12-2008

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by

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A Thesis Presented to the Faculty

Embry-Riddle College of Engineering

Department of Aerospace Engineering

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aerospace Engineering

Embry-Riddle Aeronautical University

Daytona Beach, Florida

December 2008

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Magdy Attia, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Aerospace Engineering Department and was accepted in partial fulfillment of the requirements• for the degree of Master of Science in Aerospace Engineering.

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ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the individuals who assisted me in completing this thesis. I would like to thank my advisor, Dr. Magdy Attia, whose guidance kept me from stumbling over the hurdles I encountered. I am indebted to Dr. Mark Turner who wrote the original source codes of the program I worked with in this research effort. His willingness to modify the code to meet the specific needs of my research and answer my questions over e-mail went above and beyond my expectations. I am grateful to Dario Bruna who provided additional information related to the data input files. I would also like to thank my family for their endless support of my well-being through my trials and tribulations.

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ABSTRACT

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Title: Modular Multi-Stage Axial Compressor Design

Institution: Embry-Riddle Aeronautical University

Degree: Master of Science Aerospace Engineering

Year: 2008

Increasingly, companies are becoming more interested in reducing cost. Recent studies indicate that up to 80% of the Lifecycle costs (LCC) has been embedded in the engine's DNA at the end of the development and design phase. One concept to aid in the cost reduction is the modular design of expensive and development-intensive components, such as multi-stage axial compressors. It is the objective of this approach to utilize a "core" module in all the compressors, thus maximizing commonality and minimizing all relevant development, design, manufacture, procurement, and service costs; these reductions in cost are projected to increase affordability by five-fold. This thesis introduces the modular concept with a multi-stage high-pressure compressor design carried out to throughflow analysis. The compressor is consequently divided up into five modules, and a modular upgrade is then developed for a different application using the same core. Discussion is presented as to advantages and potential limitations.

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LIST OF SYMBOLS

English Symbols

Symbol	Definition (units)
A	Flow path cross-sectional area (m^2)
a	Speed of sound (m/s)
C_p	Specific heat at constant pressure (J/kg·K)
h	Specific Enthalpy (J/kg)
M	Mach number
$\dot{m}$	Mass flow rate (kg/s)
N	Mechanical speed (rpm)
P	Pressure (Pa)
R	Degree of reaction
r	Radius (m)
T	Temperature (K), thrust (lb)
U	Circumferential velocity, defined as (Ωr) (m/s)
V	Absolute flow velocity (m/s)
W	Weight (lb)

Greek Symbols

Symbol	Definition (units)
α	Absolute flow angle (deg)
β	Relative flow angle (deg)
φ	Flow coefficient, defined as $\left(V_{ax,3} / \ U_3\right)$
λ	Work coefficient, defined as $\left(\Delta h_o / \ U_3^2\right)$

γ	Specific heat ratio
π	Total-to-total pressure ratio
η	Efficiency

Subscripts

Symbol	Definition
o	Total, or stagnation conditions
1	Stage, or rotor inlet
2	Rotor exit, or stator inlet
3	Stage, or stator exit
ax	Axial component
h	Hub
t	Tip
tt	Total-to-total
u	Circumferential

LIST OF ABBREVIATIONS

Abbreviation	Definition
CM	Core Module
EM	Exit Module
FM	Front Module
GE	General Electric
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IHPTET	Integrated, High-Performance Turbine Engine Technology
IGV	Inlet Guide Vane
IM	Inlet Module
LCC	Life Cycle Costs
OGV	Outlet Guide Vane
RM	Rear Module
RPM	Revolutions per Minute

MODULAR MULTI-STAGE AXIAL COMPRESSOR DESIGN

I. INTRODUCTION

1.1 History of Modular Concept

The original gas turbine modular concept was first developed in the early 1960's, [1]. Its purpose was to lower the Operating and Support (O&S) elements of the Life Cycle Cost (LCC), specifically, allowing for easier maintenance and parts replacement. This flexibility decreased engine repair time and effort, and ultimately would minimize maintenance costs. Some examples of the modular engine design are the General Electric CF6–6/50 (Fig. 1) for commercial applications, and the Pratt & Whitney F-100 engine used on the F-15 fighter aircraft.

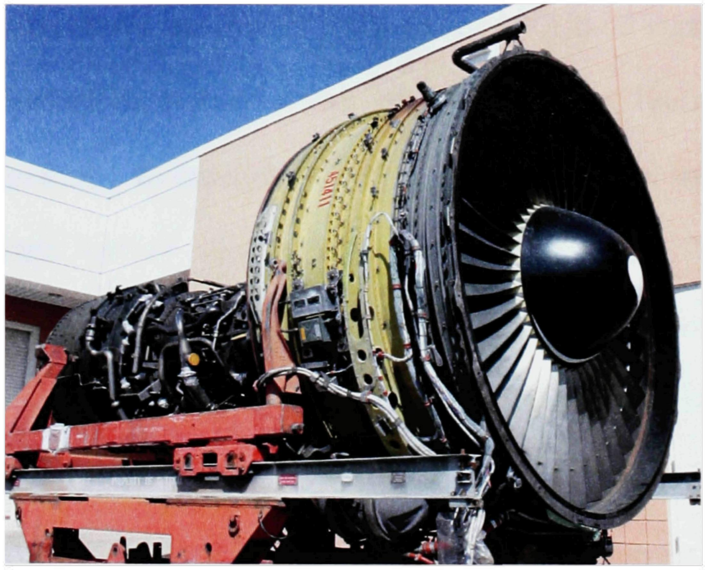
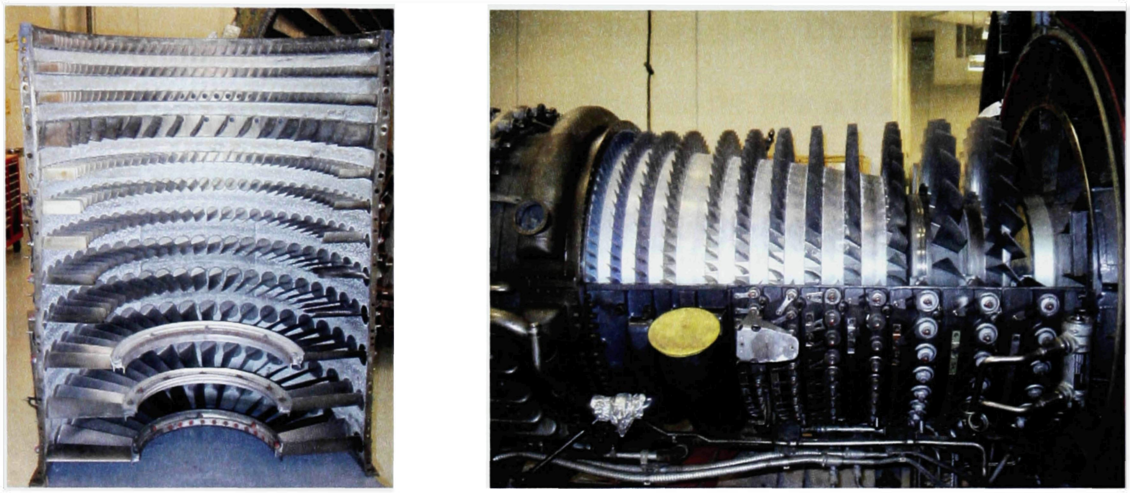


Figure 1. General Electric CF6-6 High-Bypass Turbofan Engine Located at the Gas Turbine Laboratory at the Aerospace Engineering Dept of Embry-Riddle University.

Duvall, and Goetz, [2], outline an understanding for the maintenance procedure with the modular engine concept, with emphasis on the attempts by the military to reduce gas turbine maintenance costs. Lehmann [3] covers the common core concept in sufficient detail. The core in [3] refers to the HPC, main combustion chamber, and HPT. Furthermore, the benefits of having a common core as they relate to cost savings in terms of development, operation, and maintenance are well outlined in [3]. Skira, [4], covered the cost reduction efforts that are currently ongoing in commercial and government institutions. One such effort, gaining notoriety, is the Integrated, High-Performance Turbine Engine Technology, or IHPTET. This is an ongoing collaborative effort by the Air Force, NASA, and various industrial partners. The IHPTET program has some very ambitious goals not only in terms of performance enhancements, but also in terms of cost savings. A common core is one of the most researched components of the IHPTET program. The resistance within the technical community to "modular" or "common" parts was well addressed by Stricker [5], where turbine engine Affordability is discussed. The concept of affordability redefines cost in a manner that is more realistic and more appropriate to judging the effectiveness of a certain design decision. Cost is related to the amount of improvement of a certain design or upgrade. Various improvements and upgrades can then be compared and contrasted in a more effective and fair manner. Affordability is defined, as will be discussed in a later section, as the change in capability (or improvement) non-dimensionalized, in business terms, by the development, production, and maintenance cost of said improvements. Two completely different improvements can then be easily contrasted to determine the benefit to the organization from each.

1.2 The New Modular Approach

The modular compressor design philosophy discussed in this thesis differs from the modular engine approach discussed in [3]. The modular engine approach aims at providing a common engine core. An engine core consists of the High-Pressure (HP) components: HPC and HPT, as well as the main burner. Such a configuration was seen on the GE CF6 engine such as the -6 model shown in Fig. 1. Fig. 2 (a) and (b) show the GE CF6-6 located at the Embry-Riddle Gas Turbine Laboratory, with the HPC casing removed to expose the first 12 rotors of the 16-stage HPC. This modular engine configuration, intended to accelerate maintenance and parts replacement [1], facilitated the easy removal of the HPC casing with off-the-shelf tools, as shown.



(a) (b)

Figure 2. ERAU-GTL GE CF6-6 High-Bypass Turbofan: (a) HPC Top-Half Casing, (b) Engine with HPC Casing Removed Showing 12 of 16 HPC Rotor Blades.

Recent detailed studies concerning engine Life Cycle Costs (LCC) indicate that two thirds (2/3) of the LCC are incurred after the engine is acquired by the customer. Therefore, reduction of LCC is becoming a critical acquisition criterion. Those same studies also show that 80% of the expected LCC are a function of the design, i.e., they are permanent once the product has left the design and development phase and entered the production and service phase.

Motivated by LCC concerns, and by the fact that ease of change is greatest during the design phase, the modular concept for multi-stage compressors becomes almost obvious. The concept aims to achieve the following: the compressor is subdivided into five (5) modules. They are the inlet module (IM) consisting of the inlet ducting and inlet guide vane (IGV), followed by the front module (FM) which includes the front stage but could be extended to include the front two stages. The third is the most important and is the core module (CM). The fourth module is the rear module (RM) and consists of the last stage, and the fifth is the exit module (EM) consisting of the outlet guide vane (OGV) and exit diffuser. Figure 3 shows a schematic of a 10-stage HPC compressor breakdown into 5 modules. In Fig. 3, the FM consists of one stage and so does the RM, while the core module (CM) size is maximized at 8 stages. Both the IM and EM contain each a guide vane and the inlet "swan neck" ducting, and the exit diffuser, respectively.

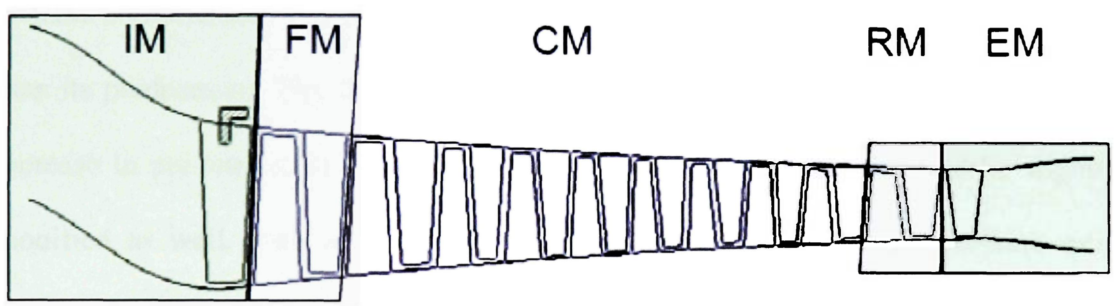


Figure 3. Schematic of a 10-Stage HPC Subdivided into Five Modules.

1.3 Thesis Objectives

The intent of the modular concept is to maximize the size of the core module for use in other compressor configurations. Pre-planning the different configurations is of utmost importance, and is the premier key success factor. The core module is then designed with sufficient aerodynamic and mechanical robustness to manage the possible configurations. For example, if a higher mass flow upgrade is planned; the mechanical evaluation of the CM airfoils must be conducted at the higher mass flow to ensure sufficient stress margin. If a different mechanical speed (rpm) is planned, then the core is evaluated at both aerodynamic speeds (original and modularly upgraded) to ensure stability and conduct sufficient airfoil tuning to handle both operating configurations. Modular upgrades can then focus on the remaining four modules only to be "connected" to the same core.

To further illustrate this concept, the following example is considered: for a larger derivative, having more mass flow rate and a higher pressure ratio, the one-and-one-half-stage FM and IM, Fig. 4(a) would be removed and replaced by an FM/IM combination that employs two and one half stages, with a larger inlet area than its predecessor, Fig. 4(b). This will allow for more flow with an accompanying increase in pressure ratio. To complete this configuration, the IM would be slightly modified as well, with a longer span IGV. To increase the overall pressure ratio further, the RM, Fig. 4(c), would be replaced by a module employing three stages instead of one, Fig. 4(d). Furthermore, and depending on the exit geometry and the radial location of the main burner, a customized diffuser/OGV assembly can be employed with ease, as shown in Fig. 4(d). When the design is completed, the two compressors, performing different duties (at different flow, pressure rise, rpm, and number of stages) in two different engines, would share an 8-stage common core. The development effort, manufacturing, tooling and assembly, procurement, and maintenance costs would be considerably reduced. Figure 5 shows an overlay of the two configurations in their final shape.

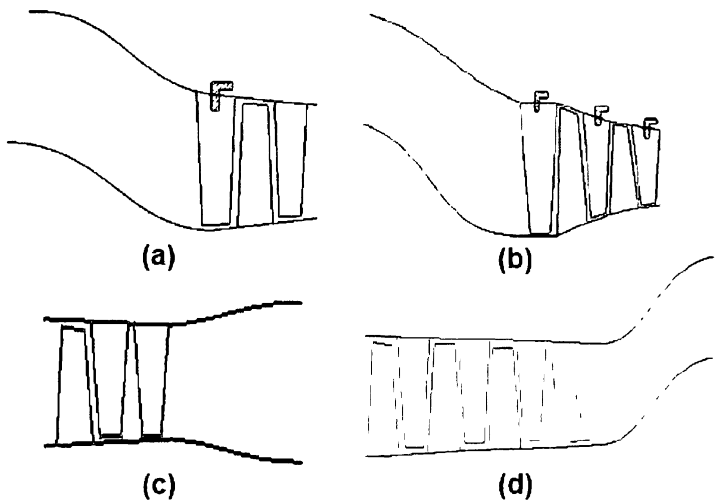


Figure 4. Module Upgrade: (a) Original Configuration IM/FM One and One Half Stage, (b) IM/FM Upgrade, Larger Inlet Area, Two and One Half Stages, (c) Original RM/EM One and One Half Stage, and (d) RM/EM Upgrade, Increased Pressure Ratio, Custom OGV and Diffuser, Three and One Half Stages. (Not to scale).

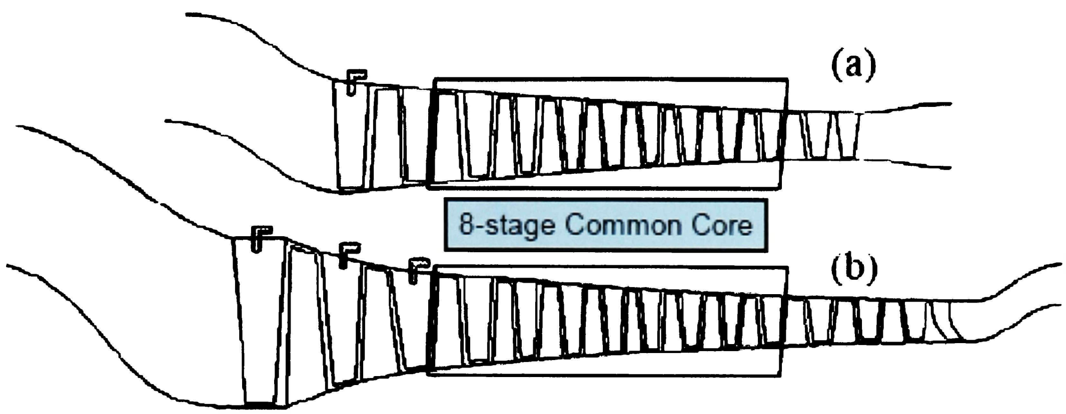


Figure 5. Modular Upgrade with an 8-Stage Common Core: (a) 10-Stage Original Configuration, (b) 13-Stage Modular Upgrade: Higher Flow Rate, and Pressure Rise, with a Customized OGV/Exit Diffuser (EM).

This thesis will conduct a meanline design of an HPC, and then subdivide it into the 5 modules. An assessment of the aerodynamic health of the core module will be conducted. An upgrade of the compressor will then be carried out using the outlined modular concept. The aim is to introduce what would be the first phase in a scenario whereby a company is in need of several axial compressors, which will be going into different engines, all with different design parameters. The modernism of this situation is to maximize common parts (core) without impacting efficiency and performance. A discussion of the benefits of the modular compressor design, as well as some of the design considerations and limitations will follow.

II. METHODOLOGY

2.1 Design Conditions

This section covers the design methodology; tasks and issues involved in bringing this concept to a point where the blading of the CM can be initiated with confidence. The first engineering task, after having been made aware that a number of compressors are to be designed, is to decide which of the compressors will be subdivided into modules. It is customary that the choice of which compressor to design first is made at a higher level in the organization. But, assuming it is up to the engineering community, and that there are more than two compressors to be designed, the preferred starting point is the middle compressor. This ensures that modular variations do not stray too far from the initial configuration. If two compressors are to be designed, then the larger one should be the focus of the modularization, and if possible, the smaller compressor should consist mainly of the core with minimal additions.

Given a set of design boundary conditions, Table 1, a modular approach is adopted for the design of all four compressors. Flow rate in Table 1 is non-dimensionalized by the HPC-2 flow. This thesis will focus on the meanline design of the compressor to be modularized, HPC-2, with a brief discussion of the most demanding upgrade, HPC-1. HPC-3 is intended to be a modular scale of HPC-2, and HPC-4 is a modular downgrade of HPC-2.

Table 1

Design Specifications and Boundary Conditions for Four (4) Different Compressors

	HPC - 1	HPC – 2	HPC 3	HPC – 4
Flow (-)	1.4	1.0	1.6	0.7
Pressure Ratio	25:1	13:1	18:1	9:1
RPM	9,700	9,000	8,000	10,000

After some initial considerations as to the given specifications, HPC-2 is chosen as the main compressor to be modularized, since it is the middle compressor. Considerations of the aerodynamic loading on all configurations, led to the choice of a total number of stages to be 10. Prior to meanline design, a brief and general discussion about aerodynamic loading and the interface stage is warranted, as well as a high-level study of the impact on aerodynamic speed to address whether a change in mechanical speed is necessary.

2.2 Aerodynamic Loading and the Interface Stage

The interface stage is defined as the first stage in the common core. In this case, it is the second stage in the HPC-2 configuration. It is the stage which will be subjected to the more extreme operating conditions in the four different configurations. Each configuration has the potential of presenting the interface stage with different operating conditions. A successful design for the interface stage will all but guarantee a stable core in all four configurations. In general, compressor stability depends on surge margin at a given operating condition, with specific surge inception mechanisms still under investigation by the compressor community. However, typically in a well-matched multi-stage compressor the front and rear stages rock about the middle stages as the compressor is throttled. Therefore, design-point stage-by-stage aerodynamic loading should appropriately consider this load shifting behavior and assign work coefficients accordingly.

To assess the stability of the core, the inlet flow function to the core is evaluated. Compressor off-design performance is characterized by pressure ratio variations with inlet flow function and depicted on a compressor map. Thus, minimizing the variations in inlet flow function should have a stabilizing effect on the compressor. The flow function (FF) is defined as:

$$FF = \frac{\dot{m}\sqrt{T_{o,inlet}}}{P_{o,inlet}} \qquad (1)$$

The core compressor, consisting of eight stages, Fig. 6, has a total pressure ratio of 7.35:1. This allows for a very well behaved compressor, with fairly soft characteristics. Soft characteristics are speed lines which span a fairly large range of flow function before running into the rotating stall and surge region of the map.

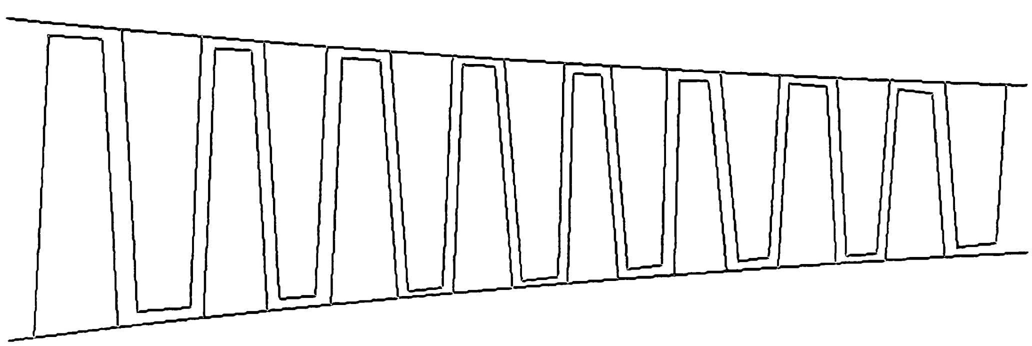


Figure 6. 8-Stage Common Core (CM).

The flow function entering the core compressor in the original configuration, HPC-2 (Table 1), is calculated using Eq. (1) above while accounting for the pressure and temperature rise in the first stage. This condition prescribes the design point for the core. In the upgrade configuration, HPC-1 (Table 1), it is required that the flow increases by 40%. To balance this requirement, and provide a similar flow function to the core for stability purposes, the pressure rise in the first two stages of HPC-1 must be carefully chosen. For a compressor stage total-to-total adiabatic efficiency, with constant C_p assumption, the equation is reduced to:

$$\eta_{tt,\,stage} = \frac{\pi^{\left(\frac{\gamma-1}{\gamma}\right)} - 1}{\left(\frac{T_{o,exit}}{T_{o,inlet}}\right) - 1} \qquad (2)$$

Given the inlet conditions, the total pressure ratio (π), and a reasonable estimate of the efficiency, the stage exit total temperature could be estimated easily and with confidence. For example, a stage having a total pressure ratio of 1.51:1 could easily be designed at a total-to-total adiabatic efficiency of 93%. Using Eq. (2), the total temperature will increase by approximately 11% across that stage.

With this formulation, and prior to embarking on the meanline design of HPC-2, it is necessary to assess if the conditions of HPC-1 could be met with minimal disruption to the core and to the performance of HPC-1 as well. The main question to be answered here is whether the assumption of replacing the single-stage FM in HPC-2 with a two-stage FM, for HPC-1, is feasible. For the core, with the 40% increase in flow, it is necessary that the term $\left(P_o / \sqrt{T_o}\right)$, Eq. (1), is augmented by approximately

40% as well. To simplify matters, the inlet flow function to the core is non-dimensionalized by dividing by a reference FF, defined as:

$$FF_{ref} = \frac{\dot{m}_{inlet,HPC-2}\sqrt{T_{o,inlet,HPC-2}}}{P_{o,inlet,HPC-2}} \tag{3}$$

An iterative sensitivity study was conducted, and a stage pressure ratio of 1.51:1 was chosen for the first stage (FM) of HPC-2, operating at 93% efficiency. The core flow function, as prescribed by the HPC-2 configuration, can be written in terms of the reference FF as follows:

$$\begin{aligned} FF_{core,HPC-2} &= \frac{\dot{m}_{inlet,HPC-2}\sqrt{(1.11)T_{o,inlet,HPC-2}}}{(1.51)P_{o,inlet,HPC-2}} \\ FF_{core,HPC-2} &= 0.70\,FF_{ref} \end{aligned} \tag{4}$$

For the upgraded configuration, and after some iterative calculations, stages 1, and 2 were assigned total pressure ratios of 1.56:1, and 1.48:1, respectively. Their total-to-total efficiencies were estimated at 87%, and 91%, respectively. Using Eq. (2), the total temperature rise is expected to be 13.5%, and 11.5%, respectively. Therefore, the FF entering the core, as prescribed by the HPC-1 configuration can now be determined as:

$$FF_{core,HPC-1} = \frac{1.4\,\dot{m}_{inlet,HPC-2}\sqrt{(1.135)(1.115)T_{o,in,HPC-2}}}{(1.56)(1.48)P_{o,inlet,HPC-2}}$$
$$FF_{core,HPC-1} = \frac{1.4\sqrt{(1.135)(1.115)}}{(1.56)(1.48)}FF_{ref} = 0.682\ FF_{ref} \tag{5}$$

It is evident, by comparing the results of Eqs. (4), and (5), that the flow function entering the core changes by less than 2.6% between the two configurations. An exact match can be achieved by iterating on the pressure ratios for the FM of HPC-1. The portion of the desired increase in total pressure ratio for HPC-1, not provided by the FM, can now be provided by the RM.

To further study the stability of the core, an assessment of the aerodynamic speed is needed to determine whether a change in mechanical speed is warranted. Aerodynamic speed, termed NRT, is defined as:

$$NRT = \frac{rpm}{\sqrt{T_{o,inlet}}} \tag{6}$$

The total temperature at the inlet to the core for the HPC-1 configuration will be larger than for the original HPC-2 configuration. If this increase is substantial, the core could operate with significantly lower aerodynamic speed, i.e., to the far left side of the map. This may cause the core to operate dangerously close to its surge margin. Using the above method for evaluating the FF, the aerodynamic speed is assessed at the inlet to the core. A reference speed is defined as follows:

$$NRT_{ref} = \frac{rpm_{HPC-2}}{\sqrt{T_{o,inlet,HPC-2}}} \quad (7)$$

Thus, an aerodynamic speed for the core is calculated for both the HPC-2 [original] and the HPC-1 configurations as follows:

$$\begin{aligned} NRT_{core,HPC-2} &= \frac{NRT_{ref}}{\sqrt{1.115}} = 0.947\ NRT_{ref} \\ NRT_{core,HPC-1} &= \frac{NRT_{ref}}{\sqrt{1.135(1.115)}} = 0.888\ NRT_{ref} \end{aligned} \quad (8)$$

As shown, the core aerodynamic speed for HPC-1 has been decreased to 94% of its value for HPC-2. This drop, for today's highly loaded compressors, may not be acceptable, even with the core module designed to be moderately loaded; having a 7.35:1 pressure ratio and 8 stages. The best available option is to consider increasing the mechanical speed of the HPC-1 configuration. The speed needs to be increased by the ratio of the square root of the temperature ratio of the air entering the interface stage; an increase of 7.77% (to 9,700 rpm) would bring the aerodynamic speed to within 1.05%. Other potentially acceptable combinations exist, all made possible by a careful design of the interface stage and sufficient pre-planning.

2.3 Meanline Design

The 10-stage HPC-2, shown in Fig. 5(a), has the stage pressure ratio distribution shown in Fig. 7. The HPC-1 stage pressure ratio distribution is overlaid on top of the HPC-2 distribution to further illustrate the modular upgrade concept. A common core is shared; stages 3 through 10.

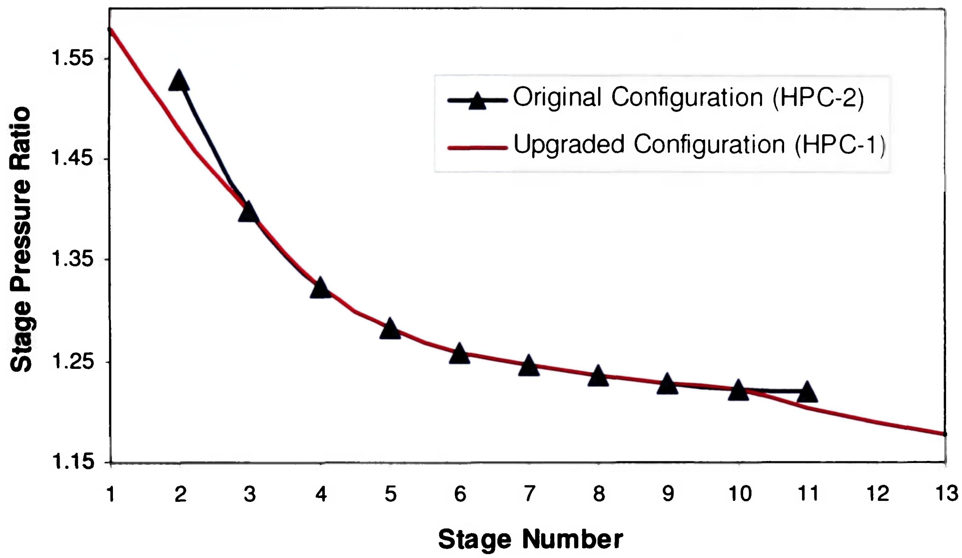


Figure 7. Proposed Stage Pressure Ratio for the 10-stage HPC-2 and the 13-stage HPC-1 Modular Upgrade.

The stage work coefficient distribution in Figure 8 is a typical one for highly loaded compressors, with the objective being to load the front of the compressor for optimum performance. The FM of HPC-2 is represented by the blue line, stage 2; while its modular upgrade for the HPC-1 is represented by the red line, stages 1, and 2. However, Stage 3, which is the first stage in the common core, has been assigned a slightly decreased duty.

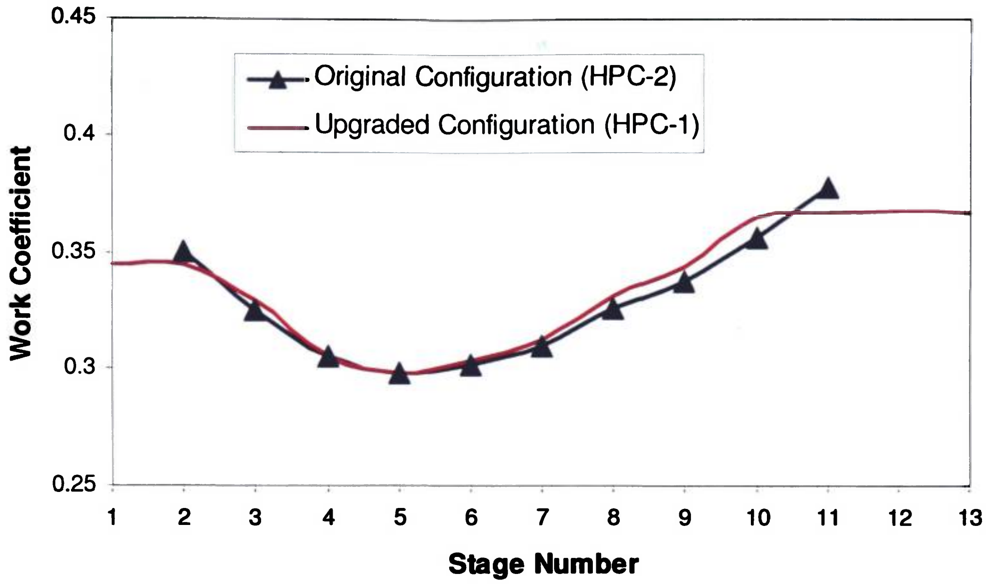


Figure 8. Proposed Stage Work Coefficient for the Original (HPC-2) and Upgraded (HPC-1) Configurations.

The Degree of Reaction is shown in Fig. 9, and depicts a typical distribution as well. Degree of reaction is defined as:

$$R = \frac{\Delta h_{rotor}}{\Delta h_{o,stage}} = \frac{\left(\frac{1}{2}W_1^2 - \frac{1}{2}W_2^2\right)}{\left(\frac{1}{2}W_1^2 - \frac{1}{2}W_2^2\right) + \left(\frac{1}{2}V_2^2 - \frac{1}{2}V_1^2\right)} \tag{9}$$

Special consideration is taken on assigning a value of degree of reaction for the interface stage, stage 3. This is consistent with the reduced aerodynamic duty for this stage, as depicted in Fig. 9 and discussed above. Higher degree of reaction means more compression in the rotor blade, and a higher static enthalpy change. Therefore, for the same stage pressure ratio and stator exit conditions, a higher DeHaller Number for the stator is prescribed for added stability. DeHaller number (DH) is an acceptable preliminary measure of stability, and is defined as the stator exit to inlet velocity ratio:

$$DH = \frac{V_3}{V_2} \tag{10}$$

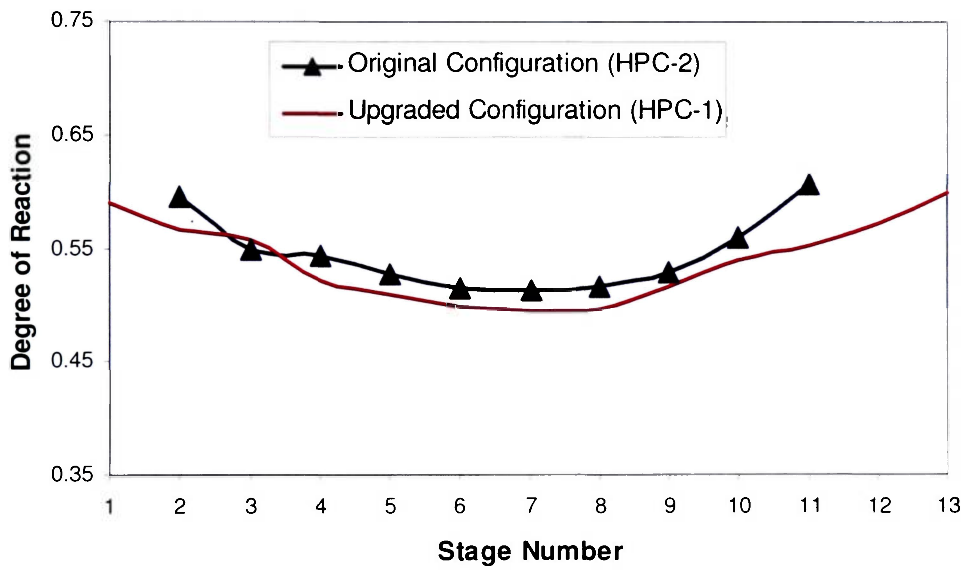


Figure 9. Proposed Stage Degree of Reaction for HPC-2, and its Modular Upgrade, HPC-1.

The proposed distribution of flow coefficient is shown in Figure 10 for completion. Where the flow coefficient is defined at the exit of the rotor:

$$\varphi = \frac{V_{ax,2}}{U_2} \tag{11}$$

With the meanline design completed, confidence in the stability of the core compressor is established. A brief discussion of some mechanical and geometrical issues is warranted to complete the design.

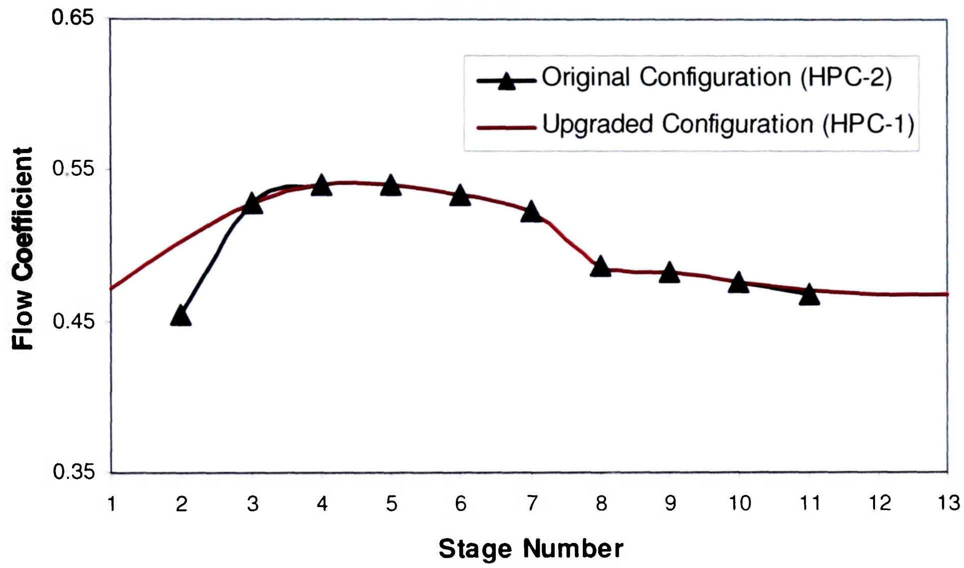


Figure 10. Proposed Stage Flow Coefficient for HPC-2, and its Modular Upgrade, HPC-1.

2.4 Mechanical and Geometric Considerations

For geometric considerations, the core compressor should be designed to facilitate the geometric additions of the upgraded modules. The core compressor is shown in Fig. 6. As shown, the hub and tip hade angles at the inlet and exit are mild. Hub and tip hade angles are the angles between the hub, and tip lines, and the X-axis, respectively. A core compressor with an excessively ascending hub, for instance, will be very difficult to add a front stage to. This will endanger the modular upgradeability of the compressor, and if allowed to proceed, will jeopardize performance and quickly erode any cost savings. In similar fashion, other geometric features should be considered as well, such as airfoils aspect ratios, for instance.

The mechanical robustness is also very important to the success of this approach. Having to redesign any of the core airfoils for mechanical reasons will also erode much of the cost savings realized by having a common core. To prevent this from happening, tuning and mechanical stresses should be considered with care. For mechanical stresses, the airfoils of the core compressor should be analyzed under the most extreme conditions; those belonging to the configuration with the largest flow rate, HPC-1. For tuning, the change in mechanical speed (7.77%), which was suggested above in the section entitled "Aerodynamic Loading and the Interface Stage", if allowed to proceed, is to be taken into consideration. The natural frequencies of the core airfoils are to be calculated at both rpm ranges and plotted concurrently on their respective Campbell Diagrams. Crossings are to be avoided particularly at the lower frequencies that can be easily excited. However, this potential problem must not be allowed to sit until the blading phase, but must be fully engaged during the conceptual phase by forming an integrated product team [6] consisting of aerodynamic as well as mechanical engineers, as discussed in the next chapter. Historical Campbell Diagrams can be collected and studied for like-size airfoils since detailed FEA computations are not feasible at this stage. Additional tuning considerations exist for the front and rear 1-2 stages of the core, depending on the prevailing design philosophy. For instance, a different FM for HPC-1 will most likely employ a different number of airfoils. This will mean that the frequency drivers will be different for the interface stage for the two configurations. The interface stage must be designed such that the natural frequencies of the airfoils are tuned to avoid the drivers of all applicable FMs. If possible, the designer is directed to attempt to employ the same number of airfoils. Aerodynamic loading issues can be remedied by managing the airfoil chord or 3D stacking, for example, to provide sufficient stability.

2.5 Summary of Methodology

The successful modular design must consider a few issues at the onset. Paramount is the stability of the core compressor. This is accomplished by carefully considering the inlet flow function, as well as the corrected speed, as discussed. The interface stage must be designed to be fairly insensitive to the different configurations. Lowering its expected work is a good starting point. Designing airfoils capable of handling much incidence swings without significant increase in losses is another enhancement. Mechanical and geometric issues should also be carefully evaluated, as presented. Many of these issues are easily treated and remedied, provided that sufficient planning is carried out before the blading phase. A generalized approach to understanding and evaluating the benefits afforded by the modular concept is outlined in the conclusions and recommendations section.

III. COMPUTER PROGRAMS SUMMARIES

3.1 Preliminary Design in Microsoft Excel

The principal purpose for preliminary design of a high-pressure compressor is: (1) to obtain a clear picture of the aerodynamic and thermodynamic properties, (2) establish the dimensions of the compressor, and, (3) use the preliminary design as a check on the final design. It is not expected that these preliminary design calculations be precise, but rather they should be within an accepted tolerance.

Microsoft Excel was employed to handle the robust and numerous aerodynamic and thermodynamic calculations required for such a preliminary design. Inlet conditions were taken from a standard commercial airliner with high-bypass turbofan engines; an altitude of 30,000 feet and flight Mach number of 0.85 were used. A pressure ratio value of 3.0 was given to the fan and intermediate-pressure compressor (IPC); this value would be used along with the boundary conditions, shown in Table 1, for configurations 1 and 2. The fan and IPC were not to be designed in this process; the focus in this thesis is entirely on the high-pressure compressor section.

The design of the baseline compressor, HPC-2, was done around the control of the stage pressure ratios, axial velocities, and exit air angles with a constant radius of the centerline of the compressor. The "goal seek" command in Excel was used for iterative solving and macros were used to speed up recurring processes. Graphs were plotted from the data and used for visual trending. The data was then properly formatted to create the input files of the design codes.

3.2 Data Grouping in Matlab

The outputted data created by the through-flow codes was in the form of a text file. The data was grouped by blade rows and broken down within those stations by inlet and exit conditions and streamline numbers. The codes themselves did not allow for the data to be directly plotted and opening the txt file in Microsoft Excel would not have guaranteed proper entry into the cells.

To handle the large amounts of raw data, a Matlab code was written to read the entire data file, and then using a series of 'for' loops, pull the out required data. With HPC-2 having 10-stages, plus IGV and OGV, there were 22 blade rows. Similarly, HPC-1 was comprised of 13-stages, plus IGV and OGV, thereby having 28 blade rows. Two-dimensional matrices were used for the majority of the variables, reading in both the inlet and exit conditions for each streamline in every blade row.

While Matlab has the full capability to plot graphs, the data was written into an Excel spreadsheet; some of the output data was given in the form of a ratio to the inlet values and final calculations were carried out. With the data organized on spreadsheets in Excel, graphs along the axial locations at mid radius were plotted to investigate the trends. For the inlet values to the interface stage, radial distribution graphs were plotted to see the trends from hub to tip. These graphs can be seen in the next chapter, Results and Analyses.

3.3 First Through-Flow Code Attempt: UD0300M

3.3.1 History of UD0300M

UD0300M is a computer program that was developed for the design of axial compressors in turbine engines. UD0300M was created in the early 1980's at the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. The purpose of the program is to perform, during a single run, an aerodynamic analysis of the flow within the compressor, determine the geometry of the compressor blading, and compute the compressor performance, [7]. While the program consists of two sections, blade geometry definition and aerodynamic analysis, this work would only need the latter.

The flow through the compressor is assumed to be axisymmetric and inviscid. The fluid properties are computed for a perfect or ideal gas. The streamline curvature method of solution is employed to solve the system of equations. The momentum equation includes entropy gradients in the cross-streamwise and streamwise directions, and also the blade forces, [7].

3.3.2 Discussion

With the code being written in Fortran77, it was time consuming to create the input files because of the formatting requirements with the text file. While the results from this program were useful, a complete convergence of the 10-stage compressor was not obtained.

3.4 Turbomachinery AXIsymmetric Design Code: T-AXI

3.4.1 History of T-AXI

T-AXI is a turbomachinery design system described in [8]. T-AXI uses an inviscid, axisymmetric solver based on multiple interacting streamtube Euler equations. The input files, wall.xxx and stack.xxx were created from the preliminary design of HPC-2 & later HPC-1. The 'xxx' in the filenames are labeled 'hpc-1' & 'hpc-2'. The wall files hold the annulus and blade dimensions and the stack files contain the inlet conditions, blade count, blade dimensions, and angular momentum.

The format and input variables differed from that of UD0300M, but this allowed for the systematic production of the walls and stack files from the preliminary design in Excel.

3.4.2 Convergence of HPC-2

The initial convergence of HPC-2 was relatively quick compared with the previous runs in UD0300M. With the annulus and blade dimensions firm, the angular momentums were modified by percentages of less than ten for both the rotors and stators. The outputted data file was run through the Matlab code to give a visual representation and trending of the compressor. From this point, sensitivity studies were performed to fine tune HPC-2, with much scrutiny being placed on the interface stage to reduce the chances of difficulties arising with the upgrade. With the creation of the Matlab code and the link to the Excel spreadsheet, if changes were made to the input file, the new graphs were available relatively quickly to verify the new design. The ability to make minute changes and see the immediate effects was an advantage.

3.4.3 Extracting the "Core"

The majority of the values in the input file were required to be non-dimesionalized by the leading edge tip radius of stage one rotor. After conferring with Dr. Turner, creator of T-AXI, the geometric data was non-dimensionalized by the leading edge tip radius of stage 3 (interface stage) rotor to insure that the input data of the core would be identical for both configurations. With a smooth trend of HPC-2, the IM, FM, RM, and EM, the geometric and aerodynamic data was removed from the input files to prepare for the buildup of HPC-1.

3.4.4 Building HPC-1 Around the "Core"

It was necessary at this point to go back to the preliminary analysis with the geometry of the core, which was now frozen, and examine the annulus transition from the FM into the core and from the core to the RM. The annulus shape was smoothed and multiple second-order polynomials were used to define the shape axially. The IM, FM, RM, and EM which defined the 13-stage HPC-1 configuration were non-dimensionalized and wall.hpc-1 and stack.hpc-1 were created.

IV. RESULTS AND ANALYSES

4.1 Inferface Stage

The resulting data for the core did not immediately line up with HPC-1 when first running the preliminary data for HPC-2. As discussed in earlier sections, the correct merge of the interface stage with the front module of HPC-2 would be the key to the stability of the core. The trick to this is that the second stator of HPC-2 must give the same corrected flow and angles as the first stator in HPC-1 as well as the adjustment in the aerodynamic speed based on the square root of the total temperature entering the core. Recalculating NRT using equation 6, Table 1 shows the values from the data outputted by T-AXI.

Table 2

Aerodynamic Speed for HPC-1 and HPC-2

	Aerodynamic Speed $(RPM/\sqrt{K})$
HPC-1	468.115
HPC-2	467.681
% Difference	0.09%

With the corrected aerodynamic speed virtually identical, managing the flow function and velocity triangle entering the core of HPC-2 was the next task to bring the two conditions within range. While always maintaining the integrity of the core, the adjustments were easily made to the FM, the first two stages, of HPC-2 by controlling the absolute tangential velocities. With these changes implemented the velocity triangles, Figure 11, line up to almost match, illustrating that the flow is entering the core for both HPC-1 & HPC-2 at the same angles and velocities. The radial distribution of the relative flow angle, Figure 12, also shows a good match.

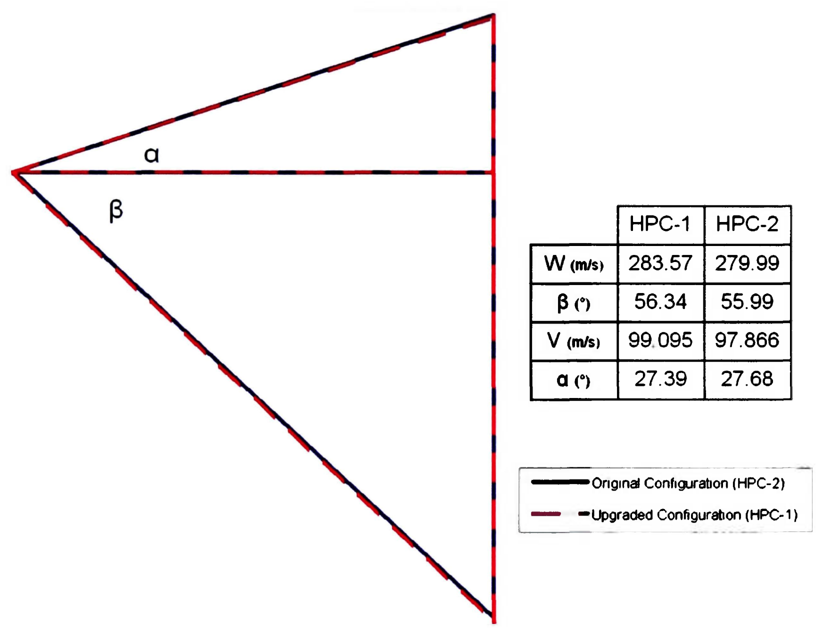


Figure 11. Core Inlet Velocity Triangles at Mid-Radius for HPC-1 and HPC-2.

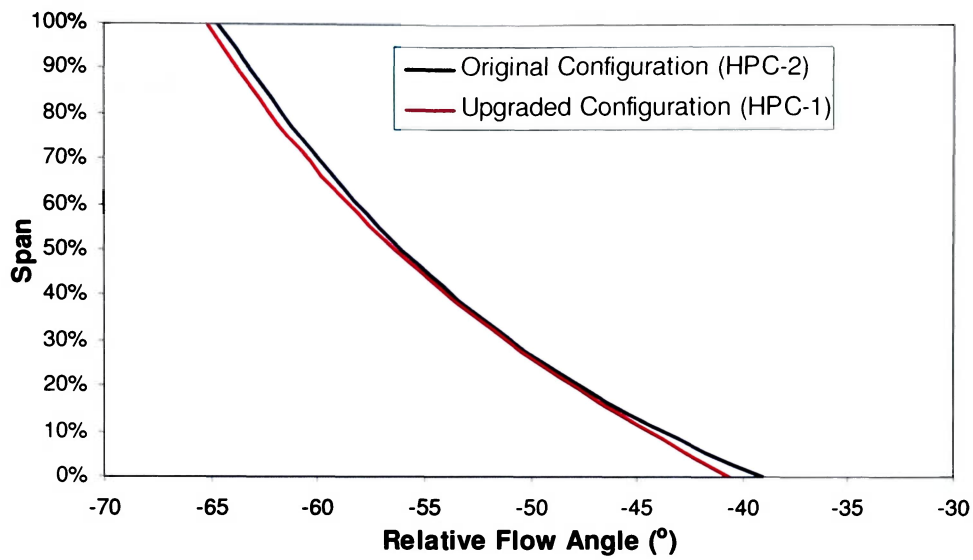


Figure 12. Throughflow Results: Inlet Relative Flow Angle (β) at the Interface Stage for HPC-1 and HPC-2.

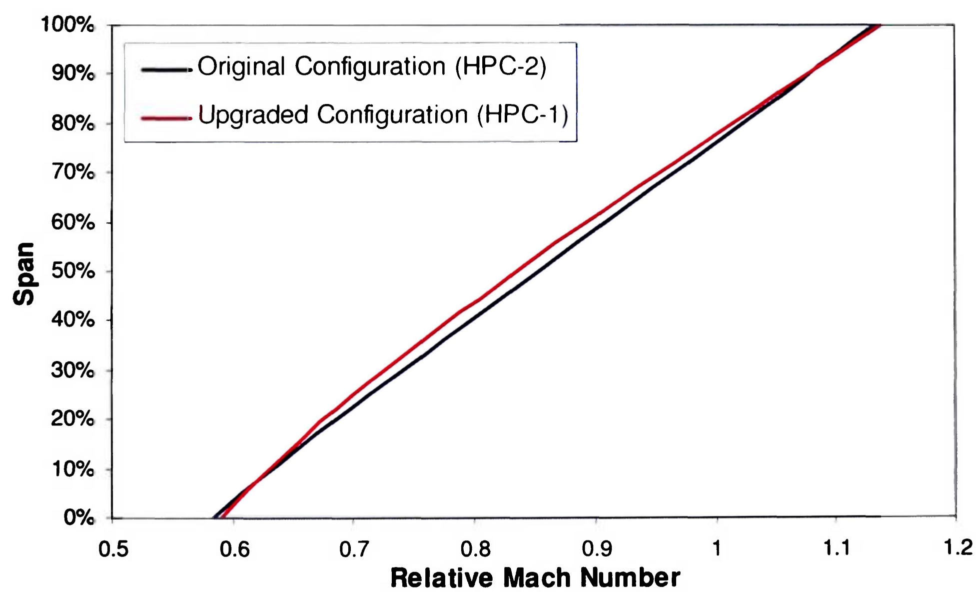


Figure 13. Throughflow Results: Inlet Relative Flow Mach Number at the Interface Stage for HPC-1 and HPC-2.

Figure 13 shows the inlet relative Mach Number at the Interface Stage. The close match provides the final proof of the achievability of the concept.

Using the flow function equation, Eq. 1, with the T-AXI data entering the rotor of the interface stage for both configurations, the flow function for HPC-1 & HPC-2 were found to be 97.590 and 95.804 {(kg/s)√(K)/psi}, respectively. The calculated percent difference for flow function between the two configurations is 1.83%.

4.2 Graphical Comparison

While the results of HPC-2, which were obtained prior to any design of HPC-1, show smooth trend lines, the reader is invited to pay close attention to the proximity of the core data, stages 3 through 10, in the graphs that follow. The graphs for HPC-1 & HPC-2 have been overlaid to illustrate the achievability of the modular concept.

The proposed stage pressure ratio in Figure 7 and the outputted data from T-AXI of the stage pressure ratio in Figure 14, show an identical trend as well as very similar numbers. Table 3 shows the overall pressure ratios for both the core and the compressor for HPC-1 & HPC-2. The pressure ratio of the core module differs by less than 1% for both compressors.

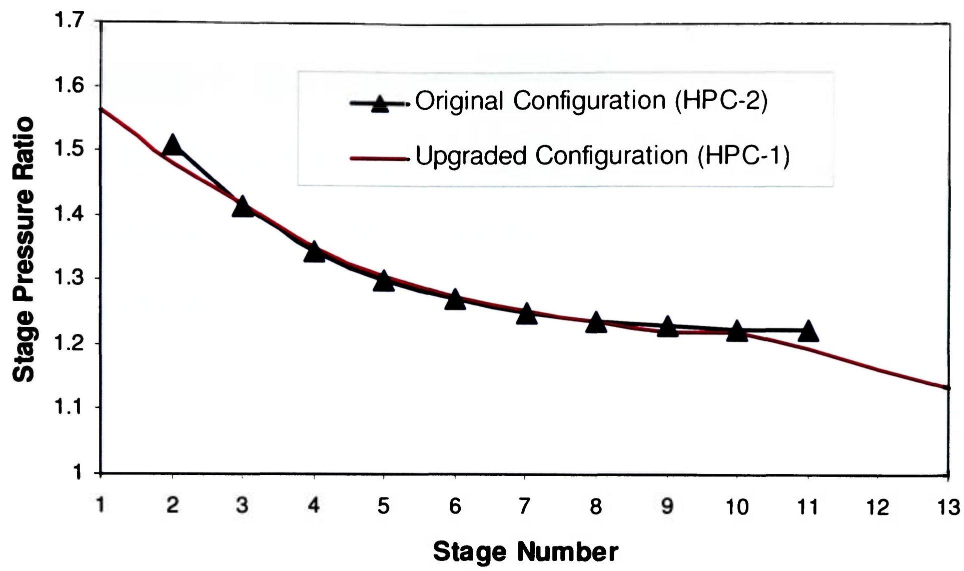


Figure 14. Throughflow Results: Stage Pressure Ratio for the 10-stage HPC-2 and the 13-Stage HPC-2 Modular Upgrade.

Table 3

Overall Pressure Ratio and Core Pressure Ratio for HPC-1 and HPC-2

	Overall Pressure Ratio	Core Pressure Ratio
HPC-1	27:1	7.39:1
HPC-2	13.5:1	7.35:1

When graphically representing the work and flow coefficient values from the T-AXI output in Figures 15 and 16, it is shown that the values are in the same ranges as the proposed graphs, Figures 8 and 10, but a smoother trend line is present. An important observation here is that the work and flow coefficients for the rotors of the interface stage, stage 3, are very similar. The work coefficient, Figure 15, also shows that the earlier stages, IM, FM, and interface stage are not required to overwork.

The author also took into consideration the possibility of removing the last stage of HPC-1, stage 13. This would still have given an overall pressure ratio of 24:1 and there was confidence that stage 12 would be able to accommodate for the necessary requirements. The modular concept would have allowed for a simple procedure to modify the RM.

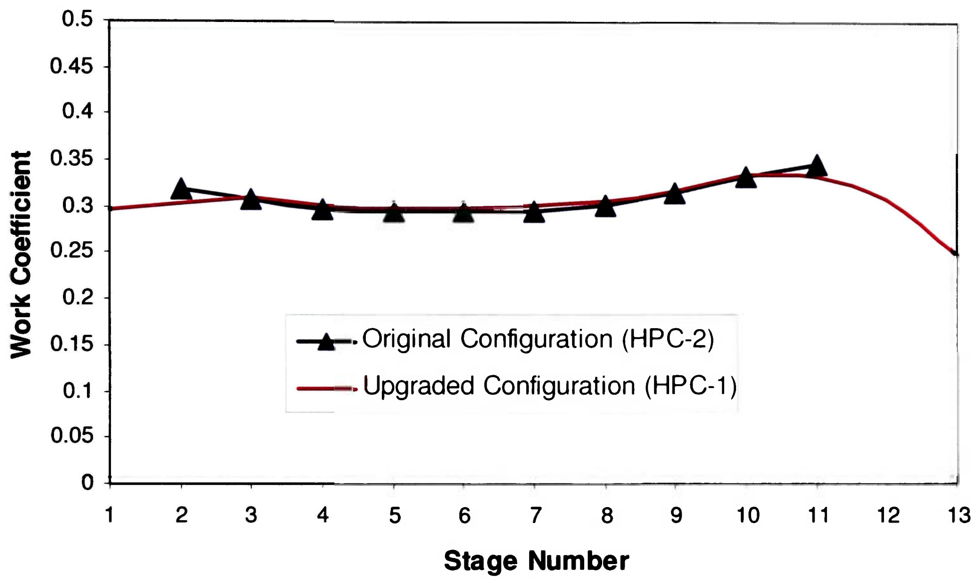


Figure 15. Throughflow Results: Stage Work Coefficient for the Original (HPC-2) and Upgraded (HPC-1) Configurations.

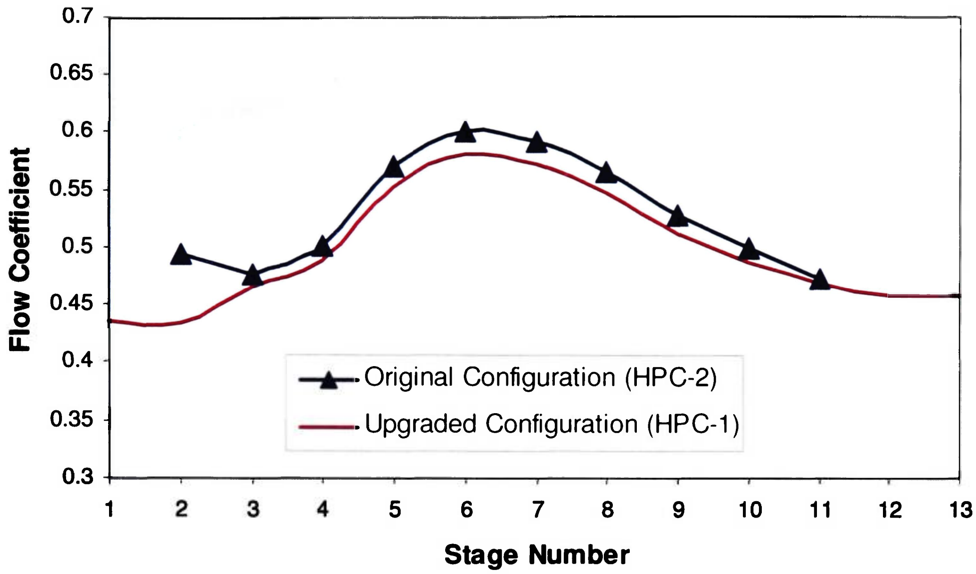


Figure 16. Throughflow Results: Stage Flow Coefficient for HPC-1, and its Modular Upgrade, HPC-2.

In Figures 17 and 18, the adiabatic and polytropic efficiencies are shown, respectively. Efficiency for the IM and FM were assumed in preliminary analysis to be lower. This was done in anticipation of irregular aerodynamic duty, as was discussed.

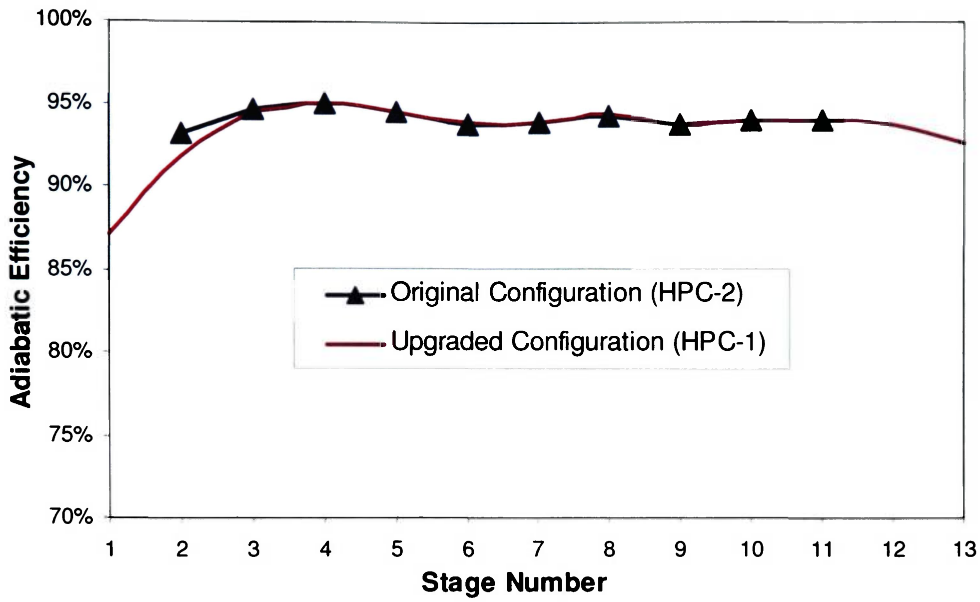


Figure 17. Adiabatic Efficiency for HPC-1, and its Modular Upgrade, HPC-2.

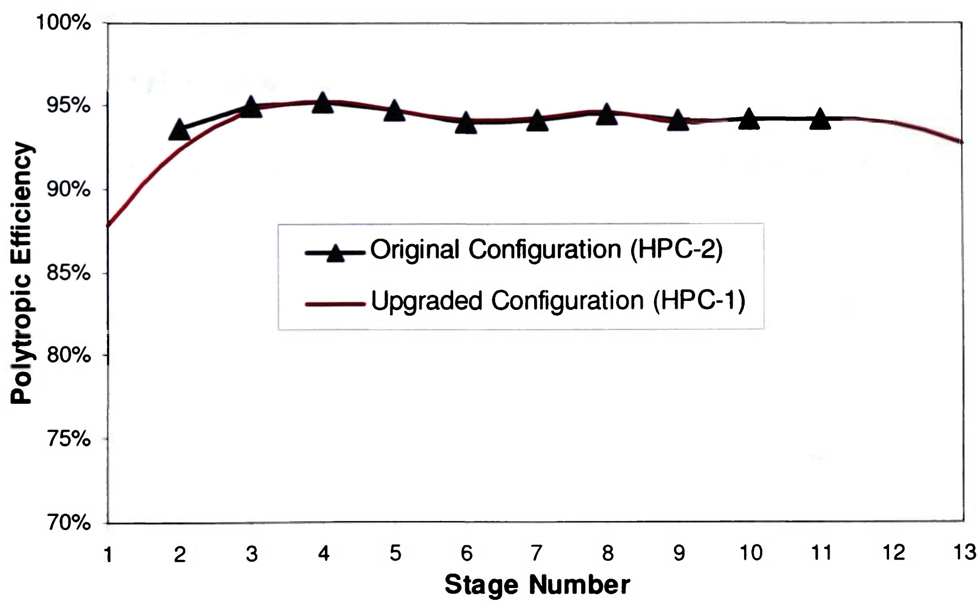


Figure 18. Polytropic Efficiency for HPC-1, and its Modular Upgrade, HPC-2.

V. CONCLUSIONS AND RECOMMENDATIONS

5.1 Benefit Analysis

In this section, the various benefits of this concept are discussed in detail. Affordability explains how to effectively judge a modular upgrade versus a clean sheet design. The section on development and maintenance cost reduction outlines some of the gains to be seen in those areas from adopting the modular concept. And part commonality touches on the concept of Lean Engineering and how to effectively use an integrated product team (IPT) to build a better compressor.

5.1.1 Affordability

For an organization to decide to pursue a component upgrade, a cost-benefit analysis is in order. This analysis has morphed over time into an assessment of the affordability of the proposed change. Affordability is defined in general as the change (or increase) in capability divided by the change (or increase) in cost, [5]. Fitting this definition to a gas turbine engine with the thrust to weight ratio and Thrust Specific Fuel Consumption (TSFC) being the key factors driving the capability term, the gas turbine engine affordability index is defined as:

$$\frac{\Delta Capability}{\Delta Cost} = \frac{\Delta\left(\frac{(T/W)_{\max power}}{TSFC_{SLS}}\right)}{\Delta Cost_{Dev} + \Delta Cost_{\Pr} + \Delta Cost_{Maint}} \tag{12}$$

Where:

$\Delta T/W_{MaxPower}$ ≡ Change in Engine Thrust to Weight ratio at maximum power, Sea Level Static

$\Delta TSFC_{SLS}$ ≡ Change in Thrust Specific Fuel Consumption, Sea Level Static

$\Delta Cost_{Dev}$ ≡ Change (Increase) in Development Cost

$\Delta Cost_{Pr}$ ≡ Change (Increase) in Production Cost

$\Delta Cost_{Maint}$ ≡ Change (Increase) in Maintenance Cost

While affordability has become the top priority for both military and commercial aircraft engine groups, they are no longer satisfied with small cost savings here and there, but rather with reaching a goal that is significant, yet feasible. The suggested goal in the turbine community is to provide an order of magnitude improvement in the affordability index, [5].

To narrow this definition to the compressor component, the capability term can be re-defined as being driven by the flow and pressure ratio of the compressor. The cost term maintains the same formulation but with a more focused scope; towards compressor costs only. The affordability index for the compressor component then becomes:

$$\left(\frac{\Delta Capability}{\Delta Cost}\right)_{comp} = \frac{\Delta\pi \,.\, \Delta\dot{m}}{\Delta Cost_{Dev} + \Delta Cost_{Pr} + \Delta Cost_{Maint}} \qquad (13)$$

The value of the modular concept becomes clearly evident by examining the above equation. The three components of the cost term are greatly reduced for a modular upgrade versus the cost of a clean sheet design, significantly increasing its affordability, and consequently, its profit margin.

5.1.2 Development and Maintenance Cost Reduction

The development of an axial compressor is a multi-discipline exercise. Initially there is the meanline design defining the annulus geometry, number of stages, and axial and radial work distribution. Throughflow analysis provides boundary conditions for blading. Often, lengthy iterations are carried out between the aerodynamicist and mechanical engineer to design an airfoil that performs well, but also one that is well tuned and meets the minimum criteria for mechanical integrity and life. In addition to the above, there is also the design of the attachments such as blade and stator roots, disks, and casings. Bleed extraction circuits, and bleed cavities are also important design considerations. Upon detailed drafting and modeling, and specifying the material, procurement is engaged to negotiate for the right parts at the best prices. Manufacture then sets up for the production phase via tooling, machining and final assembly. An extensive testing phase follows, prior to commissioning and mass production. Assuming that there are no problems, it is typical for a company to spend 2-3 years to bring a compressor from the proverbial drawing board to its first test flight. This is why most companies rarely embark on a clean sheet design, but rather they try to increment old designs.

Incrementing existing designs is an exercise that soon runs into several dead ends. Geometry can be one such hurdle; hub and tip hade angles can limit the extrapolation of the annulus to add stages or, at the very least, hinder the efficient design of the new disks. The performance of the existing compressor is also in question when altering the inlet flow function as prescribed by the new configuration. Lastly, the existing airfoils may not have sufficient stress margins to handle the increase in flow, which leads to a proportional increase in aero loads. While all of these are insurmountable obstacles that lead to minimizing performance gains from incrementalism, it is clear to see that they could be easily remedied during the initial design phase, with sufficient pre-planning.

Having sufficiently planned ahead for upcoming compressors, the core module is designed first, bladed and tested. Upon the successful completion of the CM, many of the upcoming compressors parts are instantly ready for production. When the modular upgrades are initiated, it is easy to see how only a small fraction of the budget for a new compressor is needed. Additionally, with the increased lead time, procurement and manufacturing can further streamline and cut cost.

Service and maintenance assembly and disassembly tools, replacement parts, expertise, and instructions manuals are readily available. Part numbers and drawing numbers are already common leading to the reduction of mistakes on the shop floor, and during purchasing, and shipping. This allows the organization to realize substantial savings and pass them on to the customer securing the order. This can also secure future service contracts at greater margins, a major objective of all engine companies.

5.1.3 Part Commonality

Lean Engineering is quickly becoming a household phrase in the aerospace industry. The concept of lean is based on the elimination of waste, as outlined by Murman et al [6]. Lean manufacture and lean supply chain management increase the efficiency of the organization through continuous improvement and enhanced productivity after the product has been designed and drawings issued. However, recent studies have shown that up to 80% of the product LCC is embedded in the proverbial product DNA before drawings are completed. The role of Lean engineering then is to consider the issue of waste elimination during the design phase.

Much of this is accomplished via intelligent use of the Integrated Product Team (IPT) concept. An effective IPT will be composed of representatives from each stakeholder organization within the enterprise, [6]. The definition of a stakeholder organization is any and every group which will come in contact with the product, and whose financial performance is impacted by this product. This includes engineering, procurement, sales and marketing, manufacture, service, and often suppliers and vendors. Each organization is called upon to contribute to the design requirements, and engineering is tasked with satisfying as much of the "wish lists" as possible.

One of the most beneficial outcomes of an IPT, through lean engineering, is the reduction of overall part count. One way to achieve this goal is by maximizing common parts among various components. Consider the compressor example presented; during the development phase, aeromechanical iterations are eliminated for the common core airfoils, and so are 3D models for CNC machining, for instance. Attachments such as roots, platforms, and shrouds, already exist, so do disks, casings, and bleed ports and cavities. Procurement can now negotiate a lower price through volume purchasing of a smaller number of parts. Vendors and suppliers also realize substantial savings and will eventually pass them on. Quality assurance has fewer parts to manage. Manufacturing will spend less on tooling and assembly. The chance for mislabeling, or assembling the wrong components, when more than one configuration is on the shop floor at the same time (a common occurrence) is completely eliminated for the core module. Common part numbers, and assembly instructions and tools, further simplify and streamline maintenance and service across the fleet.

The number of different parts required for four "Leaned" modular axial compressors compared to four axial compressors without the use of Lean Engineering is illustrated in Figure 19. The source of the data in Figure 19 is extrapolated from a recent design of a 16-stage axial compressor for industrial application. The trends of the numbers are consistent with current aerospace industry practice and the validity of the numbers were compared to the high pressure compressor section of a General Electric CF6-6 located in the Gas Turbine Research Laboratory at Embry-Riddle Aeronautical University, Figure 1. The purpose of Figure 19 is to illustrate the significant savings gained using the concept of lean engineering; to show a small glimpse of the effectiveness of modularizing an axial compressor. This is clearly not just an incremental change but rather a leap in the ability to eliminate waste. The reduction in the numbers of different parts required instantly condenses the part Research & Development and procurement processes, and therein a domino effect begins eliminated waste and creating value in all the processes and phases in the Life Cycle.

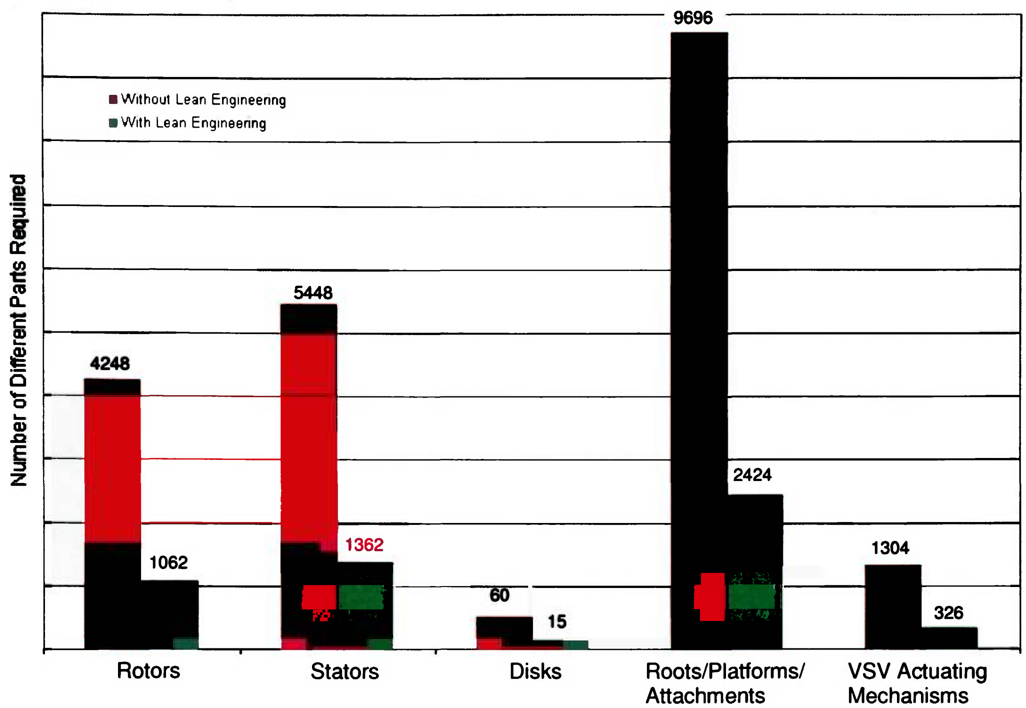


Figure 19. A Comparison of Number of Different Parts Required for Four (4) Axial Compressors

The basis of the modularization of an axial compressor goes hand in hand with concept of lean engineering. The method reported in this thesis is an outline of the procedures to approach the design and development of different compressors (modular upgrades) at the same time. The significance of this method is that while you are developing and designing the components you are creating value, once the design is complete, you begin to eliminate waste through the ways mentioned above.

After reviewing the concepts and procedures prescribed in [6], the best way to apply lean engineering to an axial compressor was through a modular approach. The design of the 4 lean compressors is ongoing and the method discussed in the thesis is most definitely being used maintaining the practice of lean engineering.

The gains in the modularization process will not be cost free, but while the aerospace industry is characterized by having greater complexity and higher degrees of cyclicity (Murman et al [6]), the ideas of this Lean strategy will have extensive cost savings. This concept leaves the door open to future technological upgrades and entails no restrictions on the possibilities of performance and effectiveness.

5.2 Conclusion

The concept of modular multistage axial compressor design has been presented. The concept prescribes a division of the compressor into 5 modules, with the intent being to maximize the size of the core module. This module is then designed (and bladed) with sufficient robustness to handle the possible upgrades, and downgrades. Pre-planning this process, in anticipation of the coming upgrades, is the key success factor. An example design is analyzed using an inviscid, axisymmetric solver based on Euler's turbomachinery equations. Aerodynamic issues are addressed and mechanical issues are discussed. Substantial cost savings can be realized by adopting this approach. The savings impact all phases of the LCC including development, procurement, tooling and manufacturing, maintenance, as well as the ability of the organization to offer the customer future upgrades at substantial margins.

REFERENCES

[1] Cohen, H., Rogers, G.F.C., Saravanamuttoo, H.I.H., 2001, *Gas Turbine Theory*, 5th ed., Prentice Hall, New York, NY, pp. 145-148.

[2] Duvall, T.J., Goetz, T.J., 1977, "A Study of Opportunistic Replacement Tactics for Modular Jet Engine Management," LSSR-29-77A, Wright-Patterson Air Force Base, OH.

[3] Lehmann, E.A., 1979, "Multiple Application Core Engine: Sizing and Usage Criteria," AIAA 79-1123, presented at the AIAA/SAE/ASME 15th Joint Propulsion Conference, Las Vegas, NV.

[4] Skira, C.A., 1995, "Cost Reduction of Advanced Turbine Engines," AIAA 95-3024, presented at the AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, San Diego, CA.

[5] Stricker, J.M., 2002, "Turbine Engine Affordability," AIAA 2002-3619, presented at the AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, IN.

[6] Murman, E., Allen, T., Bozdogan, K., Cutcher-Gershenfeld, J., McManus, H., Nightingale, D., Rebentisch, E., Shields, T., Stahl, F., Walton, M., Warmkessel, J., Weiss, S., and Widnall, S., 2002, *Lean Enterprise Value*, Palgrave, New York, NY.

[7] Law, H., Puterbaugh, S., 1982, "A Computer Program for Axial Compressor Design (UD0300M)", AFWAL-TR-82-2074, Wright-Patterson Air Force Base, OH.

[8] Turner, M., Merchant, A., and Bruna, D., 2006 "A Turbomachinery Design Tool for Teaching Design Concepts for Axial-Flow Fans, Compressors, and Turbines", ASME GT2006-90105, presented at the ASME IGTI Turbo Expo, Barcelona, Spain.

APPENDIX

T-AXI Input Files

HPC-2 (stack.hpc-2)
The overall information for each blade row is:
Number_of_blades rotation_speed Hub_clearance Tip_clearance
Geometry, loss, blockage and angular momentum are input starting at the hub
r_le r_te x_le x_te Loss Blk rV_theta

```
1.399057  583.9587   0   1.173550313 8.8211906E+06  1   1
```

Above are gam, TT_in(deg R), type(0-comp, 1-turb), ma, Re, BL switch & visc flag

```
16        0.000000  0.000000  0.000000
0.485041  0.485041  0.008783  0.160607  0.000000  0.030000  0.205871
1.076778  1.076778  0.000000  0.178617  0.000000  0.030000  0.205871
999.000000
18        1.287412  0.000000  0.008144
0.493838  0.523866  0.265719  0.565014  0.000000  0.000000  0.481293
1.065424  1.038088  0.288166  0.542567  0.000000  0.000000  0.481293
999.000000
32        0.000000  0.004735  0.000000
0.532760  0.552328  0.642725  0.801414  0.000000  0.000000  0.201047
1.027903  1.004223  0.628723  0.815416  0.000000  0.000000  0.201047
999.000000
30        1.287412  0.000000  0.006247
0.556207  0.585630  0.831166  1.042240  0.000000  0.000000  0.456662
1.000000  0.974810  0.846997  1.026409  0.000000  0.000000  0.456662
999.000000
48        0.000000  0.003611  0.000000
0.590057  0.607039  1.072073  1.182575  0.000000  0.000000  0.205806
0.969523  0.949704  1.062323  1.192325  0.000000  0.000000  0.205806
999.000000
44        1.287412  0.000000  0.004707
0.610174  0.634578  1.202343  1.350383  0.000000  0.000000  0.445689
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999.000000
60        0.000000  0.002683  0.000000
0.638089  0.652569  1.370895  1.453622  0.000000  0.000000  0.205884
0.921963  0.905372  1.363595  1.460922  0.000000  0.000000  0.205884
999.000000
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0.655376  0.672554  1.469327  1.583999  0.000000  0.000000  0.440475
0.902412  0.889882  1.477927  1.575399  0.000000  0.000000  0.440475
999.000000
78        0.000000  0.002067  0.000000
0.674087  0.680751  1.598430  1.664238  0.000000  0.000000  0.205719
0.888047  0.880278  1.592623  1.670045  0.000000  0.000000  0.205719
999.000000
84        1.287412  0.000000  0.002843
0.681911  0.690188  1.676272  1.768286  0.000000  0.000000  0.439158
```

0.879038 0.872121 1.683173 1.761385 0.000000 0.000000 0.439158
999.000000
94 0.000000 0.001753 0.000000
0.691082 0.695405 1.778975 1.833336 0.000000 0.000000 0.205736
0.871065 0.866111 1.774178 1.838133 0.000000 0.000000 0.205736
999.000000
98 1.287412 0.000000 0.002465
0.696165 0.701460 1.843398 1.918829 0.000000 0.000000 0.439772
0.865318 0.860980 1.849055 1.913172 0.000000 0.000000 0.439772
999.000000
110 0.000000 0.001553 0.000000
0.702061 0.704872 1.928080 1.973769 0.000000 0.000000 0.201114
0.860297 0.857151 1.924048 1.977801 0.000000 0.000000 0.201114
999.000000
102 1.287412 0.000000 0.002223
0.705372 0.708784 1.982367 2.045937 0.000000 0.000000 0.438937
0.856643 0.853928 1.987134 2.041169 0.000000 0.000000 0.438937
999.000000
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0.853452 0.851550 2.051492 2.096332 0.000000 0.000000 0.161879
999.000000
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0.710993 0.714315 2.101304 2.158698 0.000000 0.000000 0.410175
0.851609 0.849334 2.105608 2.154393 0.000000 0.000000 0.410175
999.000000
132 0.000000 0.001326 0.000000
0.714707 0.716200 2.166276 2.197394 0.000000 0.000000 0.148121
0.848916 0.847263 2.163531 2.200140 0.000000 0.000000 0.148121
999.000000
136 1.287412 0.000000 0.001928
0.716506 0.718446 2.204305 2.254112 0.000000 0.000000 0.410901
0.846911 0.845056 2.208040 2.250376 0.000000 0.000000 0.410901
999.000000
150 0.000000 0.001250 0.000000
0.718665 0.719480 2.260644 2.287497 0.000000 0.000000 0.138948
0.844716 0.843371 2.258275 2.289867 0.000000 0.000000 0.138948
999.000000
154 1.287412 0.000000 0.001833
0.719646 0.720629 2.293575 2.337379 0.000000 0.000000 0.410629
0.843078 0.841537 2.296860 2.334093 0.000000 0.000000 0.410629
999.000000
168 0.000000 0.001198 0.000000
0.720732 0.721082 2.343174 2.366608 0.000000 0.000000 0.119512
0.841251 0.840142 2.341106 2.368675 0.000000 0.000000 0.119512

999.000000						
172	0.000000	0.001188	0.000000			
0.721174	0.721174	2.374270	2.391451	0.000000	0.000000	0.000000
0.839979	0.839979	2.372754	2.392967	0.000000	0.000000	0.000000

HPC-2 (walls.hpc-2)

-0.141217	2.541451	0.000000	0.000000
2.691451	0.721174		
2.591451	0.721174		
2.491451	0.721174		
2.441451	0.721174		
2.391451	0.721174		
2.374270	0.721174		
2.366608	0.721082		
2.343174	0.720732		
2.337379	0.720629		
2.293575	0.719646		
2.287497	0.719480		
2.260644	0.718665		
2.254112	0.718446		
2.204305	0.716506		
2.197394	0.716200		
2.166276	0.714707		
2.158698	0.714315		
2.101304	0.710993		
2.092969	0.710984		
2.054855	0.709222		
2.045937	0.708784		
1.982367	0.705372		
1.973769	0.704872		
1.928080	0.702061		
1.918829	0.701460		
1.843398	0.696165		
1.833336	0.695405		
1.778975	0.691082		
1.768286	0.690188		
1.676272	0.681911		

1.664238	0.680751
1.598430	0.674087
1.583999	0.672554
1.469327	0.655376
1.453622	0.652569
1.370895	0.638089
1.350383	0.634578
1.202343	0.610174
1.182575	0.607039
1.072073	0.590057
1.042240	0.585630
0.831166	0.556207
0.801414	0.552328
0.642725	0.532760
0.565014	0.523866
0.265719	0.493838
0.160607	0.485041
0.008783	0.485041
-0.041217	0.485041
-0.091217	0.485041
-0.191217	0.485041
-0.291217	0.485041
999.00000	999.000000
-0.300000	1.076778
-0.200000	1.076778
-0.100000	1.076778
-0.050000	1.076778
0.000000	1.076778
0.178617	1.076778
0.288166	1.065424
0.542567	1.038088
0.628723	1.027903
0.815416	1.004223
0.846997	1.000000
1.026409	0.974810
1.062323	0.969523
1.192325	0.949704
1.213446	0.946383
1.339280	0.926014
1.363595	0.921963
1.460922	0.905372
1.477927	0.902412
1.575399	0.889882
1.592623	0.888047
1.670045	0.880278

1.683173	0.879038
1.761385	0.872121
1.774178	0.871065
1.838133	0.866111
1.849055	0.865318
1.913172	0.860980
1.924048	0.860297
1.977801	0.857151
1.987134	0.856643
2.041169	0.853928
2.051492	0.853452
2.096332	0.851550
2.105608	0.851609
2.154393	0.849334
2.163531	0.848916
2.200140	0.847263
2.208040	0.846911
2.250376	0.845056
2.258275	0.844716
2.289867	0.843371
2.296860	0.843078
2.334093	0.841537
2.341106	0.841251
2.368675	0.840142
2.372754	0.839979
2.392967	0.839979
2.442967	0.839979
2.492967	0.839979
2.592967	0.839979
2.692967	0.839979

HPC-1 (stack.hpc-1)

```
The overall information for each blade row is:
  Number_of_blades  rotation_speed  Hub_clearance Tip_clearance
Geometry, loss, blockage and angular momentum are input starting at the hub
   r_le   r_te   x_le   x_te   Loss  Blk  rV_theta
  1.399057  583.9587    0    1.642970438 8.8211906E+06  1    1
Above are gam, TT_in(deg R), type(0-comp, 1-turb), ma, Re, BL switch & visc flag
  12       0.000000  0.000000  0.000000
  0.369250  0.369250  0.008783  0.225771  0.000000  0.030000  0.170777
  1.192568  1.192568  0.000000  0.255281  0.000000  0.030000  0.170777
  999.000000
  16       1.387544  0.000000  0.011260
  0.382072  0.429843  0.330867  0.785336  0.000000  0.000000  0.470000
  1.178252  1.134977  0.364952  0.751251  0.000000  0.000000  0.470000
  999.000000
  20       0.000000  0.006551  0.000000
  0.438479  0.466410  0.859409  1.086297  0.000000  0.000000  0.190871
  1.124375  1.090619  0.839389  1.106317  0.000000  0.000000  0.190871
  999.000000
  24       1.387544  0.000000  0.008513
  0.475390  0.516619  1.155618  1.455383  0.000000  0.000000  0.475915
  1.081118  1.045945  1.178100  1.432901  0.000000  0.000000  0.475915
  999.000000
  32       0.000000  0.004848  0.000000
  0.524303  0.550376  1.508309  1.682002  0.000000  0.000000  0.203000
  1.037322  1.007054  1.492983  1.697328  0.000000  0.000000  0.203000
  999.000000
  30       1.387544  0.000000  0.006247
  0.556207  0.585630  1.721051  1.932125  0.000000  0.000000  0.479496
  1.000000  0.974810  1.736882  1.916294  0.000000  0.000000  0.479496
  999.000000
  48       0.000000  0.003611  0.000000
  0.590057  0.607039  1.961959  2.072460  0.000000  0.000000  0.205806
  0.969523  0.949704  1.952208  2.082210  0.000000  0.000000  0.205806
  999.000000
  44       1.387544  0.000000  0.004707
  0.610174  0.634578  2.092228  2.240268  0.000000  0.000000  0.467973
  0.946383  0.926014  2.103331  2.229165  0.000000  0.000000  0.467973
  999.000000
  60       0.000000  0.002683  0.000000
  0.638089  0.652569  2.260780  2.343507  0.000000  0.000000  0.205884
  0.921963  0.905372  2.253481  2.350807  0.000000  0.000000  0.205884
  999.000000
  62       1.387544  0.000000  0.003483
  0.655376  0.672554  2.359212  2.473884  0.000000  0.000000  0.462499
```

0.902412 0.889882 2.367812 2.465284 0.000000 0.000000 0.462499
999.000000
78 0.000000 0.002067 0.000000
0.674087 0.680751 2.488315 2.554124 0.000000 0.000000 0.205719
0.888047 0.880278 2.482508 2.559930 0.000000 0.000000 0.205719
999.000000
84 1.387544 0.000000 0.002843
0.681911 0.690188 2.566157 2.658171 0.000000 0.000000 0.461116
0.879038 0.872121 2.573058 2.651270 0.000000 0.000000 0.461116
999.000000
94 0.000000 0.001753 0.000000
0.691082 0.695405 2.668860 2.723221 0.000000 0.000000 0.205736
0.871065 0.866111 2.664063 2.728018 0.000000 0.000000 0.205736
999.000000
98 1.387544 0.000000 0.002465
0.696165 0.701460 2.733283 2.808715 0.000000 0.000000 0.461761
0.865318 0.860980 2.738940 2.803057 0.000000 0.000000 0.461761
999.000000
110 0.000000 0.001553 0.000000
0.702061 0.704872 2.817965 2.863654 0.000000 0.000000 0.201114
0.860297 0.857151 2.813934 2.867686 0.000000 0.000000 0.201114
999.000000
102 1.387544 0.000000 0.002223
0.705372 0.708784 2.872252 2.935822 0.000000 0.000000 0.460884
0.856643 0.853928 2.877019 2.931054 0.000000 0.000000 0.460884
999.000000
112 0.000000 0.001424 0.000000
0.709222 0.710984 2.944740 2.982854 0.000000 0.000000 0.161879
0.853452 0.851550 2.941377 2.986217 0.000000 0.000000 0.161879
999.000000
118 1.387544 0.000000 0.002067
0.710993 0.714315 2.991189 3.048583 0.000000 0.000000 0.430684
0.851609 0.849334 2.995493 3.044279 0.000000 0.000000 0.430684
999.000000
132 0.000000 0.001326 0.000000
0.714707 0.716200 3.056161 3.087279 0.000000 0.000000 0.148121
0.848916 0.847263 3.053416 3.090025 0.000000 0.000000 0.148121
999.000000
136 1.387544 0.000000 0.001928
0.716506 0.718446 3.094190 3.143997 0.000000 0.000000 0.431446
0.846911 0.845056 3.097925 3.140261 0.000000 0.000000 0.431446
999.000000
150 0.000000 0.001250 0.000000
0.718665 0.719480 3.150529 3.177382 0.000000 0.000000 0.148948
0.844716 0.843371 3.148160 3.179752 0.000000 0.000000 0.148948

999.000000
154 1.387544 0.000000 0.001786
0.721468 0.724362 3.183423 3.226956 0.000000 0.000000 0.430770
0.843019 0.840956 3.186688 3.223691 0.000000 0.000000 0.430770
999.000000
158 0.000000 0.001139 0.000000
0.724800 0.726612 3.233303 3.258968 0.000000 0.000000 0.152527
0.840536 0.838769 3.231039 3.261233 0.000000 0.000000 0.152527
999.000000
162 1.387544 0.000000 0.001633
0.727051 0.729926 3.265039 3.303645 0.000000 0.000000 0.414597
0.838369 0.836365 3.267934 3.300749 0.000000 0.000000 0.414597
999.000000
168 0.000000 0.001036 0.000000
0.730402 0.732341 3.309840 3.334594 0.000000 0.000000 0.168609
0.835934 0.834082 3.307656 3.336778 0.000000 0.000000 0.168609
999.000000
174 1.387544 0.000000 0.001476
0.732833 0.735706 3.340754 3.375802 0.000000 0.000000 0.380605
0.833654 0.831687 3.343382 3.373173 0.000000 0.000000 0.380605
999.000000
178 0.000000 0.000934 0.000000
0.736161 0.737932 3.381219 3.401960 0.000000 0.000000 0.078183
0.831269 0.829603 3.379389 3.403790 0.000000 0.000000 0.078183
999.000000
182 0.000000 0.000908 0.000000
0.738506 0.738506 3.408585 3.422306 0.000000 0.000000 0.000000
0.829355 0.829355 3.407374 3.423516 0.000000 0.000000 0.000000

HPC-1 (walls.hpc-1)
-0.141217 3.572306 0.000000 0.000000
3.722306 0.738506
3.622306 0.738506
3.522306 0.738506
3.472306 0.738506
3.422306 0.738506
3.408585 0.738506

3.401960	0.737932
3.381219	0.736161
3.375802	0.735706
3.340754	0.732833
3.334594	0.732341
3.309841	0.730402
3.303645	0.729926
3.265039	0.727051
3.258968	0.726612
3.233303	0.724800
3.226957	0.724362
3.183423	0.721468
3.177383	0.719480
3.150530	0.718665
3.143997	0.718446
3.094190	0.716506
3.087280	0.716200
3.056162	0.714707
3.048584	0.714315
2.991189	0.710993
2.982854	0.710984
2.944740	0.709222
2.935822	0.708784
2.872252	0.705372
2.863655	0.704872
2.817965	0.702061
2.808715	0.701460
2.733283	0.696165
2.723222	0.695405
2.668860	0.691082
2.658172	0.690188
2.566158	0.681911
2.554124	0.680751
2.488315	0.674087
2.473885	0.672554
2.359212	0.655376
2.343508	0.652569
2.260780	0.638089
2.240268	0.634578
2.092228	0.610174
2.072461	0.607039
1.961959	0.590057
1.932125	0.585630
1.721052	0.556207
1.682003	0.550376

1.508309	0.524303
1.455384	0.516619
1.155618	0.475390
1.086297	0.466410
0.859409	0.438479
0.785336	0.429843
0.330867	0.382072
0.225771	0.369250
0.008783	0.369250
-0.041217	0.369250
-0.091217	0.369250
-0.191217	0.369250
-0.291217	0.369250
999.00000	999.000000
-0.300000	1.192568
-0.200000	1.192568
-0.100000	1.192568
-0.050000	1.192568
0.000000	1.192568
0.255281	1.192568
0.364952	1.178252
0.751251	1.134977
0.839389	1.124375
1.106317	1.090619
1.178101	1.081118
1.432901	1.045945
1.492983	1.037322
1.697329	1.007054
1.736882	1.000000
1.916295	0.974810
1.952209	0.969523
2.082211	0.949704
2.103331	0.946383
2.229165	0.926014
2.253481	0.921963
2.350807	0.905372
2.367813	0.902412
2.465284	0.889882
2.482509	0.888047
2.559931	0.880278
2.573059	0.879038
2.651271	0.872121
2.664064	0.871065
2.728018	0.866111
2.738940	0.865318

2.803058	0.860980
2.813934	0.860297
2.867686	0.857151
2.877020	0.856643
2.931054	0.853928
2.941377	0.853452
2.986217	0.851550
2.995494	0.851609
3.044279	0.849334
3.053416	0.848916
3.090025	0.847263
3.097926	0.846911
3.140262	0.845056
3.148160	0.844716
3.179752	0.843371
3.186688	0.843019
3.223691	0.840956
3.231039	0.840536
3.261233	0.838769
3.267935	0.838369
3.300750	0.836365
3.307657	0.835934
3.336779	0.834082
3.343383	0.833654
3.373174	0.831687
3.379389	0.831269
3.403791	0.829603
3.407374	0.829355
3.423516	0.829355
3.473516	0.829355
3.523516	0.829355
3.623516	0.829355
3.723516	0.829355