MATCHING BETWEEN METAMODEL AND OPTIMIZATION TOOL APPLIED IN A MULTISTAGE AXIAL-FLOW COMPRESSOR AIMING DESIGN IMPROVEMENTS

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Abstract

*The use of optimization techniques in turbomachines, in special applied in gas turbines, have been growing in the last decades. The computational advance and the search for high performance machines makes the optimization techniques a fundamental step during the design phase, from reduced order techniques until 3D techniques as CFD [1], [2], [3].This work presents the development of optimization techniques applied in a multistage axial flow compressor studied by NASA [4] as showed in the*Figure 2. *This compressor has originally 5-stages, but only the first 3-stages were evaluated in the NASA report [4], including a Variable Inlet Guide Vane (VIGV) row. In this work, an evolutive algorithm, [5] and metamodel were used in the optimization process of this axial-flow compressor design based on blade-to-blade (blade section design) calculations.The metamodels is applied to save time during the simulation [6], [7] into the optimization environment. This aspect is important in the turbomachine development phase, due to the high number of possible configurations. The use of metamodel with an optimization tool in the turbomachine design phase is very important to help the designer during technical decisions around the machine configuration. The results from this matching between metamodel and optimization tool, showed that multistage axial-flow compressor performance can be improved, based on geometrical enhancements determined by optimizer couple with blade-to-blade calculations.*

1 Introduction

The use of optimization techniques in turbomachineries, in special applied in gas turbines, have been growing exponentially in the last decades.The computational advance and the search for the high performance and efficiency machine makes the optimization techniques a fundamental step during the development design. It is vital for the engineer to eliminate inadequate designs and to obtain a near optimum configuration during the preliminary design process before proceeding with the final design refinements, see Figure 1.

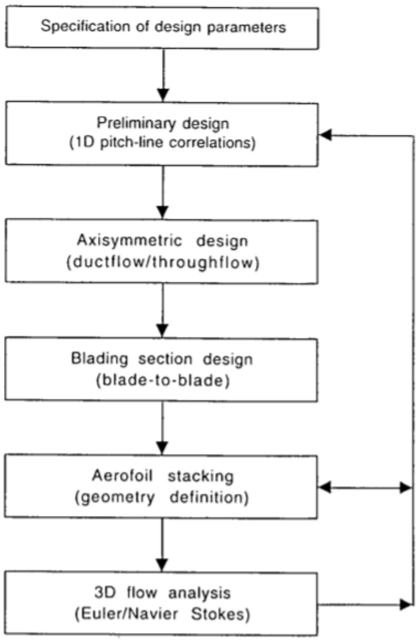

Figure 1.Typical turbomachimery aerodynamic design system.

The accuracy of the computational fluid dynamics results and the modifications of the design parameters during the Computer-Aided Design CAD and Computer-Aided Engineering (CAE) phases, help to exploring several configurations to achieve the optimal design, saving time and costs during the project, before the manufacture and test phases. However, the 3D CFD analyses are expensive computationally and can spend several time. The modification in the design parameters based on 3D CFD requires a new mesh and new simulation. In order toreduce the number of design evaluations in 3D CFD simulation, in terms of risk, time and cost, an alternative is to adopt throughflowand Q3D blade-to-blade calculations with optimization techniques.In axial compressors, the throughflow analysis is used for the detailed air-angle design and determines the spanwise variation of the velocity triangles. The blade-to-blade code will predict loading, exit angle viscous loss, key aerodynamic parameters such as Mach numbers, pressure fields and temperature.If the values of any of these parametersselectedduring the preliminary design process are not consistent with the performance required by the customer, no amount of subsequent 3D CFD computational effort or development testing will enable the performance to be achieved [8].

In the evolutionary optimization, the algorithm performs several configurations to achieve the optimal design, and then the process could be unviable due to the time spent. An alternative to solve this problem are the surrogate models for the optimization problems. The metamodels emulate the real problem through some points, which will be optimized. This procedure transforms complex design to the surrogate model that can optimize easily compare to original design saving time during the optimization process.

In this work, a metamodel will be implemented and coupled to thegenetic algorithm to optimize a 3 stages axial flow compressor.

2 Gas Turbine Engine

The gas turbine engine are widely applied in the aeronautical and energy area. The engine could be responsible to generate thrust or energy depend on the application. Historically the gas turbine engine have been development around the word and a great attention have been spend in the improve of efficiency, fuel consumption, more thrust in the compact engine and decrease the noise for aeronautics application. The main components of a gas turbine engine are compressor, combustor and turbine. this work is focus on axial compressor component.

2.1 Axial Compressor

The axial compressor is responsible for increase the pressure and temperature to delivery to combustor. The stage of compression is compost by rotor and stator blades, where the stator are blades fix and the rotors normally have high speed rotations per minute, the axial compressor are multistage to reach a high pressure ratio. The process of increase the pressure in air could be complex due to the gradient pressure adverse. It make the compressor design be match between the rotor and stator blades to reach the compression which the high efficiency in the each stage, consequently in the axial core compressor. For this work the axial core compressor design of 3 stages were redesign for the optimization process by reschedule the stagger angle of IGV.

2.2 The 3 stages core compressor

In this work, the performance of 3-stages axial compressor was performed, the original compressor is a 5-stage axial compressor was evaluated based on the reference [4]. The overall aerodynamic design for the core compressor designated. The blade aerodynamic design details and experimental overall performance for the compressor, which consist of the inlet guide vanes (IGV) and the first three stages were performed and analyzed. Table 1shows the compressors parameters.

Table 1: Axial compressor Design requirements.

Mass flow	29.71 kg/s
Pressure ratio	4.474 -
Rotation	16042.3 RPM
Inlet tip velocity	430.29 m/s

A high compression ratio per stage is desired in the compressor design, because this way it is possible to decrease the stage number for a given required compression.

In addition to the temperature increase, the efficiency of the compression process influences the pressure ratio per stage which can be determined by equation 3.1.

$$R_s = \frac{p_{03}}{p_{01}} = \left[1 + \frac{\eta_s \Delta T_{0s}}{T_{01}}\right]^{\frac{\gamma}{(\gamma-1)}} \qquad (1)$$

The diffusion factor is determined by the energy transfer rate between the fluid and the blade, theoretically high values of energy transfer are desired, but there are limits to this diffusion, one of the factors used for this limitation is the number called Haller, the which relates the outlet velocity and flow inlet, a recommended value is 0.72 (SARAVANAMUTTOO, 2001).

Haller's number is acceptable during the preliminary design phase, however for more advanced stages of the project it is necessary to determine the diffusion factor which considers the flow between the grids, where the flow is decelerated on the pressure side of the blade. One way to determine the diffusion factor is calculated by equation [9].

$$D \approx \frac{V_{max} - V_2}{V_1} \approx \frac{V_1 + \Delta C_w - \frac{s}{c} V_2}{2} \approx 1 - \frac{V_2}{V_1} + \frac{\Delta C_w}{2V_1}\frac{s}{c} \qquad (2)$$

The degree of reaction of a turbomachine determines the increase of the static pressure performed by the rotor, it is measured by the ratio between the static enthalpy change in the rotor and the stagnation enthalpy change in the stage.

This phenomenon is associated with the blade mounting curvature and is usually represented as a percentage, and can be calculated as a function of the speed triangle, where a reaction rate of 50% has a symmetrical velocity triangle and a more efficient machine.

$$\wedge = \frac{C_a}{2U}(\tan\beta_1 + \tan\beta_2) \qquad (3)$$

From these equation the velocities triangle are calculated and the axial flow path is obtained. The axial compressor data was designed in to a commercial softwareAxial® and Axcent® developed by NREC, to obtain its geometry. Figure 2 show the flow path in the axial compressor.

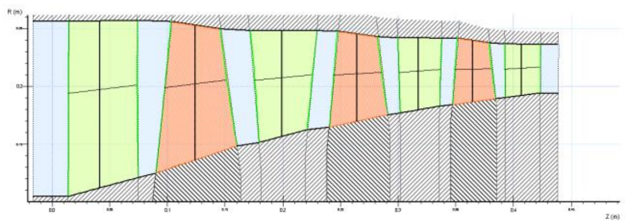

Figure 2. Axial compressor flowpath 2D view.

Figure 3 present the axial comrpessor blade view and the Figure 4 present the 3D geometry of the axial compressor.

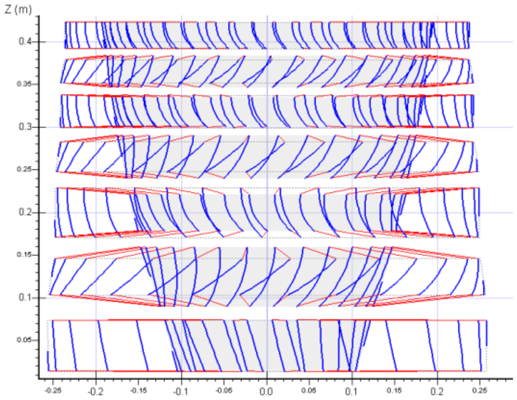

Figure 3.Axial compressor detailed croqui compressor view.

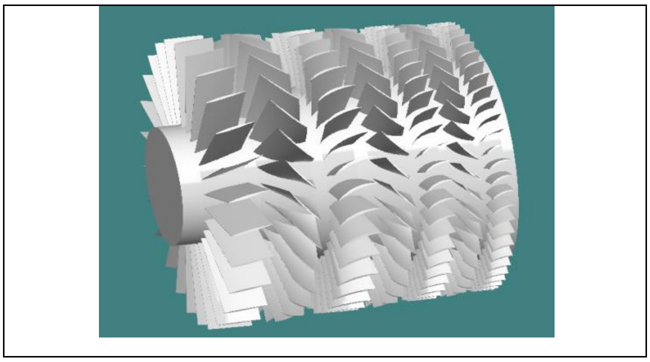

Figure 4.Axial compressor 3D compressor view.

In this work, only the first three stages were considered. It has a pressure ratio of 4.474 and design efficiency of 79.9%.

3 Blade-to-Blade Design Phase

The Blade to Blade (B2B) is a study of fluid mechanics by computational numerical algorithm its perform some analysis about flows in two dimensional aspects. In the turbomachinery field is a fundamental tool during the design phase duethe fast prediction of key aerodynamic parameters.

Normally the computers are utilized to simulations of the design and the calculations which are required to simulate the interaction of gas and liquid with surfaces defined by boundary conditions.

There are several software and techniques research that provides enhances the speed and accuracy of complex simulation scenarios present in the turbomachineryarea , handle with turbulent or transonic flows.

The B2B simulation in the turbomachinery describes machines that transfer energy between a fluid and a rotor. The energy comes from a fluid to a rotor in theturbine, and in the compressor conveys energy from a rotor to a fluid. This way, the B2Bcan perform some simulations in the aerodynamic design of turbomachinery than in other engineering application [2].

The complexity involving thedesign of compressor or turbine is unviable without the aid of B2B due to the cost and time that to need to spend [10].

The governing equations used in the fluid dynamics can be represented by the vector form for a single-component fluid, wich is written to describe the mean flow properties, is cast in integral form for an arbitrary control volume V with differential surface area dA as follows [11].

$$\frac{\partial}{\partial t}\int_V \boldsymbol{W dV} + \oint [\boldsymbol{F} - \boldsymbol{G}]\boldsymbol{dA} = \int_V \boldsymbol{HdV} \quad (4)$$

Where the vectors W, F, and G are defined as:

$$W = \begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{Bmatrix}, F = \begin{Bmatrix} \rho v \\ \rho V u + p\hat{\imath} \\ \rho V v + p\hat{\jmath} \\ \rho V w + p\hat{k} \\ \rho V E + pV \end{Bmatrix}, G = \begin{Bmatrix} 0 \\ \tau_{xi} \\ \tau_{yi} \\ \tau_{zi} \\ \tau_{ij}v_j + q \end{Bmatrix} \quad (5)$$

the vector H contains source terms such as body forces and energy sources.

Where the parameters ρ, v, E, and p are the density, velocity, total energy per unit mass, and pressure of the fluid, respectively. The τ is the viscous stress tensor, and q is the heat flux [11].

Total energy E is related to the total enthalpy H by:

$$E = H - p/\rho \qquad (6)$$

And,

$$H = h + |V|^2/2 \qquad (7)$$

4 Optimization process

The optimization process consisting of minimizing or maximize one or more parameters in the Project, these parameters are defined how the target to be achieved in the process and are always linked to constraints.

There are several projects in engineering which present conflicts parameters to be optimized, and the designer has a trade-off between all parameters and constraints present in the Project. This characteristic need to be handling to achieve the best configuration possible considering all aspects involved.

4.1Genetic algorithm

The concept of genetic algorithm was development based on the Species Theory proposed by Charles Darwin. In his theory Darwin say that in the society with scarce sources the individuals will dispute this resources and only the stronger Will survive, so Will reproduction Will be between this stronger individuals, i.e., benefits that create benefits between the individuals, transmitting his potentials for another's individuals, which Will be more fitness in the society and consequentlyan optimized society presenting a set of good individuals [12]. These individuals with better fitness reproduce more, have more probability of transmitting his genes to next generation. However, due to the genetics operators, crossover, and mutation, the chromosomes of springs are not exactly the same of the parents. This way, his can evolute and adapt in the environment generating individuals more fitness. This concept was introduced in the optimization process by John Holland in 1970 [12] and [13].

In most of the applications that use genetic algorithms (GAs), the most commonconstruction of a codification is to use the binary form. It due to Genetic algorithm theory was development based on this representation, anyway, some authors considering this representation not natural and arenot necessary in most cases. The recombination is performed through crossover operator, which represent the main operator in the genetic algorithm [14]. The mutation has less contribution. The operators can be represented by Figure .

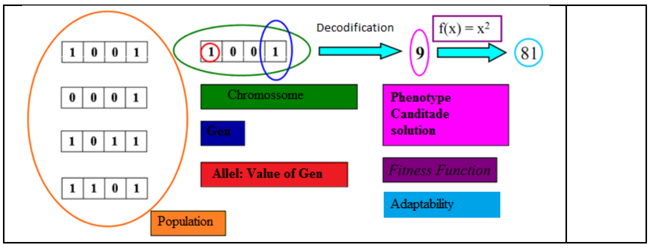

Figure 5: GA nomenclature.

4.2 Surrogate Model

The use of surrogate models for optimization is an essential step to save time during the exhausting optimization process, normally a general optimization problem is written as

Objective minimize y(x)

s.t.gi(x) ≤0, i=1, …, nc,

xl ≤ x ≤ xu

where nc is the number of state functions which is in line with the number of inequality constraints, where xl and xu are the lower and upper bound of design variables, respectively, the object function y(x) and state functions gi (x) are evaluated by an expensive analysis code [15].

Traditionally, the optimization problem is solved by optimizer algorithm as so as GA. It may become prohibitive due to the large computational cost associated running the expensive analysis code. Alternatively, the surrogate modeling can be help on this process, in an attempt to dramatically improve the efficiency and save time. The basic framework of thesurrogate model is shown inFigure .

Figure 6: Framework of thesurrogate model.

4.3The Kriging model

Papers The Kriging method is an interpolation that presents the set observed in all sample points. The Kriging method predicts a statistical of the unknown function minimizing the quadratic mean squared error. That can be equivalent to apolynomial of any order, it can be adequate for non-linear functions that have several extremes. Due to work deterministic experiment as so as a random function, defined by the sum of the function fT(x) β tending to global function and the Gaussian function Z(x) calculated by:

$$y(x) = f^T(x)\beta + Z(x), x \in \mathbb{R}^m \qquad (10)$$

Where, $f(x) = [f_0(x), \dots, f_{p-1}(x)]^T \in \mathbb{R}^p$ is defined as a set of regression functions and $\beta = [\beta_0, \dots, \beta_{p-1}]^T \in \mathbb{R}^p$ denote the respective coefficient. In general, fT(x) β is considered as a Constant or low order polynomial.

The Constant function is enough to the most f problems. This way, fT(x) β is considered as a Constant β0. The Z[·] denote a random stationary process, the variance σ2 and covariance different of zero, equation bellow [16].

$$cov\,[Z(x), Z(x')] = \sigma^2 R(x, x') \qquad (8)$$

Here R(x,x′) is the correlation function which is only dependent on the Euclidean distance between any two sites x and x′ in the design space [17]. In this study, a Gaussian exponential correlation function is adopted, and it is of the form:

$$R(x, x') = \exp\left[-\sum_{k=1}^{m} \theta_k |x_k - x'_k|^{p_k}\right], 1 < p_k \le 2 \qquad (9)$$

5. The optimization process

For the axial compressor design optimization process it was necessary to work with different programs during the development phase, due to the multidisciplinary design and the use of programming language interacting with commercial fluid dynamics and turbomachinery design software, it was necessary integration between the programs for communication during the optimization process.

The optimization process is carried out by means of changes in the angle of assembly of the blades and then performed the analysis of performance parameters, in the case of this work the pressure ratio and efficiency.

The different arrangements are made through the variation range of the design variables, and three points were used for each project change, being: height at the base, middle and top of the blade, respectively.

Through the genetic algorithm the various configurations are tested and the most promising are selected for fluid dynamics analysis.

The analysis involving fluid dynamics in turbomachinery is a complex process due to geometry and necessary mesh generation, especially compressor cases where there is an adverse pressure gradient, in this way was used the software specialized in turbomachinery development to perform the calculations of dynamics of computational fluids. The advantage of working with dedicated software lies in the numerical approach and considerations made during the iteration process, which helps in the process of numerical convergence, in this thesis we used Axcent® NRec concepts software.

The methodology used to integrate and perform the communication between the different programs was the use of the ModeFrontier® optimization platform, the program has the ability to communicate with several programming languages especially commercial

programs, which require more sophisticated protocols and allocation of information .
The program was then used for integration between the design software and fluid dynamics, the step next to the genetic algorithm responsible for the optimization, where the algorithm executes several arrangements and each case needs to be integrated for the process automation.
The Table 2 present the main parameters for optimization process.

Table 2. Optimization parameters.

Design variables	Stager angle IGV, Stators 1, 2 e 3.
Objective Function	Efficiency, Pressure ratio
Objective 1	Maximize Efficiency
Objective 2	Maximize Pressure Ratio

6 Results

After the optimization process are presented the results obtained.
The main compressor design parameters were compared to evaluate the optimized design.
The Figure 6 presents the absolute Mach number and Figure 7 presents the relative Mach number. It is observed high values of Mach number in the stator vanes. After the optimization process the absolute Mach number was smoothed and better distribution was reached. These results are important because the Mach number is related to the shock losses through blade passages.

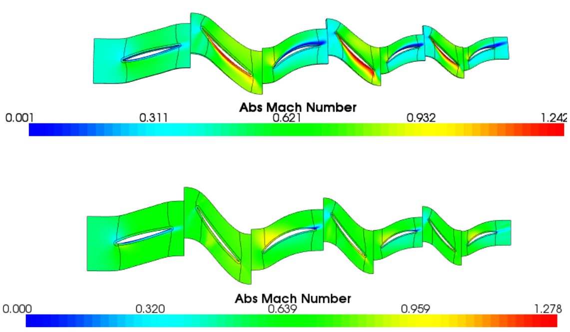

Figure 06: Absolute Mach number original (a) and optimized (b) design.

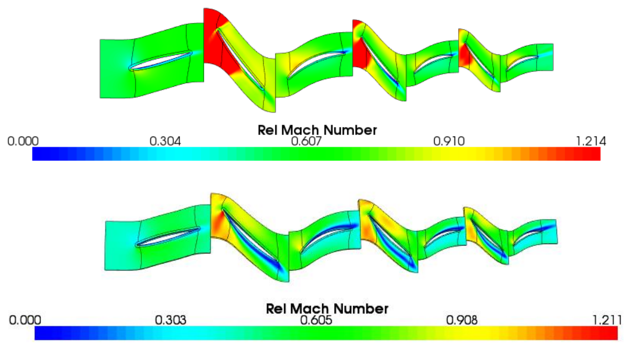

Figure 07: Relative Mach number original (a) and optimized (b) design.
The absolute pressure was compared to same case, the original design shows the high values in some local points in the Figure 8 (a) and in the Figure 8 (b) the result presents the good distribution for the axial compressor.

a

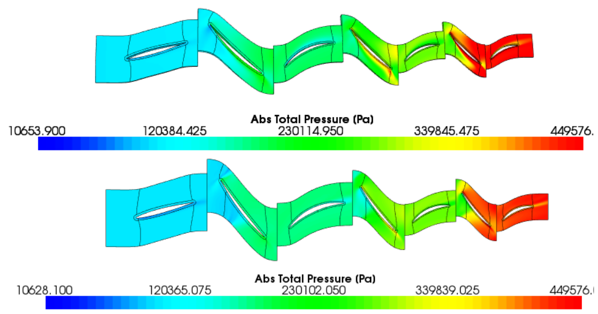

Figure 8: Absolute Pressure original (a) and optimized (b) design.
Figure 9 shows the total temperature distribution. After the optimization process the total temperature increased.

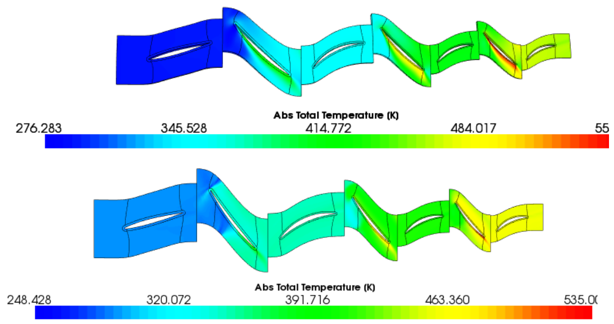

Figure 8: Total Pressure original (a) and optimized (b) design.

Figure 9 shows the static pressure through the blades passages. The static pressure increased in the last stage after the optimization processes, which reduces the Mach number. Low Mach number at the last rotor is better for anchoring the flame at the primary zone in the combustion chamber

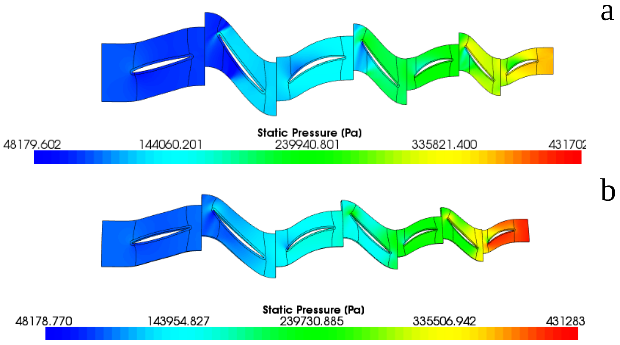

Figure 9: Static Pressure original (a) and optimized (b) design.

Conclusion

Considering the development of turbomachinery design, especially compressor cases, the use of optimization techniques presents itself as a fundamental tool to achieve optimum results against the diversity of possible configurations.
The CFD results show improvements with the reduction of the Mach Number at last rotor and at the suction surface of the stator vanes (increase in efficiency and reduction in shock losses). The static pressure presented some reduction at the last stage which improves the flame anchoring at the primary zone in the combustion chamber.
The optimization process and the metamodel used were successful in achieving optimal points considering multi-objectives, specially conflicting parameters as so as pressure ratio and efficiency in the axial compressor design.

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