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MODULAR MULTI-STAGE AXIAL COMPRESSOR DESIGN: A CONCEPTUAL STUDY WITH AN EXAMPLE

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ABSTRACT

Increasingly, companies are becoming more interested in reducing cost. Initially, cost reduction efforts were focused on the manufacturing and service side since the majority of the budget was consumed during that phase. However, recent studies indicate that up to 80% of the life cycle costs (LCC) has been embedded in the engine's DNA at the end of the development and design phase. This fact is motivating many companies to consider cost cutting initiatives much earlier in the development cycle than before. One concept to aid in such cost reduction is the modular design of expensive and development-intensive components, such as multi-stage axial compressors. With sufficient planning, any potentially negative impact on performance can be addressed and almost entirely eliminated. Conceptually, the compressor is divided into five (5) functional modules. In the successful modular design, the core module size is maximized, while all other modules are held to a minimum. It is the objective of this approach to utilize the core module in all the compressors, thus, maximizing commonality and minimizing all relevant development, design, manufacture, procurement, and service costs. This paper introduces the modular concept with an example; a multi-stage high pressure compressor (HPC) design is carried out to the preliminary meanline phase. The compressor is consequently divided up into its five (5) modules, and a modular upgrade is then developed for a different application using the same core. Discussion is presented as to the advantages and potential limitations.

KEYWORDS

Axial compressor, common parts, common core, modular design, Lean Engineering, Life Cycle Cost, design

INTRODUCTION

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.

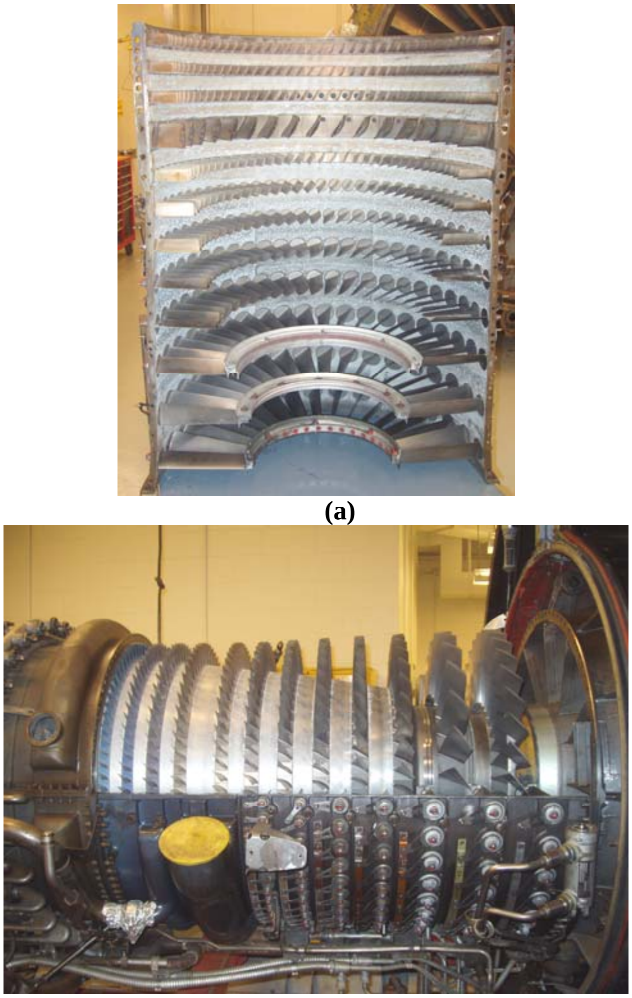
Duvall, and Goetz, [2], outline an understanding for the maintenance procedure with the modular engine concept, with emphasis on the attempts by the military to reduce gas turbine maintenance costs. Lehmann [3] covers the common core concept in sufficient detail. The core in [3] refers to the HPC, main 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, receiving much 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 as well. 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.

The modular compressor design philosophy discussed in this paper differs substantially 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.

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.



(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.

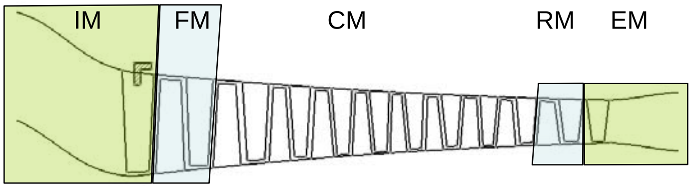


Figure 3. Schematic of a 10-stage HPC subdivided into five modules.

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, more flow and higher pressure ratio derivative, 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 would be considerably reduced. Figure 5 shows an overlay of the two configurations in their final shape.

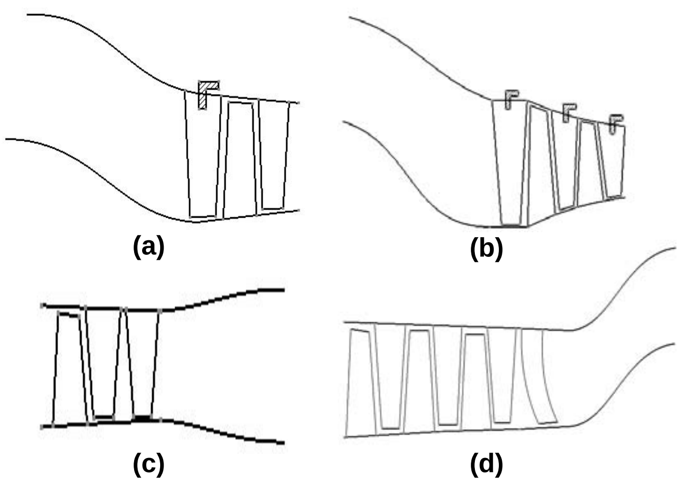


Figure 4. Module upgrade: (a) original configuration IM/FM one and one half stage, (b) IM/FM upgrade, larger inlet area, two and one half stages, (c) original RM/EM one and one half stage, and (d) RM/EM upgrade, increased pressure ratio, custom OGV and diffuser, three and one half stages. (Not to scale).

This paper 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.

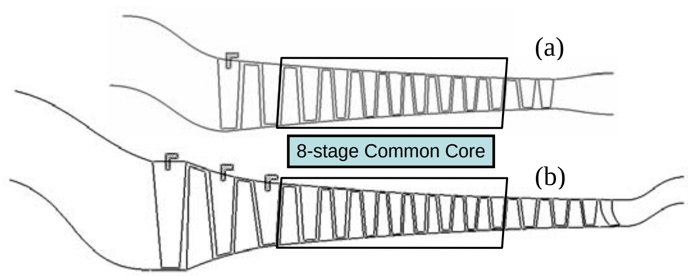


Figure 5. Modular upgrade with an 8-stage common core: (a) 10-stage original configuration, (b) 13-stage modular upgrade: higher flow rate, and pressure rise, with a customized OGV/exit diffuser (EM).

NOMENCLATURE

C_p = specific heat at constant pressure
h = enthalpy
M = Mach number
$\dot{m}$ = mass flow rate
N = mechanical speed (rpm)
R = degree of reaction
T = Temperature, thrust
U = circumferential velocity, defined as (Ωr)
V = absolute flow velocity
W = weight
α = absolute flow angle
β = relative flow angle
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
o = total, or stagnation conditions
1 = stage, or rotor inlet
2 = rotor exit, or stator inlet
3 = stage, or stator exit
ax = axial component
tt = total-to-total

METHODOLOGY

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 engineering community's first task, after having been made aware that a number of compressors are to be designed, is to decide on 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 don't 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 paper 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. The authors intend to cover the issue of scaled modular upgrades in a future article.

	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	10,000	10,000	8,000	10,000

Table 1. Design specifications and Boundary Conditions for four (4) different compressors.

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.

Aerodynamic Loading and the Interface Stage

The interface stage is defined as the first stage in the common core; stage 2 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. An incidence-tolerant and moderately loaded interface stage is a must, and is the subject of ongoing investigations by the authors. Keeping with the design philosophy of increased work in the front of the compressor, Figure 6 shows the selected work coefficient (λ) distribution. As can be seen, the interface stage will be operating at a slightly lower work coefficient than its neighbors.

The choice of λ for the interface stage is justified by contemplating the stability of the core compressor. 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.

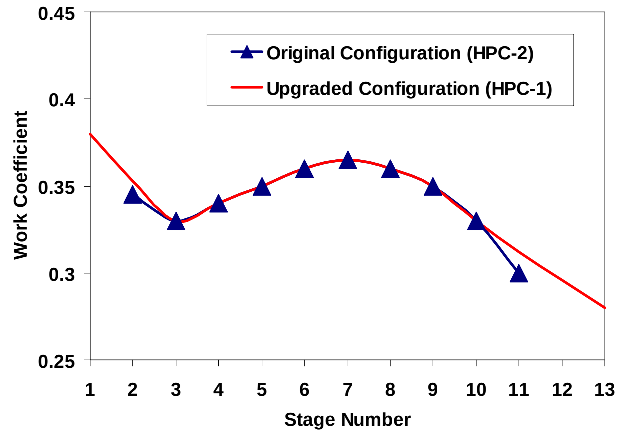


Figure 6. Stage work coefficient for the original (HPC-2) and upgraded (HPC-1) configurations.

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 (corrected flow) 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:

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

The core compressor, consisting of eight stages, Fig. 7, has a total pressure ratio of 8:1. 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.

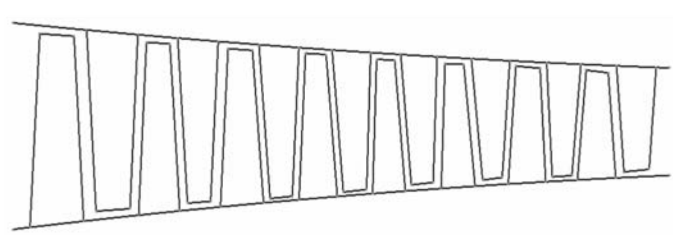


Figure 7. 8-stage common core (CM).

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:

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

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 1.37:1 could easily be designed at a total-to-total adiabatic efficiency of 91%. Using Eq. (2), the total temperature will increase by approximately 10% 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:

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

A sensitivity study of an iterative nature was conducted, and a stage pressure ratio of 1.37:1 was chosen for the first stage (FM) of HPC-2, operating at 91% efficiency. The core flow function, as prescribed by the HPC-2 configuration, can be written in terms of the reference FF as follows:

$$\begin{aligned} FF_{core,HPC-2} &= \frac{\dot{m}_{inlet,HPC-2}\sqrt{(1.1)T_{o,inlet,HPC-2}}}{(1.37)\,P_{o,inlet,HPC-2}} \\ FF_{core,HPC-2} &= 0.77\,FF_{ref} \end{aligned} \tag{4}$$

For the upgraded configuration, and after some iterative calculations, Stages 1, and 2 were assigned total pressure ratios of 1.45:1, and 1.39:1, respectively. Their total-to-total efficiencies were estimated at 89%, and 90%, respectively. Using Eq. (2), the total temperature rise is expected to be 12.6%, and 11%, respectively. Therefore, the FF entering the core, as prescribed by the HPC-1 configuration can now be determined as:

$$\begin{aligned} FF_{core,HPC-1} &= \frac{1.4\,\dot{m}_{inlet,HPC-2}\sqrt{(1.11)\,(1.126)\,T_{o,in,HPC-2}}}{(1.45)\,(1.39)\,P_{o,inlet,HPC-2}} \\ FF_{core,HPC-1} &= \frac{1.4\sqrt{(1.11)\,(1.126)}}{(1.45)\,(1.39)}\,FF_{ref} = 0.776\ FF_{ref} \end{aligned} \tag{5}$$

It is evident, by comparing the results of Eqs. (4), and (5), that the flow function entering the core changes by less than 1.5% between the two configurations. An exact match can be achieved with ease 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:

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

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

$$\begin{aligned} NRT_{core,HPC-2} &= \frac{NRT_{ref}}{\sqrt{1.1}} = 0.953\,NRT_{ref} \\ NRT_{core,HPC-1} &= \frac{NRT_{ref}}{\sqrt{1.11(1.126)}} = 0.894\,NRT_{ref} \end{aligned} \tag{8}$$

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. However, in anticipation of this fact, the core was designed to be moderately loaded; having an 8:1 pressure ratio and 8 stages. Furthermore, the first stage, the interface stage, was assigned a low aerodynamic duty (λ). Thus the authors believe that a change in mechanical speed is not warranted in this case. However, an available option is to consider increasing the mechanical speed, or rpm, of the HPC-1 configuration. An increase of 6.6% (to 10,660 rpm) would bring the aerodynamic speed inline, but is not warranted as this will lead to tuning difficulties later on. The core could be designed with sufficient margin such that only an increase of 3% (to 10,300 rpm) is acceptable. The core aerodynamic speed would then differ by only 3% from the original configuration all but ensuring stable operation for such a moderately loaded compressor. Additionally, tuning of the core airfoils would be much simplified. A cleverer alternative, to avoid the increase in rpm altogether, is to increase the FF into the core for the HPC-1 configuration, thereby forcing the core more to the right on its operating line. This alternative places the core in an area [on its map] that is historically characterized by higher surge margins, and could very well eliminate the tuning difficulties associated with two different operating rpm. Other potentially acceptable combinations exist, all made possible by a careful design of the interface stage and sufficient pre-planning.

Meanline Design

The 10-stage HPC-2, shown in Fig. 5(a), has a stage pressure ratio distribution that is shown in Fig. 8. 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.

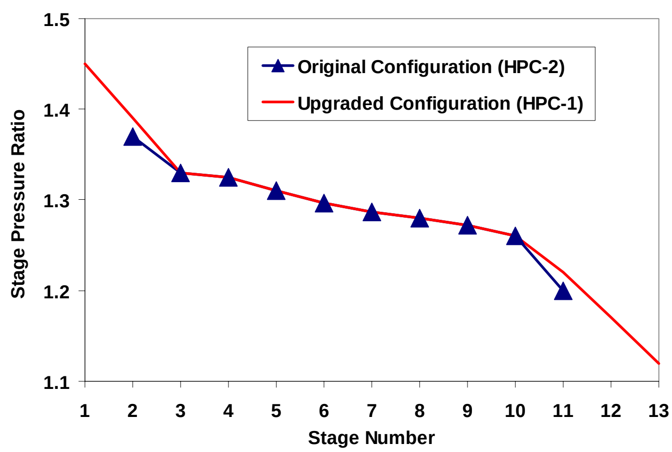


Figure 8. Proposed Stage Pressure Ratio for the 10-stage HPC-2 and the 13-stage HPC-1 modular upgrade.

The stage work coefficient distribution (Fig. 6) 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. This will be noted repeatedly throughout this section as was discussed above.

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

$$R = \frac{\Delta h_{rotor}}{\Delta h_{o,\,stage}} \tag{9}$$

Special consideration, higher reaction, is assigned to the interface stage, stage 3. This is consistent with the reduced aerodynamic duty for this stage, as depicted in Fig. 6 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:

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

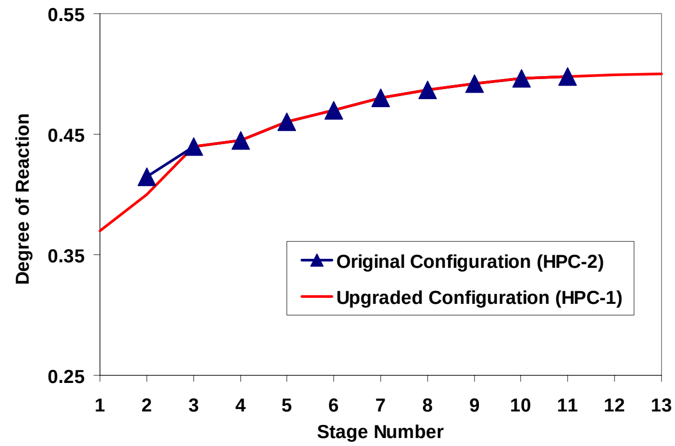


Figure 9. Proposed Stage Degree of Reaction for HPC-2, and its modular upgrade, HPC-1.

The proposed distribution of flow coefficient is shown in Figure 10 for completion. With the meanline design completed, confidence in the stability of the core compressor is established. A brief discussion on some geometrical and mechanical issues is warranted, to complete the design.

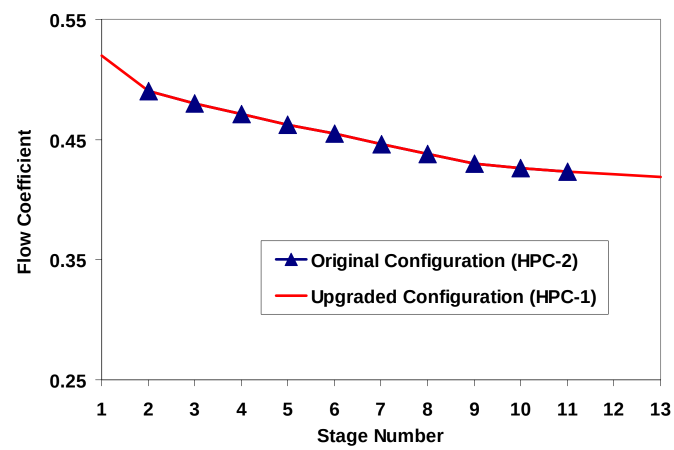


Figure 10. Proposed Stage Flow coefficient for HPC-2, and its modular upgrade, HPC-1.

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. 7. 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 (3%), 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 (stage 3) must be designed such that the natural frequencies of the airfoils are tuned to avoid the drivers of all applicable FM's. 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.

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 aerodynamic 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 (a topic for future work) is another enhancement. Mechanical and geometric issues should also be carefully evaluated, as presented. Basically, much 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 next section.

BENEFIT ANLYSIS

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.

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:

$$\frac{\Delta Capability}{\Delta Cost} = \frac{\Delta\left(\dfrac{(T/W)_{\max power}}{TSFC_{SLS}}\right)}{\Delta Cost_{Dev} + \Delta Cost_{\Pr} + \Delta Cost_{Ma\text{int}}} \quad (11)$$

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:

$$\left(\frac{\Delta Capability}{\Delta Cost}\right)_{comp} = \frac{\Delta\pi \,.\, \Delta\dot{m}}{\Delta Cost_{Dev} + \Delta Cost_{\Pr} + \Delta Cost_{Ma\text{int}}} \quad (12)$$

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.

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.

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.

CONCLUSION

The concept of modular 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 and aerodynamic as well as 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 and service contracts at substantial margins.

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