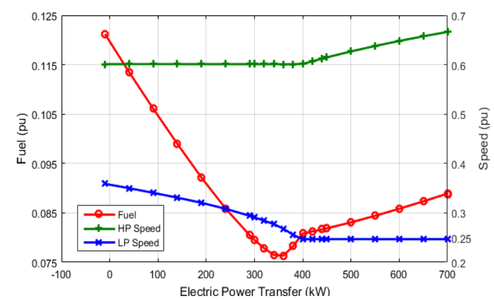

Figure 3. Fuel consumption and LP-HP speeds (ground idle)

Illustrated in Figure 4, the calculated thrust also decreases up to 85%, which is favorable for ground idle to have less braking effort, noise and fuel consumption.

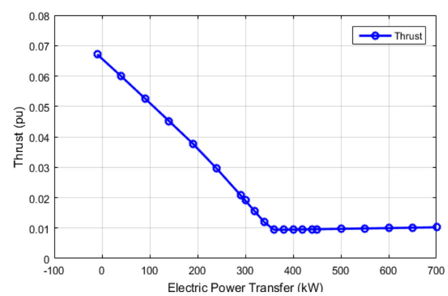

Figure 4. Calculated thrust (ground idle)

Increased surge margin, as expected due to higher HPC corrected speed, is another achievement which is shown in Figure 5. However slipping back beyond 350 kW up to 400 kW. This is mainly due to HPC upstream pressure increase due to increase T41 at constant massflow while beyond 400 kW, massflow starts to increase consistently with pressure ratio.

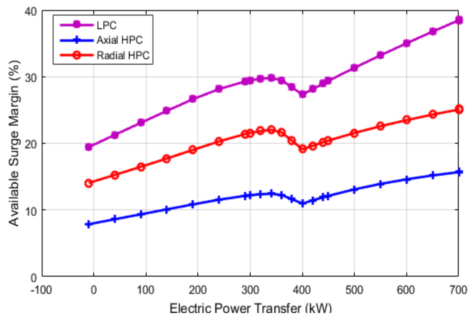

Figure 5. Available surge margin (ground idle)

Flight Idle

During descent, flight idle mode is selected where bleeding pressure should not be lower than a minimum for its application in ECS. Results for flight idle at 20000ft, presented in Figure 6 and Figure 7, show the fact that up to 150kW power transfer, the LP fuel injection can decrease while keeping the HP speed at its minimum permissible value. Since the power is extracted from LP shaft its speed decreases by 2%. Between 150 kW and 410 kW, p30 limit controller protects against the supply pressure for ECS [20] which has been assumed to be 210kPa for this engine. Within this range the LP speed considerably decreases (by 25. Beyond 400kW of power transfer the control system keeps the LP shaft minimum permissible speed which causes the fuel to increase again. The amount of fuel burn reduction during descent is up to 43% at 400 kW (Figure 6).

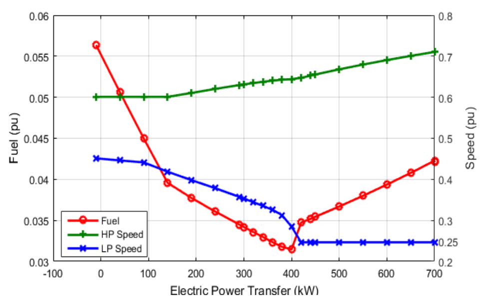

Figure 6. Fuel consumption and shaft speeds (flight idle-20000ft)

Shown in Figure 7, the available surge margin for the LPC, axial HPC (AHPC) and radial HPC (RHPC) also increases, where the LPC gains almost 40 %, with power transfer from the LP to HP shaft which is encouraging to implement this idea.

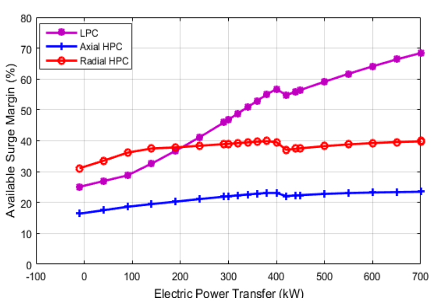

Figure 7. Available surge margin (flight idle-20000ft)

Touch and go

For go-around and Touch-and-Go Landing (TGL) maneuvers, the acceleration time of the engine comes to play an important role, since faster acceleration means shorter required runway.

However, the limits of the engine such as surge/stall, over-temperature, over-speed and over-pressure define acceleration rate of the engine. Figure 8 to 13 show engine performance during acceleration from idle to full throttle setting. In Figure 8 Turbine Inlet Temperature (TIT) is lower at idle setting due to lower idle speed, while following the same trend during acceleration. Once TIT hits its limit fuel control system switches to TIT limit controller and the acceleration rate decreases.

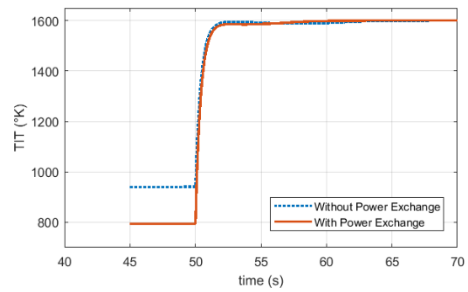

Figure 8. TIT during acceleration from idle to full throttle setting

However, shown in Figure 9, the fan speed, as an indicator of thrust for high bypass ratio engines, is retrieved quite fast from its lower value at idle setting. With power exchange, HP speed is higher which means it is closer to its full throttle value. This helps the core airflow to be higher, thus increasing fuel flow during acceleration for the same temperature limit. As a result, fan speed reaches its full throttle value 3-4 seconds faster than existing configuration.

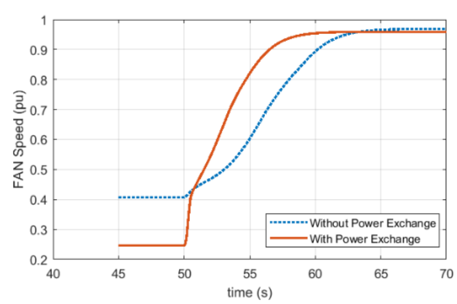

Figure 9. Fan speed during acceleration from idle to full throttle setting

Due to the initial shift in surge margin before acceleration, transient surge margin is also larger than existing ones illustrated in Figure 11 to 13. Different fluctuation patterns during acceleration in surge margin for radial and axial HPC and LPC is due to different speed matching between LP and HP shaft with power exchange compared to current configuration without power exchange. In general, higher surge margin highlights the fact that the idea of power exchange provides the ability to accelerate the engine faster while keeping the engine as safe as before.

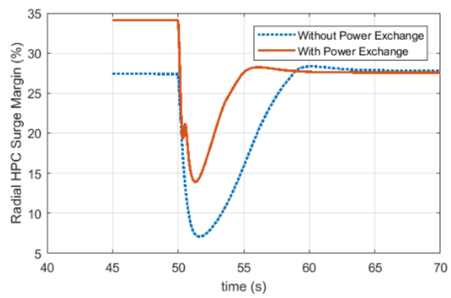

Figure 10. Radial HPC surge margin during acceleration from idle to full throttle setting

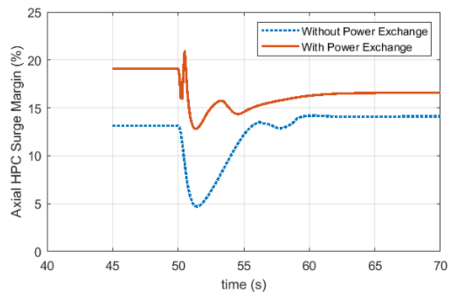

Figure 11. Axial HPC surge margin during acceleration from idle to full throttle setting

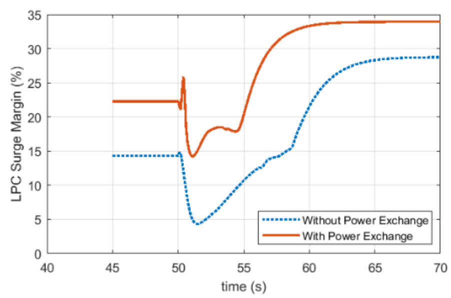

Figure %. LPC surge margin during acceleration from idle to full throttle setting

Bleeding Removal

The results provided in previous section are in the presence of the existing bleeding schedule between the LPC and the HPC. While higher speed of the HPC can result in higher amount of massflow which suggests the possibility of removal of bleeding system. Table 1 and 2 show the engine performance at ground and flight idle for the engine with bleeding system and the engine with power transfer system, replacing the bleeding system.

For ground and flight idle the amount of power transfer is 765kW and 717kW respectively. However results are not of high accuracy at low speeds of the map and due to the use of the same map for both cases, with and without bleeding system.

Table 1. Bleedless engine performance at ground idle

	Bleeding system No power Transfer	Power Exchange No bleeding
SR_{LPC}	14%	7%
SR_{AHPC}	7%	18%
SR_{RHPC}	14%	32%
LP speed	35%	34%
HP Speed	60%	73%
Fuel (pu)	0.127	0.117

Table 2. Bleedless engine performance at flight idle (20000ft)

	Bleeding system No power transfer	Power Exchange No bleeding
SR_{LPC}	19%	19%
SR_{AHPC}	16%	25%
SR_{RHPC}	33%	47%
LP speed	35%	34%
HP Speed	60%	73%
Fuel (pu)	0.056	0.043

Conclusion

In this paper the conceptual study of transferring power from LP shaft to HP shaft within MEA has been done. The results show that depending on the amount of power exchange there will be significant amount of fuel saving. In this study transferring 5% of HP nominal power will decrease the amount of fuel consumption by 40% at idle setting of the engine. It also increases compressor surge margins which enables lower idle speed setting for the engine. During acceleration due to higher available surge margins, the risk of compressor surge is significantly less than before, therefore it is possible to inject more fuel while keeping TIT limit. Results show 3-4 seconds faster acceleration with power exchange from LP to HP shaft. In addition a brief study shows that the bleeding system can be replaced by power transfer system, keeping the engine stability margins as before while achieving some benefits on fuel consumption.

Nomenclature

W	massflow
p	pressure
P	power
T	temperature
f	fuel to air ratio
LHV	fuel low heat value
$\bar{c}_p$	specific heat capacity at constant pressure
A	area
T	Torque
ω	Speed

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Acknowledgments

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.

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