Considering Turbofan Operability in Hybrid Electric Aircraft Propulsion System Design

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This paper explores the design of a hybrid electric aircraft propulsion system that uses a turbofan to power an electric system. In such a system, the gas turbine will experience a loss of power generation as altitude increases, however the electric system will not. This difference results in designs that may over size the electric system at high altitude or under size at low altitude. Two studies are performed within this paper. The first looks at extracting power from the engine for use with electric aircraft propulsion at cruise and the second reviews a design of an engine that uses thrust assist for takeoff. Both studies look at the effects of changing altitude on the amount of power extraction or insertion that can be taken from the turbofan as dictated by operability limits. Results of the paper show that low-pressure compressor surge margin and high-pressure compressor speed can be pushed to unaccepted limits with large scale power extraction or insertion, however these issues can be mitigated by adding power extraction or insertion at off-design operating points to compensate. Additionally, the benefits of thrust assist are quantified for this configuration demonstrating a reduction in thrust specific fuel consumption at cruise of over 5%.

Nomenclature

BPR	Bypass ratio
CRZ	Cruise
EAP	Electrified aircraft propulsion
F_n	Net thrust
HPC	High pressure compressor
HPS	High pressure shaft
LPC	Low pressure compressor
LPS	Low pressure shaft
MDP	Multi-design point
NPSS	Numerical propulsion system simulation
OPR	Overall pressure ratio
P	Pressure
PEX	Power extraction
PIN	Power insertion
PR	Pressure ratio
RTO	Rolling takeoff
T	Temperature
TIT	Turbine inlet temperature
TOC	Top of climb
SLS	Sea level static
V	Velocity
W_0	Mass flow entering engine
W_f	Fuel flow

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I. Introduction

In some designs of hybrid electric aircraft propulsion (EAP) systems a turbofan engine is paired with an electrical system to augment the thrust of the aircraft. This can be done by driving additional electrically driven propulsors or by electrically assisting the turbofan engine. Benefits of these types of configurations have been studied and show to increase system efficiency, decrease weight, and reduce maintenance costs. In NASA's single-aisle turboelectric aircraft (STARC-ABL), two turbofan engines are used to drive a boundary layer ingesting tail-cone propulsor. [1, 2] The subsonic single aft engine (SUSAN) transport aircraft concept (also by NASA) makes use of a single aft mounted turbofan driving arrays of wing mounted propulsors. [3] United Technologies Research Center developed a parallel hybrid turbofan design that uses battery enabled thrust assist at take-off to decrease mission fuel burn. [4] A mild hybrid study was also performed by NASA to look at the thrust assist scenario and found efficiency benefit. Each of these concepts include turbofans with requirements of a significant amount of power being added to or removed from the engine spools. These requirements fall into two categories, power added to the engine to reduce engine load at take-off and power removed from the engine at cruise to drive EAP. In both cases, using power outside the defined mission requirement is not desirable. For instance, using electric power during cruise when performing thrust assist will increase power usage dramatically or running the EAP to higher power levels during take-off when the system design only requires it to run at cruise will increase electric system weight needlessly. This paper details how an engine may be designed to take these different operating criteria into consideration and shows how the engine may be optimized to lower electrical system weight while maximizing system efficiency.

In previous work it has been shown that off-nominal power extraction (PEX) and insertion (PIN) on the high- or low-pressure spool of a dual spool turbofan engine will change the operating point of the engine potentially causing issues such as shaft over-speed, shaft under-speed, compressor stall, or low compressor efficiency. [5] These effects are a function of design power augmentation, spool choice, engine operating point, and engine power output. Design power augmentation will set the baseline for the vehicle and will define how much power augmentation the engine "expects". Changing power augmentation adjusts the engine operating point away from the design point. Spool choice defines the overall effect of the power augmentation, with high-pressure spool (HPS) PIN causing the spool to speed up and low-pressure spool (LPS) insertion causing the LPS to speed up. The engine operating point considers engine performance parameters of current operation (flow, pressure, temperature), and can be defined on the compressor performance maps. Engine power output is the gross power the turbines are producing. This power level will reduce with altitude and governs the maximum power augmentation levels therefore, engine lapse rate must be considered when designing the hybrid EAP system. Lapse rate refers to the rate that engine thrust drops off with increasing altitude, but for this paper it will also refer to the overall decrease in engine power as well. For each study a baseline engine with no power augmentation is used for reference.

The thrust assist at cruise configuration uses EAP components to compliment the thrust of the gas turbine engine at cruise. The study does not assume a specific vehicle configuration but incrementally increases PEX from the system with the assumption that this additional power is used for electrically power thrust. Engine design considers the PEX requirement at the cruise condition only. The PEX at other operating points, such as take-off, is determined based on engine capability, though increasing the PEX beyond the cruise level leads to oversizing the EAP and decreasing PEX results in electrical system underutilization.

For the thrust assist at take-off configuration, PIN is applied during the sizing process to reduce the size of the engine. To achieve this, PIN is applied at take-off to boost take-off thrust, and no PIN is applied at cruise. This technique sizes the engine for cruise and relies on an external power source when additional power is required. This creates a mismatch in sizing because the fan is designed for take-off thrust, while the remainder of the engine is designed to provide a fraction of the power needed to run the fan. Once that power is removed the fan will appear oversized and the low-pressure compressor (LPC) will be run at a reduced mass flow leading to potential engine operability problems.

Subsequent sections of this paper detail the engine model, each study, and offer the results. Specifically, a review of the engine model is shown in Section II. Details of the cruise thrust assist study is found in Section III. Followed by the take-off thrust assist study in Section IV. Finally, summary and conclusions are given in Section V.

II. NPSS Engine Model

Each study within this paper uses the gFan+ advanced concept engine built within the Numerical Propulsion System Simulation (NPSS). [6] The gFan+ was developed for phase IV of the subsonic ultra-green aircraft research (SUGAR) study conducted by Boeing in 2017. [7] The architecture of the gFan+ is a dual spool turbofan designed to provide 22,000 lbf of thrust at sea level static (SLS) conditions. A diagram of the engine with key features is shown in Figure 1. Engine design pressure ratios (PR) include fan PR of 1.46, LPC PR of 1.45, and high-pressure compressor (HPC) PR of 28, which results in an overall pressure ratio (OPR) of about 60. The engine is high bypass with a bypass ratio (BPR) of 12.

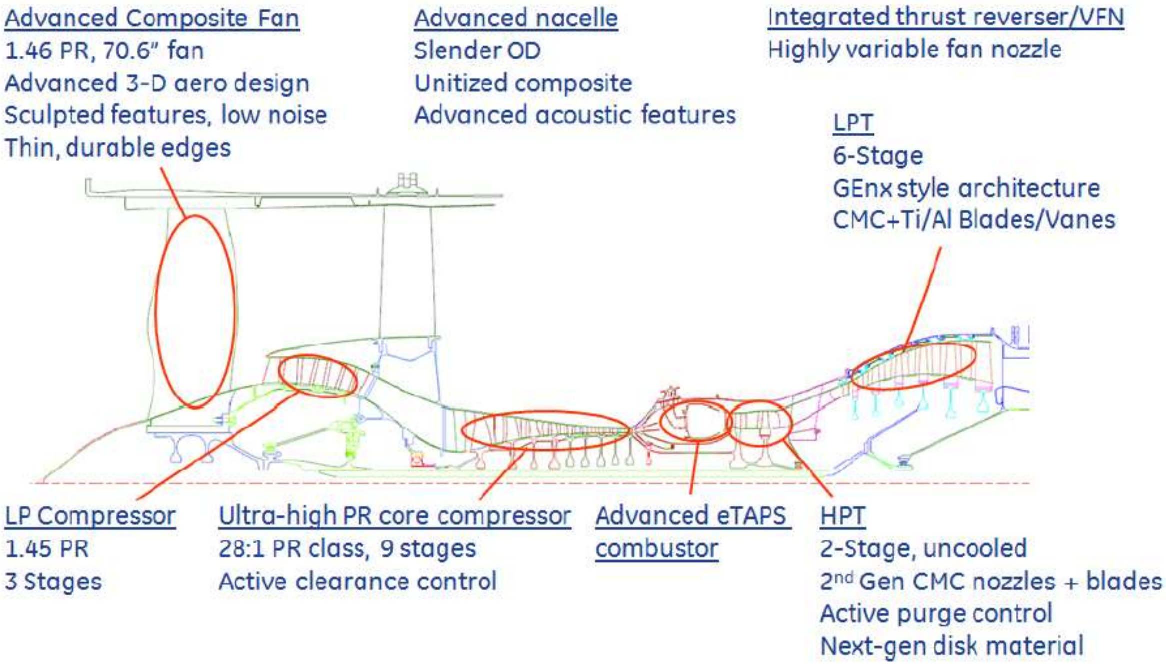

Figure 1. gFan+ layout.

For each of the studies, the gFan+ is redesigned using a multi-design point (MDP) method that makes use of 4 points, top of climb (TOC), cruise (CRZ), rolling take off (RTO), and SLS. These points are run in series within NPSS and the MDP is managed with OpenMDAO. [8] Inputs and outputs of the engine system are transferred using external files. For this model, the TOC operating point is selected as the design point where initial map placement is completed. The design point uses total airflow (W_0), fuel flow (W_f), BPR, and cooling flows (W_{cool}) to meet target net thrust, turbine inlet temperature (TIT), velocity jet (V_{jet}) ratio (bypass nozzle exit airflow velocity / core nozzle exit airflow velocity), and estimated metal temperatures at the MDP points RTO, RTO, RTO, and CRZ respectively. Net thrust, TIT, and cooling flow are determined at RTO because it is the point within the mission where the engine is run the highest power point. Velocity jet ratio is selected at CRZ for optimal thrust specific fuel consumption (TSFC). The SLS operating point is run for comparison purposes. A diagram of the above simulation architecture is show in Figure 2.

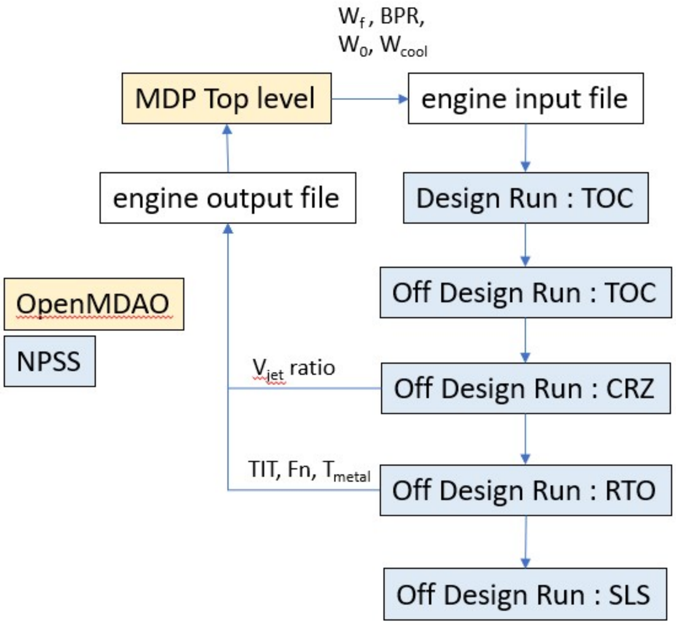

Figure 2. gFan+ simulation architecture.

Baseline engine design was performed on the engine without power augmentation, with critical engine design parameters shown in Table 1. Pressure ratios and air mass flows at the four MDP points are shown along with the compressor maps for the fan, LPC, and HPC in Figure 3. For each of the components the TOC point is located on the 100% speed line. For the fan it can be observed that the SLS and RTO point have less surge margin than TOC or CRZ. For the LPC this is the opposite as the RTO and SLS points are lower on the map. For the HPC, the TOC, RTO, and SLS points all reside in roughly the same spot on the map. The CRZ point on the HPC is lower in both PR and mass flow than TOC because it is operating at a lower power level. The TIT temperature difference between RTO and TOC shows the temperature margin for TOC. For the take-off assist study, CRZ TSFC is used as the engine's measure of efficient propulsion because most of the vehicle mission will be completed at this operating point. Baseline CRZ TSFC from this design is 0.486 lbm/hr/lbf.

Table 1 : System parameters for considered operating points.

	TOC	**CRZ**	**RTO**	**SLS**
Altitude, ft	35000	35000	0	0
Mach number	0.8	0.8	0.25	0
Thrust, lbf	3931	3145	16600	22000
TIT, degR	2900	2714	3440	3400

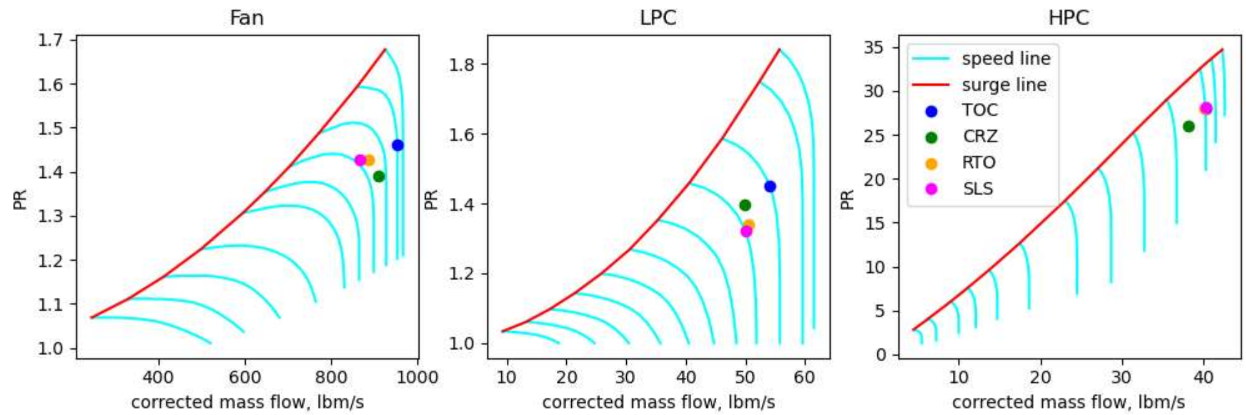

Figure 3. gFan+ simulation architecture.

III. Cruise thrust assist

In NASA's SUSAN and STARC-ABL vehicle configurations EAP is used to distribute propulsion and create high efficiency thrust. Most of the benefit of this thrust is provided at cruise and EAP operating conditions at other points are not requirements. This study will look at applying PEX to all design points and determining now this affects engine operability. It is assumed that this PEX is used for EAP purposes, however for this study total distributed thrust is not estimated and PEX is presented as a horsepower or as a percentage relative to the low-pressure turbine power (or % PEX). For each design the thrust coming from the engine (which is calculated) remains constant as PEX is added. This leads to an increase in core flow and a decrease in engine bypass ratio as the engine size increases to accommodate the PEX without generating additional engine thrust.

In the first test, PEX is placed on the LPS for all design points in a range from 0 to 4000 hp or 40% PEX, as shown in Figure 4. Here it can be seen that LPC surge margin decreases at RTO and SLS and increases at CRZ with the LPS PEX. This reduction in surge margin shows an imbalance in operation caused by keeping PEX steady as engine operating power is changed. If an engine is designed for PEX the engine will expect that power in-line with the changes in engine power production that come with different operating conditions such as changes in throttle, altitude, and/or Mach number. This means that if the engine moves higher in power/thrust PEX must also increase if the operational point is to remain the same. The HPC map movements show a trend where the speed and PR decrease at the SLS and RTO. At CRZ the PR and speed increase. This occurs because the engine is being sized with a large amount of PEX at TOC. As the engine moves lower in altitude and MN engine total power increases however the PEX remains the same resulting in the core operating at a lower power level and speed. At cruise this is the opposite as the engine is reduced in thrust PEX must remain constant and the engine core must increase power and speed to compensate. Applying PEX to the HPS causes the trends in Figure 4 to behave exactly opposite those with LPS PEX, with the exception that only 500 hp may be removed before the engine hits HPC speed limits at the RTO and SLS operating points. Because of this, only small amounts of PEX may be taken from the HPS. If more is required, it must come from the LPS.

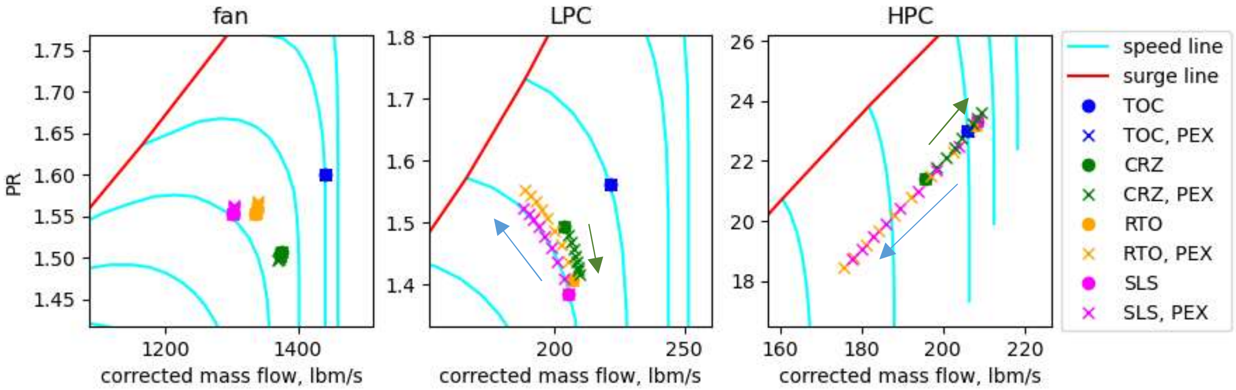

Figure 4. Compressor Map movements for engine designs with increasing LPS PEX across all points.

An option to mitigate the low surge margins observed with high LPS PEX is by increasing the PEX at TOC, RTO, and SLS relative to the CRZ point. Keeping CRZ PEX constant at 4000hp then doubling the size of the electric machines and taking 0 to 4000 additional hp from the LP at RTO and SLS (total of 8000 hp), and 0 to 400 hp at TOC (total of 4400 hp) the trends reverse as shown in Figure 5. This response is expected because the engine power imbalances are being reduced by increasing PEX when the engine naturally produces more power. When EAP is being used, this additional power could be used to provide additional thrust to either supplement required thrust at those points or by reducing engine system requirements on thrust.

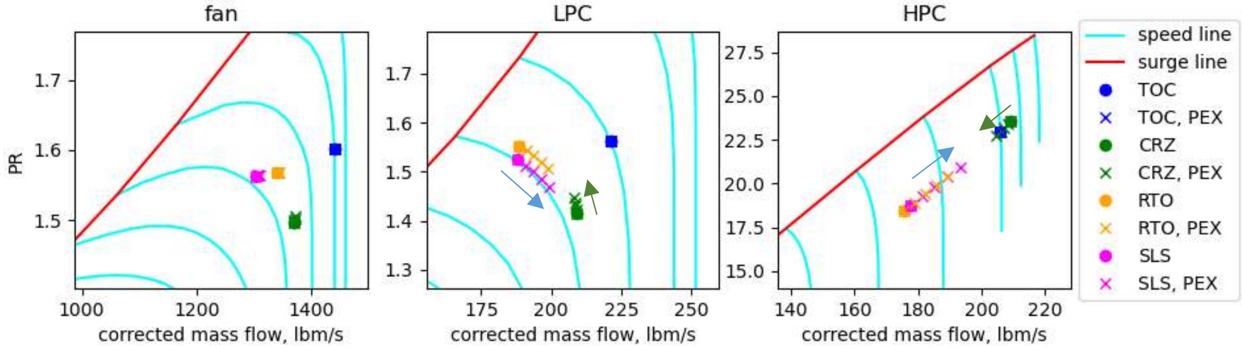

Figure 5. Compressor Map movements for engine designs with increasing LPS PEX at SLS, RTO, and TOC with CRZ PEX held constant at 4000 hp.

Another option to increase LPC surge margin with high levels of PEX is to introduce a PEX power split, HPS PEX/(HPS PEX + LPS PEX), that moves some of the total PEX from the LPS to the HPS. In this scenario, the HPS is loaded (increase power split) for the design at TOC and CRZ, then it is unloaded when LPC surge margin is low allowing the HPC to speed up and pull air from the back of the LPC. The HPS can also be loaded during CRZ to decrease HPC speed. Figure 6 shows the map movements with total PEX equal to 4000 hp, and power split is ramped from 0 to 10% at CRZ and 0 to 8% at TOC. Looking at the figure it can be observed that the LPC surge margin at SLS and RTO increases, LPC PR at CRZ increases, HPC speed at SLS and RTO increases, and HPC speed at CRZ decreases. Electric machines on the LPS would remain the same size, but additional electric machines would need to be added to the HPS to allow this method to be used.

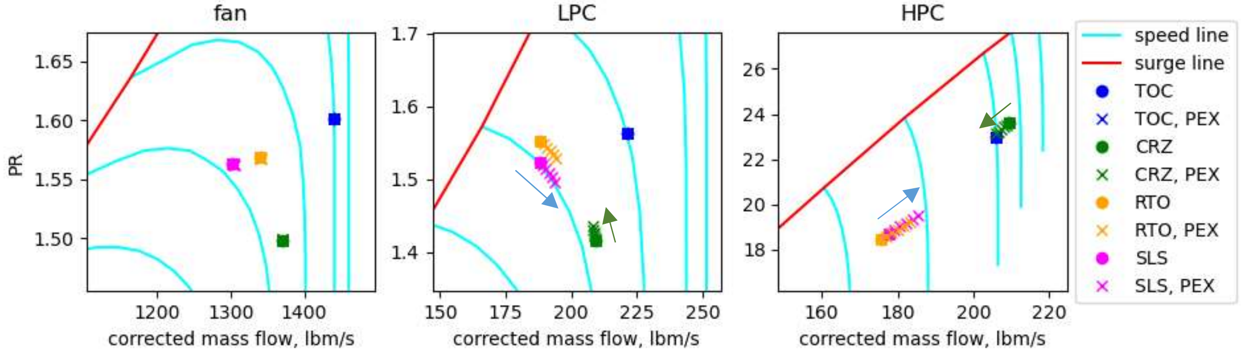

Figure 6. Compressor Map movements for engine designs with increasing PEX power split at TOC and CRZ, and with PEX held constant at 4000 hp.

This section reviews the limits of designing engines to accommodate large scale PEX and two methods of mitigating the effects. Both methods discussed require adding additional electric machines to the engine beyond the required CRZ PEX. When increasing the LPS PEX the electric machines on the LPS would need to increase in size and the additional power taken from the engine would need to be used at the off-CRZ points. This would most likely include oversizing the load motors and EAP propulsion system to use the additional power. Using power split the total power shifts from the LPS to the HPS, but the total power is not increased. This means an additional generator must be added, however downstream load motor and EAP propulsion system component sizes are not increased. This constant total power may not be ideal for certain EAP systems, for example a ducted fan design may operate well at 35,000 feet at a low power level but may surge at that same power level at SLS. Choosing which method to use requires a full system analysis that includes weight, engine thrust capability as well as a full EAP propulsion system simulation. In propulsion system designs where very large PEX is expected utilizing both methods may be the most advantageous.

IV. Take-off thrust assist

In turbofan engine design the most critical thrust requirement is the maximum thrust operating point that considers engine lapse rate. This maximum thrust point could be one of several points but is usually set by a single engine out scenario at RTO (defined here as 0.25 MN and 0 ft altitude) or TOC (defined for this study as 0.8 MN and 35,000 ft altitude). For the gFan+ the maximum thrust point is RTO, and the engine is sized according to this point. This results in the engine being oversized for TOC and CRZ. Thrust assist is meant to address this. By supplying an external power source to the engine at RTO and then removing as allowable on the way to CRZ the size of the engine can be reduced, and the engine can be operated at a higher power level that is more efficient at CRZ. In each of these scenarios any PIN applied at RTO is also applied at SLS. To study the effects of take-off assist, the engine was designed with increasing levels of PIN on the HPS and LPS at RTO.

Map movements for the LPS PIN runs are shown in Figure 7, where LPS PIN at RTO and SLS is increased from 0 to 3000 hp (PIN at CRZ and TOC remains zero). Here it shows that RTO PIN reduces the speed of the HPC, pushes the LPC toward stall, and shifts the fan operating point slightly higher. Each of these affects mainly the RTO and SLS operating point and illustrate that LPC surge margin is the main limiting factor to the LPS PIN.

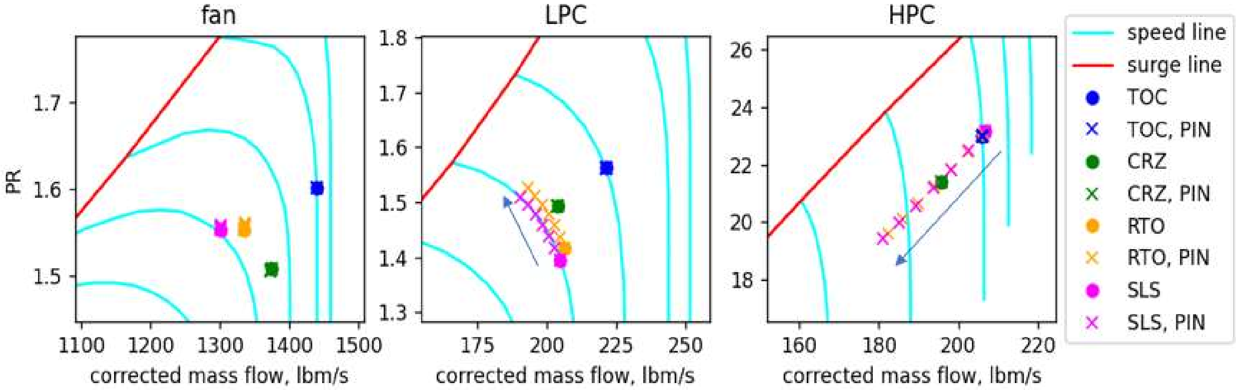

Figure 7. Compressor Map movements for engine designs with increasing LPS PIN at RTO.

Performance of the LPS PIN is shown in Figure 8. Here it can be seen that CRZ TSFC decrease by 0.01 or about 2%. This is caused by the increase in BPR and shrinking of the core, illustrated by the increase in TOC TIT. Total flow at RTO also rises as BPR increases, resulting in a larger fan as the core is smaller with the thrust requirement being fulfilled by more low velocity fan air.

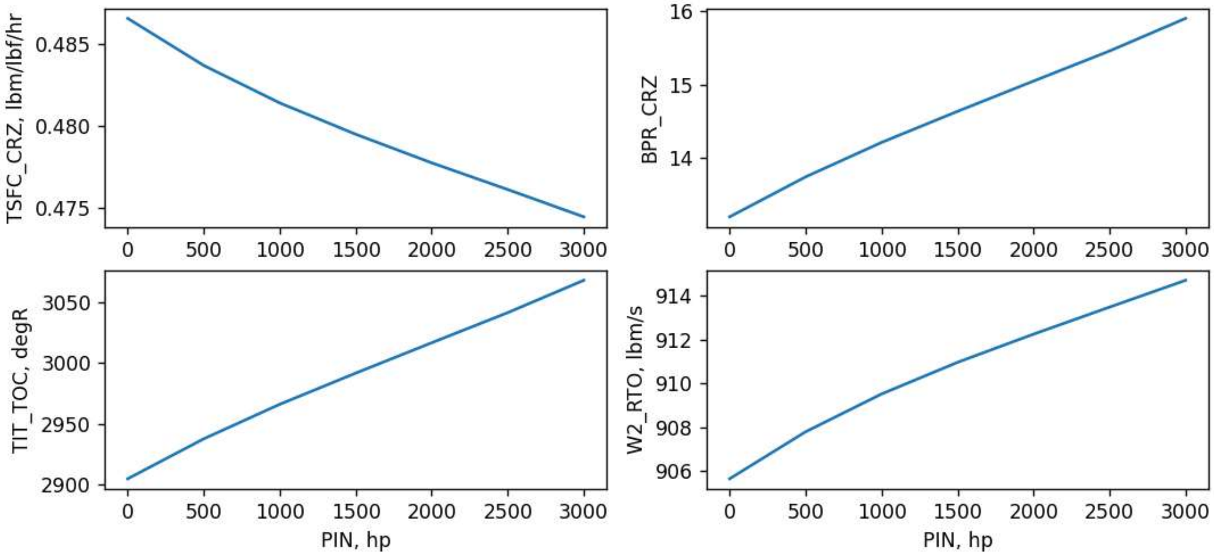

Figure 8. Performance for engine designs with increasing LPS PIN at RTO.

Map movements for HPS PIN runs are shown in Figure 9, where HPS PIN at RTO is increased from 0 to 2000 hp. Here it shows that RTO PIN increases the speed of the HPC, pushes the LPC away from stall. Each of these affects mainly the RTO and SLS operating point and illustrate that HPC speed is the main limiting factor to the HPS PIN. It can also be noticed that these effects are opposite those created by the LPS PIN because in this case the HPC is speeding up and pulling pressure from the back of the LPC.

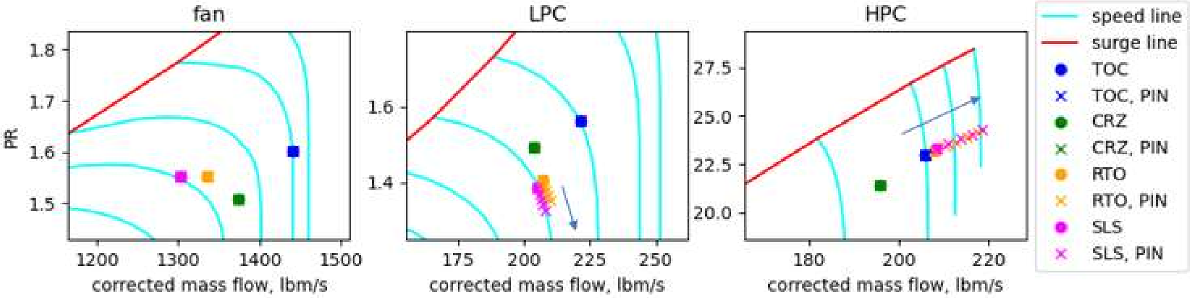

Figure 9. Compressor Map movements for engine designs with increasing HPS PIN at RTO.

Performance of the HPS PIN is shown in Figure 10. Here it can be seen that CRZ TSFC decrease by 0.001 or about 0.2%. This is caused by the same affects as for the LPS PIN, however to a much smaller degree. Using HPS PIN to counter the effects of LPS PIN can also be considered. In this case the surge margin reduction of the LPS PIN is countered by the HPS PIN and the speed increases of HPS PIN can be countered by the LPS PIN. These countermeasures combine to allow more LPS PIN and HPS PIN than with PIN on either shaft alone.

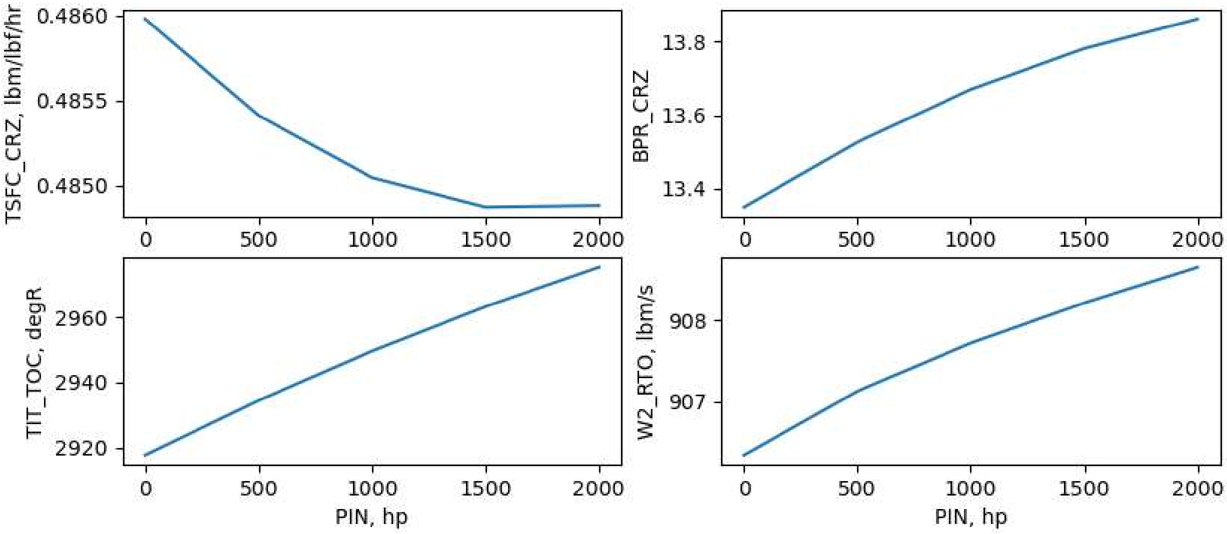

Figure 10. Performance for engine designs with increasing HPS PIN at RTO.

A second way to mitigate the surge issue with RTO LPS PIN is to consider LPS PIN at the TOC design point. Figure 11 shows LPS PIN from 0 to 500 hp with 3000 hp of LPS PIN at RTO. Here it can be seen that the TOC PIN reduces LPC surge margin and increases HPC speed at the RTO operating point and the CRZ point. This also increases both the LPC and HPC flow, decreasing the BPR. The drop in LPC operating point and reduction of BPR at CRZ coincide with a reduction of LPC efficiency and TSFC. This design choice is like that of the HPS PIN at RTO in that adding the TOC LPS PIN increases the limit margins and allows LPS PIN at RTO to increase, however it also lowers engine performance. A similar effect can be completed by changing the initial TOC map placement, however this would require speeding up the TOC HPC speed beyond 100% and may not be feasible.

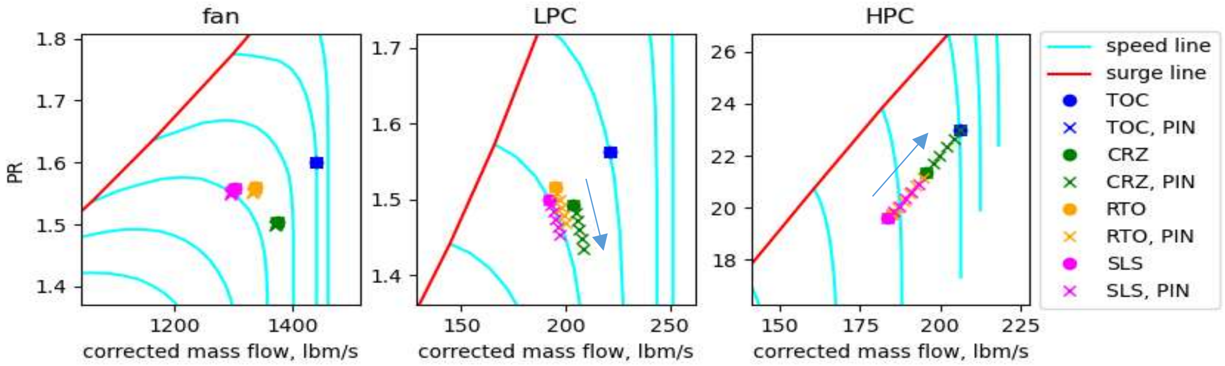

Figure 11. Performance for engine designs with increasing LPS PIN at TOC and 3000 PIN at RTO.

Three designs are studied; using LPS PIN at RTO only, including HPS PIN at RTO (HPS offset or power split offset), and LPS RTO at TOC (LPS TOC offset) offsets separately. These designs are set up to push the LPC surge margin to 15% using the LPS PIN. The HPS offset and LPS TOC offset are used to increase the LPS power further. The HPS offset is limited by TOC TIT, which is pushed to the same limit as RTO TIT. The LPS TOC offset is limited by the HPC speed at CRZ, which is set to 100% and is roughly 500 hp PIN. Results from these studies are found in Table 2. Here it can be seen that with LPS PIN at RTO only the TSFC at CRZ can be reduced by 3.09% using 3470 hp of PIN. Making use of HPS offset the CRZ TSFC can be reduced by 5.19%, using 6300 hp of RTO PIN. Using the LPS at TOC offset, TSFC at CRZ can be reduced a total of 3.37%, using 4512 hp of PIN at RTO and 500 hp of PIN at TOC. A TSFC at cruise reduction per PIN at RTO shows that using LPS PIN lowers the TSFC by the largest margin for power used (0.89% per 1000 hp). Adding the HPS offset lowers this to 0.82% per 1000 hp and the LPS TOC offset lowers this further to 0.75% per 1000 hp. This reflects that LPS PIN at RTO is the most efficient way to design the engine for RTO thrust assist. If more assist is needed, then the HPS offset should be considered followed by the LPS TOC offset.

Table 2 : Take off assist engine designs for baseline, LPS PIN at RTO, and with HPS offset or LPS at TOC offset. Limits of LPC surge margin and HPC speed and maximum TIT are observed.

	Baseline	**LPS PIN at RTO**	**with HPS offset**	**with LPS TOC offset**
LPS PIN, hp	0	3470	5100	4512
HPS PIN, hp	0	0	1200	0
Total PIN at RTO, hp	0	3470	6300	4512
TSFC at CRZ, lbm/hr/lbf	0.486	0.471	0.4608	0.4696
TSFC reduction from baseline, %	None	3.09%	5.19%	3.37%
CRZ TSFC reduction per total PIN at RTO, %/(hp/1000)	None	0.89%	0.82%	0.75%

In the design of at turbofan for take-off thrust assist, LPS PIN at RTO maximizes the reduction in CRZ TSFC. The PIN is limited by the LPC surge margin. This surge margin may be reduced by adding HPS PIN at RTO or by introducing PIN at the TOC design point, however these offsets will reduce the effectiveness of the LPS PIN at RTO. In a full propulsion system design, it is important to consider factors such as power storage for PIN, electric machine size, and engine weight. These types of analysis are beyond the scope of this paper; however, they would be required to determine the optimal PIN for a given mission profile. It should also be noted that an engine core size limit is not considered within this study and it is assumed that flow through the core can be reduced without reducing component pressure ratios.

V. Summary and Conclusions

This paper describes the design of a turbofan engine that considers thrust assist at take-off with an external power source and a power assist at cruise using the engine to power external EAP components. Both these studies show HPC speed and LPC surge margin limit how much power can be inserted or extracted from the engine design. These limits come into play as the amount of power added or removed from the system moves away from the natural lapse rate or power drop off for the engine due to environmental conditions. For power assist at cruise, margins can be maintained by adding additional power extraction at high power operating conditions such as take-off or by modifying the HPS to LPS power split. Power insertion limits for take-off assist can be reduced by adjusting the HPS to LPS power split or by increasing power insertion at the TOC operating point. These studies illustrate the limitations of designing a turbofan engine for adding or removing large amount of power and demonstrates that engine lapse rate must be considered when operating such engine configurations. Additionally, it is shown that take-off assist results in a TSFC reduction of over 5% with this engine configuration and the correct PIN scheme.

Acknowledgments

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