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Gas Turbine Analysis Strategy: Using Surrogate Modeling to Capture Bleed Flow Extraction Impacts On a High Bypass Turbofan Engine

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Abstract

This study introduces a simulation strategy that will enable an engine cycle analysis to capture the performance characteristics of the compressor, analyzed at a higher level of fidelity. This allows the engine cycle analysis to capture the engine system level impacts of compressor operation (i.e. variable stator, bleed extraction, etc.) changes in a computationally quick and affordable manner. The study demonstrates the potential of a "surrogate integration" approach to engine cycle analysis by exploring customer bleed requirements on the core of a high bypass ratio turbofan engine.

This case study specifically spans the system level impacts of variations in compressor bleed flow rate and extraction location. The traditional method of addressing these parameters neglects the impact that they carry on individual component performance and operability, which is an assumption which can no longer be neglected with the changing requirements of revolutionary engine configurations. To that end, an analysis process is developed and utilized to provide a more physics-based estimate of the component level performance characteristics, and the results of which are then used in the cycle analysis in order to better predict the engine system level impacts of these changes.

Utilization of this ability provides engine level performance and operability analyses which reveal a disparity between the traditional and herein developed bleed handling methodology's predictions. The findings reveal a need for a more stringent assessment of component level impacts from engine level processes, specifically the, during the engine conceptual design phase than the traditional method provides

Nomenclature

BPR	Engine Bypass Ratio
B5	Fifth Stage Bleed Location
B7	Seventh Stage Bleed Location
DoE	Design of Experiments
IGV	Inlet Guide Vane
OTAC	Object Oriented Turbomachinery Code
TSFC	Thrust Specific Fuel Consumption
VSV	Variable Stator Vane

Introduction

The commercial aviation industry continually faces the challenge of reducing fuel consumption for the next generation of aircraft. This challenge rests largely on the shoulders of engine design teams, who push the boundaries of the traditional design paradigm in pursuit of more fuel efficient, cost effective, and environmentally clean engines. In order to realize these gains, there is a heightened requirement of accounting for engine system and subsystem level impacts from a wide range of variables earlier in the design process than ever before [1]. One of these variables, bleed flow extraction, or simply bleed, plays an especially greater role due to the approach engine designers are taking to combat the current state of fuel efficiency. For this reason, this research examines the current method of how bleed is simulated in a cycle analysis, questions its adequacy with regards to properly capturing the bleed impacts, and develops a new bleed simulation methodology designed to replace the existing method.

The traditional method of simulating bleed within an engine cycle design relies on a variety of engine level impacts stemming from zero dimensional thermodynamic analyses, as well as the utilization of a static performance characterization of the engine compression component, the axial flow compressor. Specifically, bleed is traditionally simulated by three mechanisms:

1. Conservation of Mass Flow: When an amount of bleed air is extracted from the compressor, it is either ported away from the engine (customer bleed), or it is used downstream of the compressor for turbine cooling purposes. In the first case, the air is simply removed from the system, which means that there is less air available to be used for work extraction at the turbine section [2].

2. Balance of Work: In the case where the bleed air is ported away from the engine for customer use, there is an amount of work that must be expended by the compressor to simply prepare it for this extraction, by increasing its pressure, for the customer. This wasted work must be provided by the turbine section and will require a greater amount of fuel flow by the engine.

3. Utilization of Component Maps: The performance of any individual component within a gas turbine engine may be characterized both in terms of performance and operability by a component map. Each map is unique for any bleed flow and VSV setting. The cycle analysis includes this map and will produce acceptable results only in the case where the analysis that is being performed is done so with the same settings as were used to construct the compressor performance map [3]. Therefore, any variations in bleed flow rate or location will require the addition of a map constructed under the new bleed settings in order to maintain the same level of uncertainty.

The most important take away here is the fact that the traditional methods of simulating bleed at the cycle performance level operates under the assumption that the introduction of additional bleed to the compressor system has created no additional compressor level impact, unless additional maps are included to account for these changes.

Compressor Level Impacts

This study serves to show the difference in cycle performance predictions between the traditional bleed simulation method and the method that accounts for bleed effects via component maps. In this particular case study, the impacts of bleed flow rate and location are analyzed with respect to the compressor and engine level performance and operability (i.e. stall margin). In order to accomplish this task, an analysis method needed to be constructed to produce full compressor performance maps under a wide range of geometric, flow, speed, and bleed flow settings. The analysis chosen for this exercise is the Object Oriented Turbomachinery Analysis Code (OTAC), and a multi-stream meanline compressor model is developed to produce full performance maps for varying bleed flow rate and location. Within OTAC, a full compressor model was developed to simulate a 10-stage compressor with a design mass flow of 120 lbm/s, pressure ratio of 28, and efficiency of 80%. The 10-stage OTAC compressor model is developed to allow the user to parametrically change the bleed flow rate at any or multiple interstage locations.

A performance mapping for the compressor model operating without any bleed extraction was constructed in OTAC as shown in Figure 1. The no-bleed performance is compared to another set of speed lines with bleed. Specifically, 1.3% and 2.3% of the air flow entering the fifth (B5) and seventh (B7) stages are extracted at each of these locations respectively. When air is removed somewhere along the length of the compressor, the system is expected to experience a performance degradation [7] because the energy expended by the compressor to compress that air is wasted or no work will be extracted from it if is it used for chargeable bleed in the turbine. In addition to wasted energy, this specific modeling exercise has led the authors to hypothesize that the extraction of bleed air causes a static pressure drop in the remaining core air flow. This remaining air downstream of the extraction isothermally expands to fill the volume vacated by the bleed air. The static pressure drop is captured in the OTAC compressor model and could account for the expected performance degradation due to the presence of the bleed extraction.

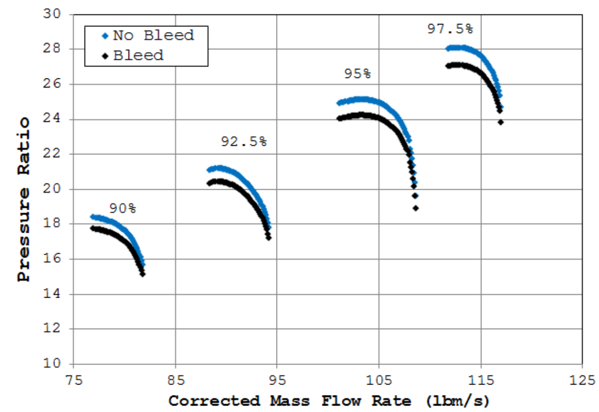

Figure 1 (a): Bleed Impact on Compressor Performance Characteristics: Pressure Ratio vs. Corrected Mass Flow

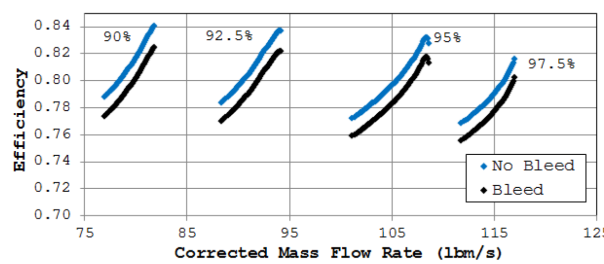

Figure 1 (b): Bleed Impact on Compressor Performance Characteristics: Efficiency vs. Corrected Mass Flow

The performance maps produced by the OTAC compressor model proved to qualify the expected behavior of the system in the presence of bleed flow extraction. The environment trended in the expected manner with the performance degradation correlating positively with increased bleed flow. Since the purpose of the research is to quantify the delta performance as opposed to absolute performance, no experimental validation is performed. However, past work, particularly the work performed during the NASA “Energy, Efficiency, and Emissions” project, laid the groundwork for verifying these expected trends, appropriately reproduced by the modeling environment [4].

Surrogate Modeling Approach

So far, the work performed enables the capability to assess the impact of bleed flow extraction at the compressor level o. The next step is to incorporate these results into an engine level analysis. However, a computational barrier must first be overcome. Currently, the OTAC model requires about an hour to generate an entire compressor map. Surrogate models are employed to overcome this computational burden at the engine cycle level.

The purpose of this surrogate modeling approach is to allow a compressor designer to quickly quantify any number of compressor level changes. To accomplish this objective, the following two steps are performed.

1. Construct a suitable design of experiments (DoE) and complete the compressor level analysis at each condition specified therein.

2. Use the collection of data resulting from step 1 to generate surrogate models relating each of the variables to each of the compressor level metrics as seen below.

$$\text{PR, Efficiency, Stall Flow} = f(X_1 \ldots X_4)$$

X_1 = Corrected Mass Flow
X_2 = Corrected Shaft Speed
X_3 = Bleed Flow Location
X_4 = Bleed Flow Rate

The purpose of design of experiments is to evaluate trends among the parametric variations of interest. This is referred to as a, design space exploration in which systematically varies the parameters of the compressor model across a wide range of simulation cases. This allows for the design space to be explored based on the design requirements and specific details of any given system. In the case of the axial compressor model used in this work, one is interested in the variation of these parameters across the entire design space, and particularly at the extremes of the design space as the engine core size gets smaller.

There are a variety of DoE designs available to meet these requirements, but a simple Latin Hypercube Design was selected. The DoE was composed of 50 individual experiments, each yielding a complete performance mapping composed of approximately 350 compressor performance points. A single operating state is characterized by the estimated pressure ratio and efficiency achieved by the compressor when operating at a fixed corrected mass flow and shaft speed.

The resulting dataset after executing the cases in the DoE is then used to construct surrogate models, which are mathematical and statistics-based characterizations of the full compressor performance. Using these surrogate models allows for rapid evaluation and quantification of bleed impacts on the full compressor performance map without having to execute the OTAC compressor model in-line with the engine cycle model [5].

A surrogate model may be developed to relate any number of variables to a single performance or operability metric. However, in order to be used as an effective replacement for the OTAC compressor model, the surrogate models needed to be capable of creating full compressor performance maps, which accomplished through strategic integration and utilization of multiple surrogate models. Specifically, three independent surrogate models are generated following the steps below (depicted in Figure 2):

1. Establish the stall flow under a given set of bleed flow and operating state point conditions. (Surrogate model 1)

2. Add a reasonable flow range estimate to attempt to bracket the operating flow range of a given shaft speed, and partition this newly bracketed flow range into evenly spaced operating flows.

3. Evaluate the pressure ratio and efficiency at each of these operating flows, and repeat for all shaft speeds of interest. (Surrogate Model 2 and 3)

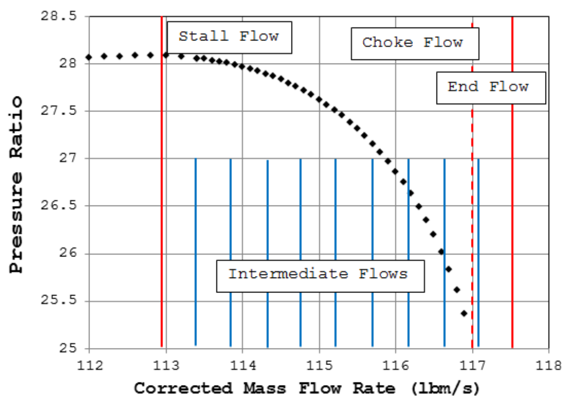

Figure 2: Operating Flow Range Bracketing

This approach successfully allowed for the replacement of the existing OTAC compressor model to provide full performance maps while sacrificing very little accuracy relative to OTAC. By using three independent mathematical models for each speed line, the resulting equations are considerably simplified. As evident in Figure 3, the surrogate models are able to reproduce the OTAC map quite accurately.

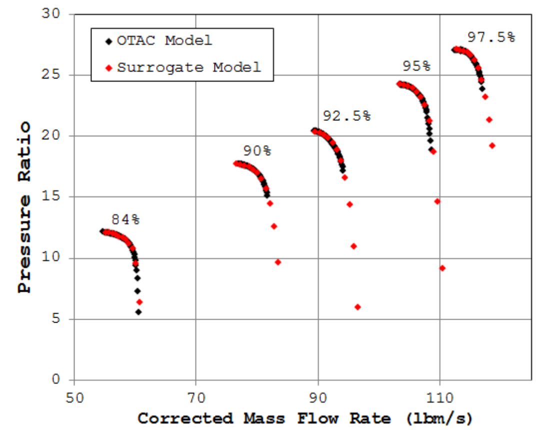

Figure 3: Comparison between Surrogate and OTAC Compressor Model

Engine Level Impacts

Now that the compressor maps that include bleed extraction effects can be accurately captured using surrogate models, the next step is to assess these impacts at the engine level with the same attention to the variations in predicted performance produced by the two bleed management methods explored herein. The engine model used for this study is similar in performance as the GE 90. The notional engine is a separate flow turbofan (SFTF) engine capable of generating nearly 115,000 pounds of thrust [6]. The SFTF model used in this work was modeled using NPSS and sized at an altitude of 35,000 feet and a Mach number of 0.8, comparable to the top of climb flight condition for a commercial aircraft. The model was then "run" down to an altitude of 5,000 feet and a Mach number of 0.25, which is of particular interest, as it represents a high-altitude take-off condition. At this operating condition, the max turbine entrance temperature is reached, corresponding to the maximum takeoff rating.

The full NPSS SFTF model uses notional component performance maps, and they are scaled to represent the performance of a GE90 class engine. Figure 4 depicts the core of the engine from the cycle analysis used in this work. The connection diagram for the bleed flow is of particular interest, where the high pressure compressor (HPC) is the only source. The cooling air for the low pressure turbine (LPT) and high pressure turbine (HPT) is extracted from the B5 and B7 locations, respectively. Additionally, any customer bleed will be drawn primarily from the B5 location.

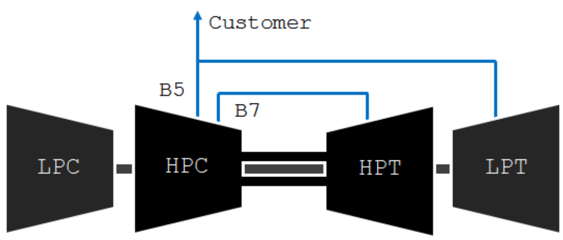

Figure 4: Core of the Engine Model

In order to assess the engine level prediction differences between the two bleed simulation methods, the following three independent test cases are evaluated:

Case 1: The first test case represent the baseline case in which the bleed flow needed for turbine cooling were set by the cycle and using traditional bleed simulation method.

Case 2: The second test case is the same as Case 1 except for an additional 5% customer bleed extracted from B5 location. The case also uses the traditional bleed simulation method with the map scaling factors set to that of Case 1. The cycle is re-balanced (i.e. conservation of mass and work balance) to account for the additional customer bleed extraction.

Case 3: The final case represents the objective of this research endeavor. The total bleed requirement (turbine cooling and additional customer bleed) are set to that of Case 2, but they are simulated by generating a new compressor performance map via the surrogate models.

Two engine level performance metrics were used to evaluate these analysis differences, thrust specific fuel consumption (TSFC) and stall margin at the take-off condition. TSFC is a common fuel efficiency metric for gas turbines, and it serves well to quantify the performance differences between the two bleed simulation methods. Stall margin quantifies the safe distance away from stall (with respect to mass flow), which is a dangerous operating condition [8, 9]. Stall margin is a common metric for engine operability.

The TSFC comparison of the three test cases is shown in Figure 5 and the stall margin comparison is shown in Figure 6. Case 1 exhibits the lowest TSFC, which is to be expected since there is no additional customer bleed extraction present. Case 2 exhibits a higher TSFC relative to Case 1, which is also expected. Since these two cases uses basically the same HPC performance maps, one can reasonably assume that the observed engine level performance differences are due to how the traditional bleed simulation method (i.e. conservation of mass and work balance) accounts for the additional customer bleed extraction. Case 3 exhibits an even higher TSFC than Case 2. Recall that the total bleed extractions for both cases are kept the same, but Case 3 uses the new bleed simulation method. This observation suggests that the impact of changing the compressor map to account for the additional bleed extraction is solely responsible for this increase in TSFC. Figure 5 shows that the TSFC difference between Case 2 and 3 increases from max power to idle power for the same corrected mass flow through the engine. This TSFC difference is expected to occur at other operating conditions such as cruise. Due the time constraints, cruise performance is not examined; however, an analogous study can be examined using results from the take-off condition. If the aircraft is well matched to the engine cycle, it would operate at the bucket of the TSFC and corrected mass flow curve. There is approximately 2.7% difference in TSFC between the Case 2 and 3 bucket points, which is not insignificant for long-haul missions.

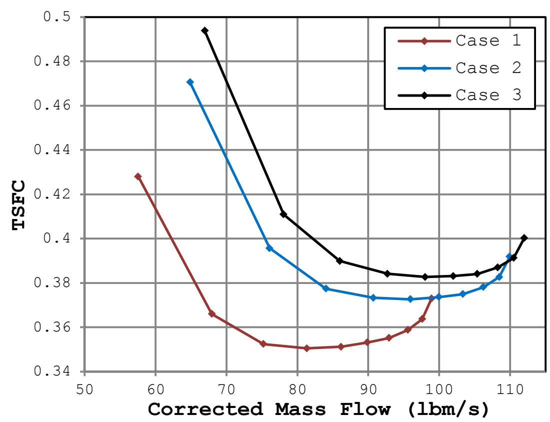

Figure 5: Engine Cycle Impact Due to Varying Bleed Flow Extraction

An engine operability assessment is examined next. The stall margins for all three cases are plotted in Figure 6. The cases where customer bleed is applied (e.g. Cases 2 and 3) manage to achieve a larger stall margin than in the baseline case, which is to be expected. Conversely to the TSFC trend, the new bleed simulation method achieved higher stall margin than the traditional bleed simulation method. The positive impact of this is that engine designs using the traditional bleed simulation method would be more conservative. However, a potentially negative impact may be found where engine designers make unnecessary compromises to meet overly conservative stall margins requirements. These results are in line with what would be expected, based on the former analyses of these experiments and the more stringent manner with which the new methodology simulates bleed.

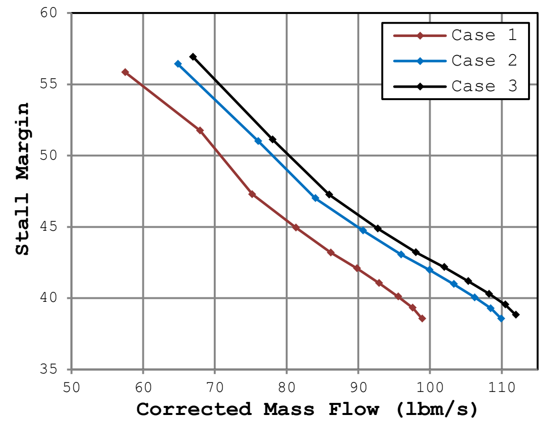

Figure 6: Operability Impact Due to Varying Bleed Flow Exaction

Conclusions

The commercial aviation industry is currently facing the challenge of reducing fuel consumption for the next generation of aircraft. The most likely approach to accomplishing this will be through the pursuit of higher bypass ratio engines. Since the size of the fan at the front of the engine is constrained to nearly its current size, this increase in bypass ratio must be accomplished through a decrease in the core size. This reduced core size, and associated reduced air flow, makes bleed flow extracted from the engine more costly than before, necessitating a way to quantify the impacts of this extraction during engine conceptual design.

Engine cycle studies incorporating a new bleed simulation method have been conducted which reveal a higher TSFC prediction compared to the traditional bleed simulation method. The cycle studies also showed that the new bleed simulation method predicts a higher stall margin (i.e. better operability) than the traditional bleed simulation.

The main conclusion from this research is the existence of a discrepancy between the two engine level bleed simulation methods. The traditional method operates on the assumption that the engine sub-level compressor performance impacts due to the introduction of bleed can be neglected. The results presented in this paper suggests otherwise. The first portion of the research qualified the extent to which bleed impacts compressor level performance. The second portion of the research showed that the bleed impact at the compressor level propagated to the engine cycle level has significant performance differences. Results presented herein suggest that the traditional bleed simulation method needs to be replaced with the newly developed methodology outlined in this paper.

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