Utilizing Electrical Power Extraction for Stability Bleed Reduction within Gas Turbine Engines

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This paper studies the role of power extraction in gas turbine stability and how an engine may be designed to utilize this extraction to replace engine stability bleed requirements with electrical system requirements. The considered engine architecture contains two engine spools and a power turbine spool. In the baseline, low-pressure compressor stall margin is maintained by bleed air from the back of the low-pressure compressor, which is then dumped to the bypass. Power extraction from the high-pressure and low-pressure shafts are then utilized as a replacement for this bleed. This study considers component performance, sizing, efficiency, and operability, but does not consider weight or cost. Analysis within this paper is general and the concepts could be applied to other dual spool engine types, including a turbofan. Results show it is possible to completely remove the stability bleed between the low-pressure and high-pressure compressor by utilizing a 35% power extraction from the high-pressure shaft or a 1.5% power extraction from the low-pressure turbine.

Nomenclature

EAP	Electrified aircraft propulsion
HPC	High-pressure compressor
HPS	High-pressure engine shaft
HPT	High-pressure turbine
LPC	Low-pressure compressor
LPS	Low-pressure engine shaft
LPT	Low-pressure turbine
P	Pressure
PEX	Power extraction
PSFC	Power specific fuel consumption
PT	Power turbine
PTS	Power turbine shaft
SLS	Sea level static conditions
T	Temperature
TEEM	Turbine electrified energy management
VBV	Variable bleed valve

Subscripts

2	Station number for LPC inlet
25	Station number for HPC inlet
3	Station number for burner inlet
4	Station number for turbine inlet

I. Introduction

In the next generation of aircraft it is estimated that electrical power loads requirements will increase. These aircraft could come in the form of more electric aircraft (MEA) [1] or from utilizing electric aircraft propulsion (EAP)

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[2][3]. This migration in requirements moves current electrical loads from hundreds of kW, into the MW range for a wide-body aircraft, through the increased use of electrical subsystems or electrically driven propulsors. Electrical power for these concepts could be provided by onboard aircraft generators driven by conventional engines or batteries. If conventional engines are utilized, then there is an opportunity to modify engine operation for this adjusted mission. This paper will discuss the potential for using power extraction (PEX) to reduce the requirements for stability bleed on conventional gas turbine engines.

During design of a gas turbine engine the components are sized to meet power or thrust requirements at a design point. This design point dictates the speed and mass flow that the turbomachinery will operate. When operating off design the balances set up at the design point are disturbed and undesired pressure may build up behind the compression components leading to compressor surge. Stability bleeds are utilized to prevent compressor surge by bleeding off a portion of the mass flow to reduce the component pressure ratio. This bleed can be thought of as a PEX, where the power is contained within the air that is being removed from the system. Utilizing bleeds in this way reduces the overall efficiency of the gas turbine, as the power contained within this air is not fully recovered. Using electrical PEX to re-balance the engine, reducing chance of surge and the requirement for these stability bleeds, allows the design to utilize this power for other purposes. This is not a new idea, and it has been proposed for use in engine control systems on conventional gas turbines using the turbine electrified energy management (TEEM) concept [4]. This electric power could be drawn from the low-pressure compressor (LPC) of a dual spool turbofan to reduce the LPC speed and pressure ratio when approaching surge.

This paper details a dual spool turboshaft engine, looking at the optimum PEX strategy and analyzing the effects on engine efficiency. The stability bleed to be analyzed is consistent with that provided by a variable bleed valve (VBV) or a bleed after the LPC and before the high-pressure compressor (HPC), inter-stage bleeds will not be considered. This study is a continuation of PEX analysis done in previous work at NASA [5, 4]. Analysis will take a deeper look into PEX spool choice and the effect of designing the turbines for varied amounts of power. Turbine efficiency is determined based on an assumed polytropic efficiency. Cooling flow for each design is updated to reflect temperatures observed across the turbine components. System weight and cost is not considered in this study however, generalities are discussed. Power specific fuel consumption (PSFC) is used as a metric for overall system efficiency.

Subsequent sections of this paper detail the engine architecture and several steady-state surge margin strategies. Specifically, a detailed description of the engine model is given in Section II, followed by an application study in Section III. A discussion on selection of surge suppression methods is given in Section IV. Finally, summary and conclusions are given in Section V.

II. Turboshaft Simulation Description

The studies run for this paper consider a dual spool turboshaft engine simulation. This simulation was developed in the numerical propulsion system simulation (NPSS) [6] with architecture shown in Figure 1. In the simulation, the air flow moves through the inlet, LPC, HPC, burner, high-pressure turbine (HPT), low-pressure turbine (LPT), power turbine (PT), and exit nozzle in series. A VBV is added to allow for the extraction of air from station 25. Cooling flows have been added that utilize HPC air to cool the HPT and LPT. In this case The HPT is cooled utilizing HPC exhaust air and the LPT is cooled utilizing HPC stage 4 bleed for chargeable flow and stage 10 bleed for non-chargeable flow. It is assumed that PT cooling flow is negligible. The high-pressure shaft (HPS) connects the HPC and HPT, while the low-pressure shaft (LPS) connects the LPC and LPT. The power turbine shaft (PTS) is shown to be free. Each shaft within the diagram is connected to a unique electric motor or generator (Gen.) that can either provide power to the shaft or extract power from the shaft. For this paper, PEX is the percent of power being taken from a shaft relative to the power taken from all shafts (HPS, LPS, or PTS).

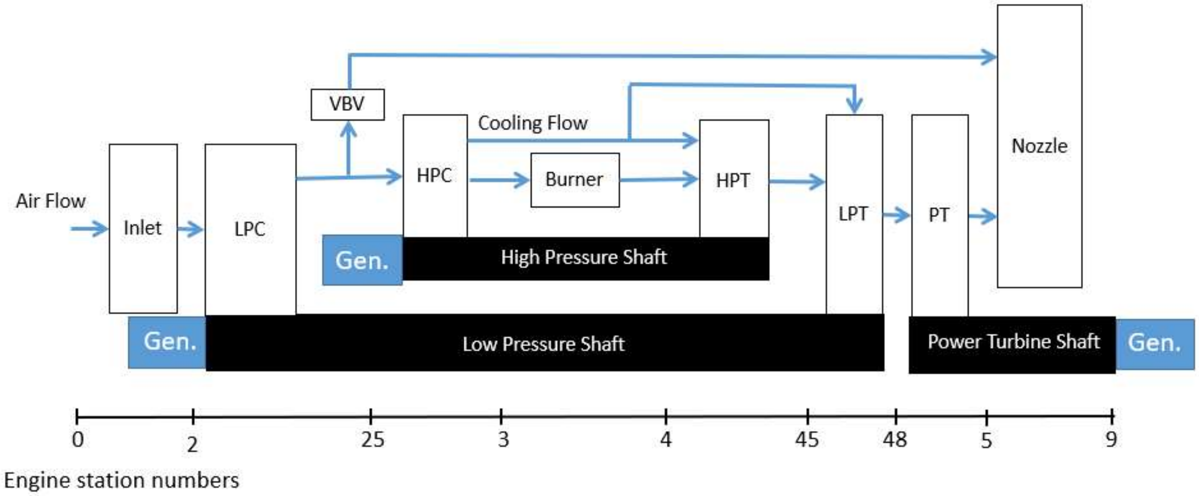

Figure 1. Turboshaft NPSS engine simulation.

The engine was sized to provide a maximum power of 40,000 hp at sea level static (SLS) conditions. Design criteria is detailed in Table 1. During the design, inlet air flow and the fuel to air ratio (FAR) are set to obtain the required power and a temperature of 3,330 R was selected for the turbine inlet temperature (T_4) limit. The baseline system is designed to utilize a VBV at part power and all PEX at max power is taken from the power turbine. Component performance maps are generic with scaling applied to meet the design point. Requirements for cooling flow are calculated based on turbine blades metal temperature limits and cooling flow effectiveness. Compressor efficiency values are set based on polytropic efficiencies related to core size, while turbine polytropic efficiencies are set to 0.90.

In addition to the baseline engine a high HPS power extraction simulation is developed to allow for a study of HPS PEX. In the HPS PEX engine simulation, 35% PEX is taken from the HPS instead of the PT at maximum power. This causes an increase HPT PR, reduction of PT PR, and a decrease in the temperatures after the HPT and LPT. Hot section cooling flows are also adjusted as needed to meet the temperature requirements. Design point data along with a comparison is contained in Table 1. With these adjustments the overall PSFC of the engine is slightly lower at the design point.

Table 1. Baseline and HPS engine turboshaft engine design point parameters.

	Parameter	Baseline	HPS PEX engine	Difference (%)
Environmental Conditions	Mach Number	0.0	0.0	-
	Altitude (ft)	0.0	0.0	-
Flows	Inlet mass flow (pps)	157	147	-6.37
	Fuel to Air ratio	0.0279	0.02784	-0.22
Cooling flows	HPT Non-chargeable (%W_3)	5.8	6.2	6.90
	HPT chargeable (%W_3)	5.4	4.9	-9.25
	LPT Non-chargeable (%W_{25})	2.6	1.5	-42.31
	LPT chargeable (%W_{25})	6.6	2.6	-60.61
Pressure Ratios	LPC pressure ratio	2.1	2.1	0
	HPC pressure ratio	22.0	22.0	0
	OPR	46.2	46.2	0
	HPT	5.56	8.920	60.43
	LPT	1.30	1.322	1.69
	PT	5.34	3.285	-38.48
Temperatures	Station 2 (R)	545.67	545.67	0
	Station 25 (R)	685.45	685.63	0.03
	Station 3 (R)	1,718.67	1,719.44	0.04
	Station 4 (R)	3,300.00	3,300.00	0
	Station 45 (R)	2,232.13	2,032.67	-8.94
	Station 48 (R)	2,030.82	1,886.91	-7.09
	Station 5 (R)	1,402.16	1,449.97	3.41
Adiabatic Efficiencies	LPC (%)	91.9	91.8	-0.11
	HPC (%)	87.1	87.1	0
	HPT (%)	91.7	92.1	0.43
	LPT (%)	90.3	90.3	0
	PT (%)	91.8	91.3	-0.54
Powers	High pressure turbine extraction (%)	0	35	-
	Low pressure turbine extraction (%)	0	0	-
	Power turbine extraction (%)	100	65	35
	Total Power (hp)	40,000	40,000	0
	PSFC	0.3139	0.3130	-0.29

Looking over the data in Table 1, differences in cycle design between the baseline and HPS PEX are dictated by three factors, power extracted from each turbine, turbine pressure ratio, and turbine efficiency. Power extracted is determined by the design, and pressure ratio is based on thermodynamic calculations. Turbine efficiency values are based on the mechanical design, turbine size, and can vary with good or bad designs. To gain a handle on the role of turbine efficiency in the cycle, a sensitivity study was performed varying the polytropic efficiencies of the HPT and PT relative to the LPT. For this study, HPT polytropic efficiency is adjusted then PT polytropic efficiency is adjusted equally and opposite relative to the LPT polytropic efficiency (PT efficiency = 2xLPT efficiency – HPT efficiency). Results from the study are shown in Figure 2, and show for the HPT PEX case that increases in HPT polytropic efficiency at the cost of PT polytropic efficiency results in lower PSFC for the data points analyzed. This is because 35% of the power is being drawn directly off the HPT. For the baseline configuration, a design minimum PSFC may be observed at 0.91 HPT and 0.89 PT polytropic efficiencies. This minimum is caused by the cycle efficiency balance between a highly efficient core and power generating turbine. A high HPT PEX engine is very sensitive to HPT efficiency, and overall PSFC of such an engine will benefit if the polytropic efficiency of the HPT is expected to be higher than that of the PT. If the PT is expected to have a higher polytropic efficiency than the HPT then the design will most likely be less efficient than the baseline. The magnitude of differences observed showed a roughly 2.5% gain or loss in PSFC with a polytropic efficiency difference of 10% (HPT 95% and PT 85% or PT 95% and HPT 85%). Figure 2 also contains adiabatic efficiencies for the two configurations and demonstrates how adiabatic efficiencies rise with larger turbines designed to provide more power extraction. In the remainder of this paper the default 0.9 polytropic efficiency is used for all examples.

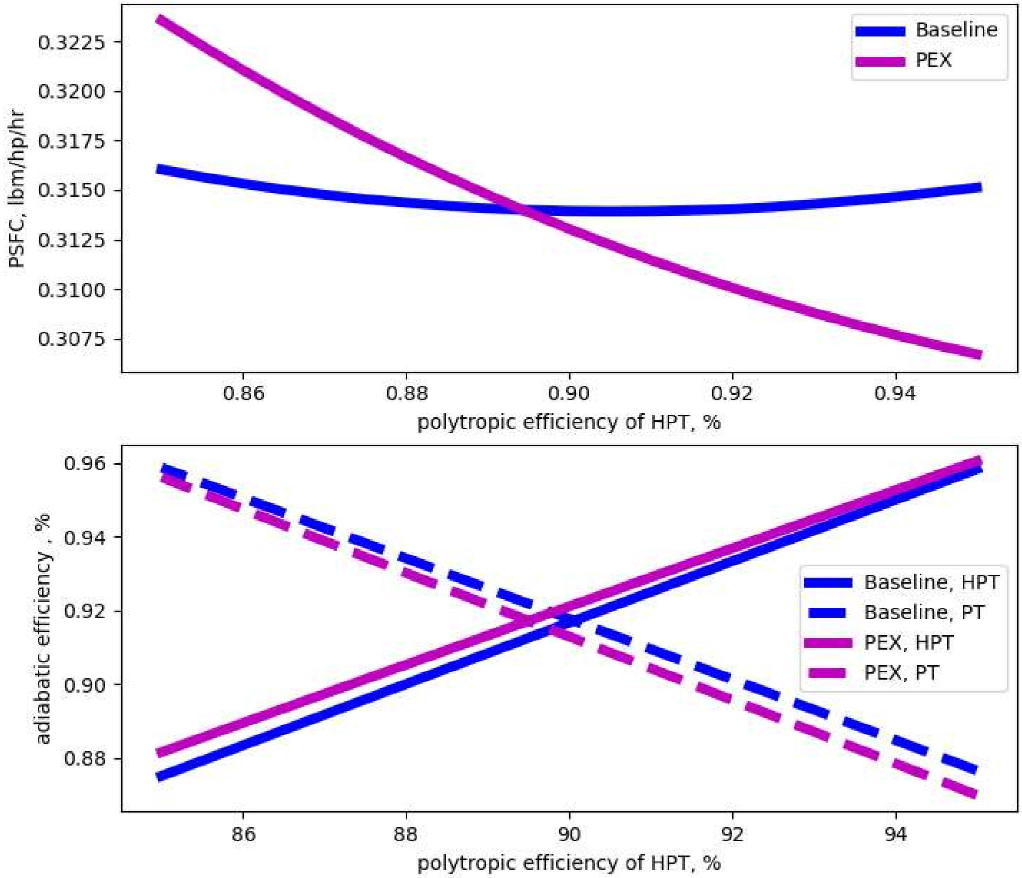

Figure 2. Engine PSFC, HPT and PT adiabatic efficiencies with changing HPT and PT polytropic efficiency for the baseline and HPT PEX engine designs.

III. Throttle Hook Study

In this section, LPC surge margin will be studied through the simulation of several throttle hooks. Three methods are used to mitigate pressure build-up on the back side of the compressor. The first utilizes a VBV to divert air and reduce the pressure. The second method utilizes electrical PEX from the LPS to reduce the speed of the low-pressure turbomachinery to drive down the pressure at station 25. The third method uses HPS power insertion, or, more accurately a removal of baseline HPS PEX to speed up the HPC and pull pressure off the back side of the LPC. In the first two examples the baseline engine configuration will be used and in the third example the HPS PEX engine variant will be used. In each example a throttle hook is performed ramping from maximum power at 40,000 hp to a minimum of 5,600 hp. This low power setting was chosen due to map limitations for the LPS run. Considering only the HPS PEX configuration the simulation could be run to a minimum power level of under 2000 hp. Traces of these throttle hooks are shown on the map in Figure 3, where the baseline run shows an engine throttle hook with no surge pressure mitigation. The VBV, HPS PEX, and LPS PEX make use of their appropriate method to meet LPC surge margin of no less than 10%. In each case the surge margin was able to meet the 10% requirement. Looking at the LPC trend, it can also be observed that at low power the LPS PEX method reaches the lowest speed. This is followed by the VBV trace and the HPS PEX trace results in the highest speed at minimum power. The HPC trend shows the baseline, VBV, and LPS PEX traces all follow a similar trend, with LPS PEX falling to a slightly higher speed than the VBV and baseline. The HPS PEX trace falls to a higher speed with reduced losses in mass flow, pressure ratio, and an increase in surge margin. This higher low power mass flow shows that the HPC is speeding up and pulling more air off the back of the LPC as the HPS PEX is reduced, which is the intent of the method.

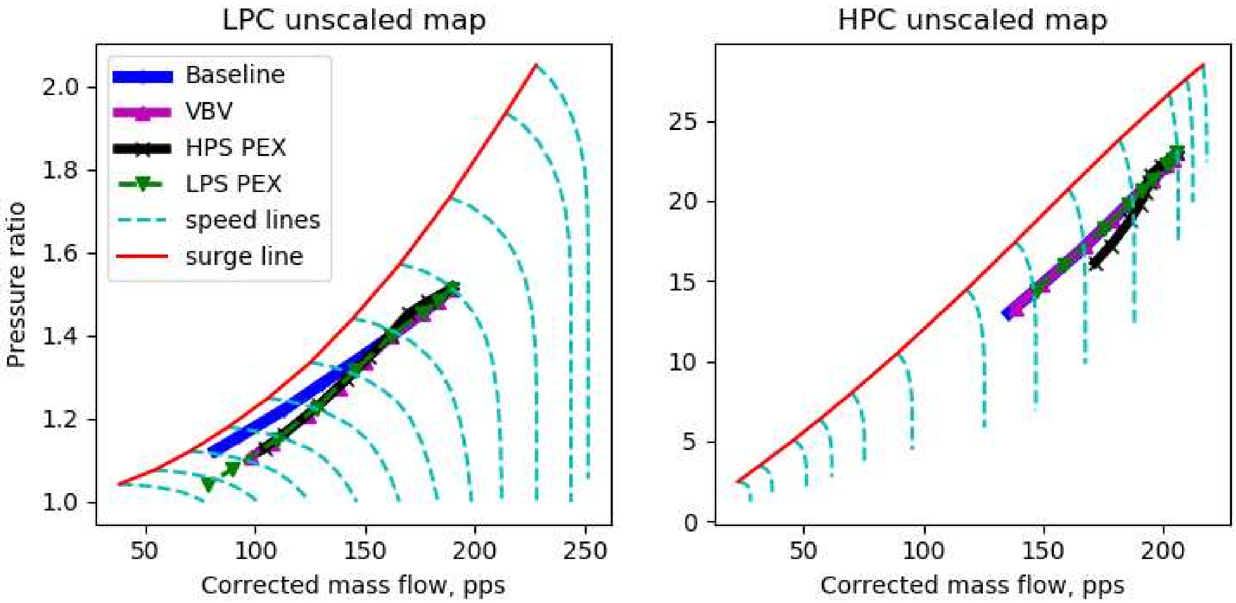

Figure 3. Compressor maps during throttle hook utilizing surge suppression methods.

Traces of throttle hook performance parameters, PSFC, T_4, OPR, and mass flow, are shown in Figure 4. The PSFC of the engine is a direct measure of the amount of fuel that is required to meet the power demand. Plotted versus power demand this shows how efficiently the engine is producing power and illustrates each method produces a similar PSFC at high power. As power is reduced the PSFC begins to separate with values of 0.466, 0.472, 0.476, and 0.487 at minimum power (ordered from smallest to largest being LPS PEX, baseline, VBV, and HPS PEX). These values may be understood by looking at the remainder of the traces in Figure 4. Given the VBV method is removing compressed air from the system without any recovery, it is unsurprising that it results in one of the highest PSFC values, but what about the HPS PEX method? The mass flow traces show that the VBV and HPS PEX methods consume the largest amount of air. Although this air is being consumed by both methods it is only passing through the HPC in the HPS PEX method. This large consumption of air through the HPC is reflected in the lower T_4 in the HPS PEX method. Higher speeds of the HPS PEX method result in higher OPR. The large PSFC for the HPS method can then be explained as cycle inefficiency, where the engine must process an amount of air that is too high for the power point. This drives down the per mass flow enthalpy rise, and although the OPR increases, which is typically good for efficiency, the T_4 falls and the new engine equilibrium point results in an increase in PSFC. Secondary effects that also contribute to the final PSFC are cooling flow and turbine efficiencies, where lower cooling flow and higher turbine efficiencies decreases PSFC.

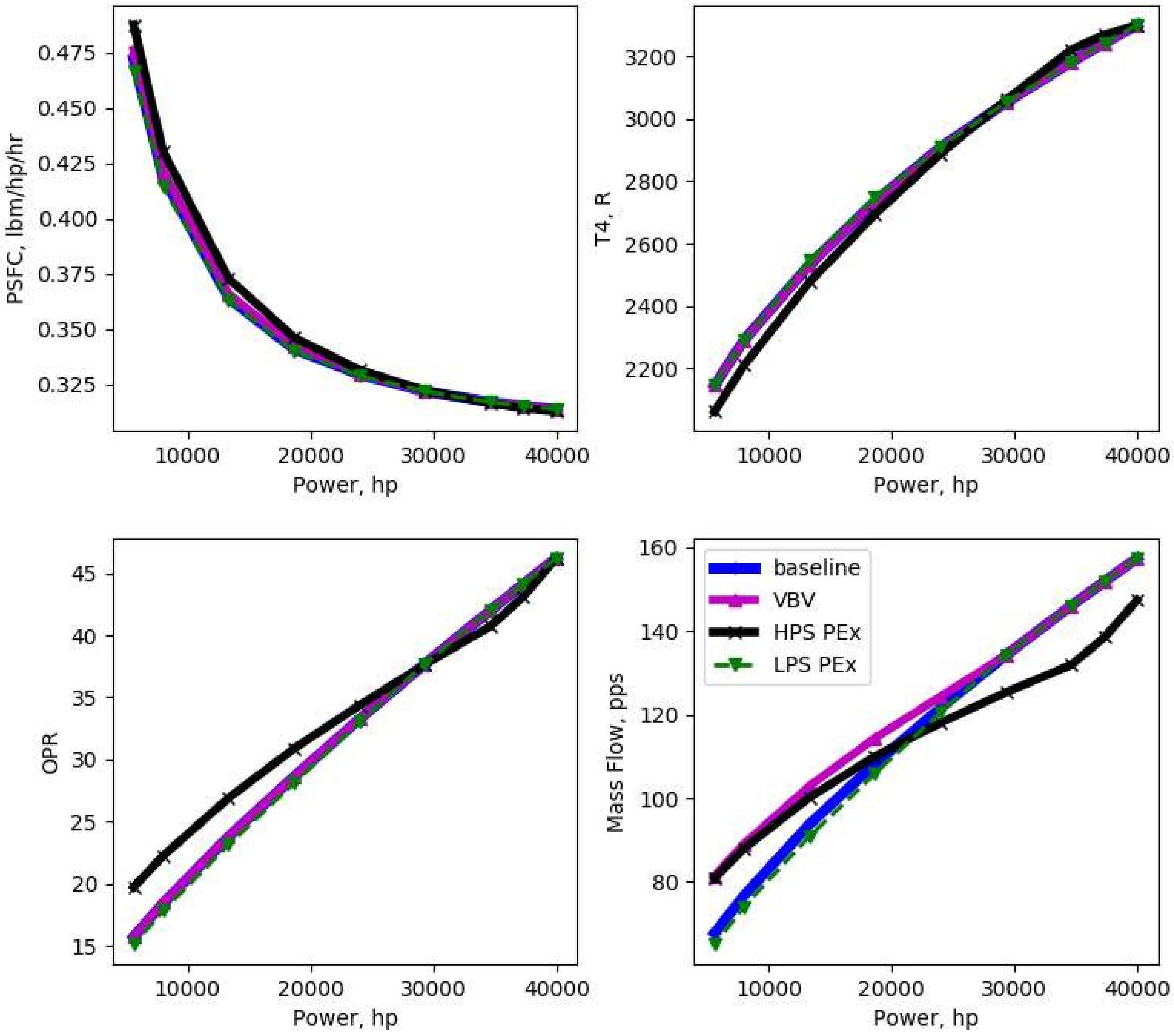

Figure 4. Performance parameters during throttle hooks utilizing surge suppression methods.

IV. Method Selection

In the previous sections three methods of surge margin reduction due to low power operation were analyzed, VBV, LPS PEX, and HPS PEX. Each of these methods showed a capability to allow for maintaining surge margin similar in capability to the current standard VBV method. This section will compare the methods and detail the advantages and disadvantages of each. A summary of these points is located within Table 2.

Table 2. Surge margin mitigation method comparison.

Surge margin mitigation method	Advantages	Disadvantages
VBV	Understood method Technology is well developed	Mechanical bleed valves and ducts need to be added High cost flow is removed from the system
LPS PEX	Lower total power requirement Highest PSFC at low powers	LPS generator is only used at low power
HPS PEX	Makes use of all electric machines at full power	Lower cycle efficiency at low power Large generator on HPS may lead to integration issues

Utilizing a VBV to reduce back side pressure from the LPC is the standard method of stall margin mitigation [7]. As such, the method is well understood, and placement of air valves and ducting is completed on a regular basis during the design process. Although this is the standard method, there are some disadvantages to the method. First, this added ducting and valves are large and heavy, and physically designing and integrating them on the engine, in locations where space is a premium, is sometimes a challenge. Second, bleeding air from the engine represents a thermodynamic loss.

The previous section details how PEX can be used to reduce or remove stability bleed requirement, however adding PEX to the engine comes with its own hardware and development costs. In both HPS and LPS PEX concepts electric machines will need to be added to the appropriate shaft. Sizing of these electric machines is determined by how much power is needed to maintain surge margin. Power levels required for the engine detailed within this paper are shown in Figure 5, where it can be seen that utilizing the HPS PEX method requires a maximum of 14,000 hp at full power and the LPS PEX method requires 600 hp at a lower power. This magnitude of differences is to be expected because the HPS of the engine is processing roughly 10 times the power of LPS. If a next generation electric motor has a specific power of 8 hp/lbm for an electric motor [8, 9, 10]. Following this specific power, the HPS and LPS PEX methods require electric machines that weigh 1,750 lbm and 75 lbm, respectively. However, the HPS PEX method takes this power at max power. Therefore, if the PT of the turboshaft is generating electricity, then the HPS PEX could be used to offset this power and reduce the size/weight of the PT generator by the same amount. This results a minor weight penalty for adding the additional electric motor for the HPS PEX configuration, assuming the connection weight of the mechanisms between the shaft and the electric machines is also negligible or scales linearly with power. With LPS PEX no such power offset could be used because, the power needs to be removed only during low power operation and the PT would need to produce all power at the maximum power point. However, the LPS PEX could be reduced somewhat by utilizing the LPS PEX to add power to the HPS, which may be a convenient option if the engine plans to make use of a HPS electric starter.

Physical integration of electric machines also needs to be considered with the PEX methods. With HPS PEX the electric machines could be attached directly to the accessory gearbox, however the increased load on the gearbox would increase its weight [11]. Utilizing general trends for superhigh-speed electric machines the HPS PEX motor ideal operating speed may be assumed to be a function of maximum power, which results in a speed of 5,000 rpm [12]. Additionally, assuming an HPS shaft speed of 17,000 rpm, results in a gearbox weight of 45 lbm, however this does not consider any other integration mechanisms. This is an important point because current accessory gearbox structures may not be designed for such large loads. For example, the Boeing 787, utilizing the GEnx engine contains only two 250 kVA generators within its HPS connected accessory gearbox [13]. For the LPS method, a gearbox may not be required because maximum electric machine speed at the lower power would be around 200,000 rpm, which is much higher than the LPS speed which is assumed to be 4,000 rpm. It should be mentioned that these electrical machine speeds are maximums and only meant to get a general idea of the magnitudes. For a complete design, motor speed and torque requirements, along with variable speed/frequency requirements that come with changes in engine shaft speed need to be considered.

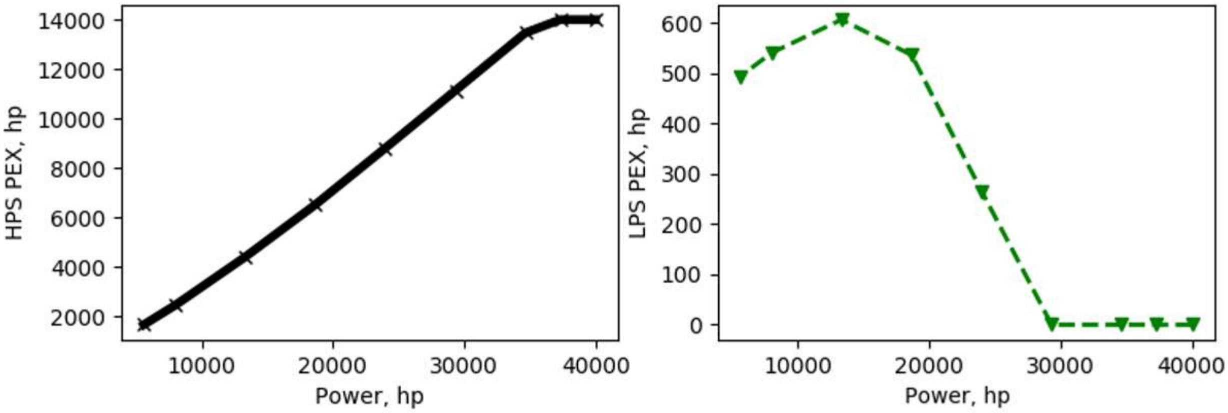

Figure 5. Power extraction for HPS PEX method and LPS PEX method.

V. Summary and Conclusions

This paper discusses utilizing power extraction to reduce or remove stability bleeds on a dual spool turboshaft engine. The standard variable bleed valve, HPS PEX and LPS PEX methods are compared in PSFC and hardware requirement. Results show each method may be used to increase low-pressure compressor surge margin, with a LPS PEX of 1.5% or HPS PEX of 35% (both defined relative to the maximum power being taken from the engine). At low power, PSFC was found to increase with the HPS PEX method and was reduced with the LPS PEX method. Differences in PSFC was found to be negligible at full power. For each PEX method, additional hardware must be added to the system, however with HPS PEX a portion of the main load would be transferred from the PT to the HPT. This would reduce the size of the main generator and redirect load to the HPS, offsetting some of the added hardware requirements. Analysis in this paper is limited to performance and requirements and does not fully analyze weight or structural issues. To gain a full understanding of which surge suppression method is superior, a system study that includes component weight and stresses (engine, gearboxes, subsystems, mission, and electric machinery) would need to be completed.

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