Axial turbine preliminary design optimization

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1. Abstract
The turbomachinery design process consists of several steps in order to obtain the a final and optimized machine geometry. The designer expertise is essential to handling many geometrical parameters as space-chord-ratio, aspect ratio, hub-to-tip ratio and so on. The use of optimization techniques as engineering tools has proved to be quite helpful in turbomachinery design, being essential to obtain optimal design values. The present paper deals with a preliminary design process of a single stage axial flow turbine using loss model correlations coupled to optimization process. The simulation was proposed to investigate the axial flow turbine used in the process of design of a single-shaft turbojet. The optimization process was realized using a type of Genetic Algorithm, named as NSGA-II, which is a known as a powerful heuristic algorithm of optimization. The use of this class of algorithm for optimization was based on the turbomachinery design complexity and due to the nonlinearity of the variables involved during the process of axial turbine design. Also, the results of the optimization process will support the designer to take decisions in different turbine geometrical parameters. The simulation results showed the new possibilities of variable arrangements by varying blade and stator angles at mid and tip span aiming to achieve the maximum isentropic efficiency of the axial turbine. Lastly, comparisons and discussions were performed between original and optimal variables of design showing all feasible arrangements.

2. Keywords:
Axial turbine, turbomachinery optimization, gas turbine

3. Introduction
The gas turbine is widely applied in the aeronautics due to the capacity to obtain high power in the small engine. In general, gas turbines present high values of thrust/weight ratio [1] and this characteristic is fundamental in aeronautical field. In Brazil a partnership between a group of research engineers from Technological Institute of Aeronautical (ITA), research engineers from the Air Force Institute of Aeronautics and Space and engineers from a local industry are developing a small gas turbine. The gas turbine under development is a turbojet version of 5 kN where the main goal is aimed at acquiring know-how to design and develop specified gas turbines.

This work is focused to particularly investigate the axial turbine component in the preliminary design phase. In the design point of view, there are several relevant aerodynamic and geometric parameters that can be simultaneously adjusted to achieve high efficiency and performance. Generally, most of these parameters are nonlinear, and due to the complexity to manipulate them and by the high number of possible combinations, the optimization process comes as an essential engineering tool in order to find the best possible solutions. Moreover, the optimization can be used to highlight and calculate the important parameters and also verify the influence of each one in the whole turbomachinery components.

Important aspects to be considered in the process of optimization during the gas turbine development are the multidisciplinary environments and tradeoffs between parameters such as temperature limit, materials, dimensions, weight and many others. In this context, to achieve high efficiency and performance without violating the design constraints some parameters and configurations should be previously verified and tested by sensitivity analysis. The idea behind this analysis is to investigate the behavior of the main variables and parameters in order to known the range of variation and if they are conflicting between each other. After this analysis and investigation, the optimization techniques are then applied to determine the best possible configurations and parameters, resulting in saved time and reduced cost of design.

Optimization means finding one or more feasible solutions, which correspond to maximum and minimum values of one or more objectives. Optimization problems involving one objective are known as Single-Objective and more than one as Multi-Objective [4]. In several real-life problems, objectives may conflict each other and the optimization with respect to a single objective may result in unacceptable solutions with respect to the other objectives. In multi-objective optimization, several optimal solutions can be found and the set of them is called Pareto-optimal. The Pareto-optimal
set is formed through domination criterion, which divide the solutions in dominated and non-dominated. The Pareto-optimal set represents spatially all the non-dominated solutions.

Among several algorithms of optimization, a type of evolutionary algorithm was used due to its high performance in finding optimal values for turbomachinery design optimizations. This type of algorithm is known to be suitable to work in multiobjective optimizations [2]. Optimization techniques involving multiobjective algorithms have the advantage of searching a global optimum of the feasible space while in single-objective algorithms seek a local optimum, not guaranteeing that this point is also achieved the global optimum. Multiobjective algorithm presents a set of optimal solutions known as Pareto front, then allowing the designer to choose the most appropriate geometrical parameters or configurations according to the design requirements [3].

The evolutionary algorithm applied in this step was the Genetic Algorithm (GA) due to has the ability to create an initial population of feasible solutions, and then recombining them by using in a way to guide their search to only the most promising areas. GA works using the operators: crossover, mutation and reproduction. Also, each objective function is evaluated and values are assigned to each according to the operators. In crossover normally two chromosomes, called parents, are combined together to form new chromosomes, called offspring (child). After the chromosomes are compared each other and by reproduction process the best chromosome or chromosomes are selected to the next generation. In mutation process the operator introduces random changes into chromosome characteristics, turning it better or worse to be or not selected to the next generation. Together, the crossover, mutation and reproduction work to find an optimal solution or solutions.

The multiobjective algorithm used in this work was the non-dominated sorting genetic algorithm II (NSGA-II), developed by Deb [4], which has the capacity to alleviate the three difficulties existing in others algorithms: computational complexity, non-elitism approach and diversity problems. The great advantage of the NSGA-II is that it works with elitism. The elitism will ensure that the GA performance always grows with the passage of generations without change the computational time, which is a great advantage when compared with other algorithms [4].

The NSGA II was coupled to axial flow turbine preliminary design to handle some aerodynamic parameters to improve the efficiency of the turbomachinery.

4. Preliminary axial flow turbine design

The preliminary axial flow turbine design is usually the first step in the process of designing a turbine component. The main parameters are defined in this step in according to the aero-thermodynamics specifications provided from engine performance, compressor design and initial requirements defined at the conceptual design phase. In this phase, some parameters for the turbine design are necessary to follow the compressors design requirements such as rotational speed. Due to the favorable stream flow coming from combustion chamber into the axial turbine, the pressure gradient is much less concerned as compared to the compressor which has an adverse pressure gradient [1]. However, some complexity is added in the axial turbine design when vane and blade film cooling are present due to the difficulties to determine or predict precisely a correct temperature from the cooling techniques [1,6]. Nevertheless, the present turbojet in study was designed to work with turbine temperature below of 1200 k and therefore the film cooling was not required.

Others parameters need to be analyzed carefully such as the components size, efficiency and loading. These parameters are important because they influence directly the weight and fuel consumption of the engine, which are critical aspects in the aeronautics engine due to involves cost and performance.

The performance is directly linked with geometric parameters, which are responsible for the flow align and energy conversion. The Figure 1 shows the stations for the parameters calculation. The section 1 represents the parameters in the stator inlet; section 2 the stator outlet; and section 3 rotor outlet, the passage between stator outlet and rotor inlet are considered the same and there are not variations in the parameters. The first step is the calculation parameters in the mean line blade span.
4.1. Meanline Design Phase

The turbine preliminary design is initially based on the meanline condition and use the free vortex theory to extrapolate the parameters from hub to tip, the rotational and tangential speed are defined in according to the speed compressor which is ever more critical due to deceleration of the fluid [1,6]. The design parameters of the axial turbine are given by table 1.

<table>
<thead>
<tr>
<th>Parameters of original design</th>
<th>(m)</th>
<th>(\eta)</th>
<th>(T_0)</th>
<th>(p_{01}/p_{03})</th>
<th>(N)</th>
<th>(U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow</td>
<td>7.95</td>
<td>0.88</td>
<td>1173</td>
<td>2.15</td>
<td>28150</td>
<td>378</td>
</tr>
<tr>
<td>Isentropic efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature drop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>4.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean blade speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After the design considerations and using the loss model development by Ainley and Mathieson [7], the geometrical data and the efficiency obtained from equations 1 to 7 are showed in the table 2.

\[
\psi = \frac{C_p \Delta T_0}{U^2} \tag{1}
\]

\[
\hat{\psi} = \frac{T_2 - T_3}{T_1 - T_3} \tag{2}
\]

\[
\tan \alpha_2 = \tan \beta_2 + \frac{1}{\phi} \tag{3}
\]

\[
\tan \beta_2 = \frac{1}{2\phi} \left( \frac{1}{2} \psi - \hat{\psi} \right) \tag{4}
\]
\[ \tan \alpha_3 = \tan \beta_3 - \frac{1}{\phi} \]  
(5)

\[ \tan \beta_3 = \frac{1}{2\phi} \left( \frac{1}{2} \psi^- \right) \]  
(6)

\[ \eta_{1s} = \frac{\Delta T_s / T_{t3}}{1 - \left( P_{t3} / P_{t1} \right)^{\gamma - 1}} \]  
(7)

Table 2: Axial turbine original parameters.

<table>
<thead>
<tr>
<th>Blade row</th>
<th>Nozzle</th>
<th>Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>s/c</td>
<td>0.86</td>
<td>0.83</td>
</tr>
<tr>
<td>h</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>h/c</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>c</td>
<td>0.0395</td>
<td>0.0269</td>
</tr>
<tr>
<td>s</td>
<td>0.053</td>
<td>0.0425</td>
</tr>
<tr>
<td>n</td>
<td>28</td>
<td>47</td>
</tr>
<tr>
<td>( \eta_{1s} )</td>
<td>88</td>
<td>%</td>
</tr>
</tbody>
</table>

The parameters present in the Table 2 were set in the commercial software Axial Nrec®, which was used to development of the turbomachinery design. The velocity triangles are calculated in the inlet and outlet, after that the croqui and the 3D geometry was generated, the fig. 4 shows the croqui geometry in this step.

For the performance calculation was applied the AMDC loss model. Afterward these parameters have been determinate, the design was extrapolated for the 3D parameters. The results can see in the Figure 3 to 7.
Figure 3. Axial turbine 3D design view from Axial NRec®.

Figure 4. Stator 3D view from Axial NRec®.

Figure 5. Rotor 3D view from Axial NRec®.

5. Optimization Process
After the axial turbine preliminary design has been conclude the optimization process could perform some improvements in the results considering the fundamental parameters, as so as efficiency, loading and drop pressure. Several studies have been development in the turbomachinery optimization[7,8,9]. There are different algorithms, design variable, constraints and objective function that can be use, the choice of the best arrangement depend on the designer expertise. The most commonly algorithm applied for these cases are the evolutionary algorithms, especially the genetic algorithm[9]. These algorithms are chosen due to viability to work with multi-objective problems, where is possible to reach the global optimization design. Others advantages are the viability to work with discrete functions. The Figure 6 presents the typical flow chart for the optimization process. In this work was applied the NSGAIΙ for the optimization process.
5.1. The Genetic Algorithm NSGA II

The algorithm NSGA II (Nondominated Sorting Genetic Algorithm) was developed by Deb [3]. The algorithm presents the upgrade and reviews some weaknesses presented by the first version of the NSGA developed by the same author. In the first version the critical point of the algorithm was related about the high computational time and the range of the elitism and the need to specify the parameter sharing.

For the NSGA II these problems were eliminated, Deb proposed some changes in these key parameters. The main difference from other genetic algorithms is the way of individual classification in the society, the adaptability in the NSGA II is given according to the Pareto front that determines the non-dominance of each individual. The algorithm starts the process forward in the best front not dominated, it follows for the second best and so on until the worst in existence since the size of the entire population Rt is 2N. During this process the elitism is maintained always ensuring that the best individuals remain in the population [3].

The crossover operators ensure the development of individuals, and are responsible for the diversification of the population; the mutation operator is responsible for ensuring the operation of the entire search space.

In this algorithm a fast non-dominated sorting produce is implemented. The sorting of the individuals from some population according with the level of non-domination is a complex task: due to non-dominated sorting algorithms are in general computationally expensive for a large population size, so is adopted a solution performs an intelligent sorting strategy.
The algorithm implements a modified definition of dominance in order to solve constrained multi-objective problems efficiently.

The NSGA II allows both continuous, real-coded, and discrete, binary-coded, design variables. The original feature is the application of a genetic algorithm in the field of continuous variables. A parameter-less diversity preservation mechanism is adopted. Diversity and spread of solutions is guaranteed without use of sharing parameters, since NSGA II adopts a suitable parameter-less niching approach. It uses the crowding distance, which estimates the density of solutions in the objective space, and the crowded comparison operator, which guides the selection process towards a uniformly spread Pareto frontier.

5.2. The Design Variables
The design variables are responsible for handle some parameters in order to reach the best arrangement to optimum design.

In this project the design variables were:
- Inlet blade angle at mid span (Stator)
- Inlet blade angle at top span (Stator)
- Inlet blade angle at mid span (Rotor)
- Inlet blade angle at top span (Rotor)

The ranges for the designs variable were imposed in the mid and top span for each blade, Stator and Rotor. These variables there are influence in the geometry and consequentially in the efficiency of the turbomachinery.

5.3. The constraints
In order to keep feasible design results some constraints are necessary, respect to manufactory problems, Mach number and the loss associated with the high Mach number.

5.4. The objective function
The objective functions are the mathematical modeling equation responsible to handle the design and get to optimum design expected.
In turbomachinery preliminary design several aspects would consider to model the objective function and reaches the optimum arrangement, this choice is linked to the objective design.

6. Couple to Axial Preliminary Design
For the optimization process two different software were couple, the Axial NRec® and the ModeFrontier®. The fig. 10 presents the workflow of the design integration.

In this process the random population is create in the optimization software, so the design parameters values are choice and tested in the Axial Software.

The couple was implemented via Excel® macro, run in the Axial and then run in the ModeFrontier® mode.

The Excel macro was created to link the Nrec® and ModeFrontier® software, and run the following steps:
- Open the Axial,
- Load the file,
- Run and close the program.

For the optimization software, after the Axial® to be set to run in the Excel macro mode, is possible to create the integration between the software.

The Excel file is load in the modeFrontier via direct node, so the Excel will be the link to software communication.

The shift, in the design variable are tested and the objective final is compared with the stop criteria, so the steps are repeated until the stop criteria to be reached.

For this work the stop criteria was the iteration number of 1000 due to this number to be enough to reach a convergence results.

The table xx show the optimization parameters range for the design variables.
There are some aerodynamics and structures constraints, so the angle ranges were choice considering these aspects.
### Table: Design variables Range

<table>
<thead>
<tr>
<th></th>
<th>Range 1</th>
<th>Range 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>β angle stator (mid span)</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>β angle stator (tip span)</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>β angle Rotor (mid span)</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>β angle Rotor (tip span)</td>
<td>0</td>
<td>70</td>
</tr>
</tbody>
</table>

7. **Results**

The results shown the efficiency improvement, the new arrangement to the blade angles implied in the better flow alignment and deflection on the blade surface.

The fig. 11 show all arrangements possible to design configuration, the optimization process present the large range for the tip angle, on the other hand, the angle in the mid span is restrict in few options to reach the maximum efficiency.

[Figure 8. modeFrontier Framework example.](image)

[Figure 9. variable arrangement to reach the maximum efficiency.](image)
The parallel graphic gives to designer the possibility to test a lot of configuration and permit to decide the best option take care all the constraints involved in the design, as so as, the manufactory issues, robustness, etc. The influence of the beta angle in the stator is showed in the Figure 10, the angle in the mid span has more influence in the high efficiency, so the highest efficiency is for beta angle between 13 to 15 degree in the mid span.

![Figure 10: Inlet Stator angle at mid and tip span.](image1)

For the rotor the same comparison was performed the Figure 11, the highest efficiency is reach for 60 degrees.

![Figure 11: Inlet Rotor angle at mid and tip span.](image2)

The new angles were choice based in the bubble graphic, the table present the comparison between the original and optimized design, the efficiency in the optimized design was carry out the improvement.
Table 1: Original and optimized angle comparison.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Original</th>
<th>Optimized</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>β angle stator (mid span)</td>
<td>10</td>
<td>15</td>
<td>deg</td>
</tr>
<tr>
<td>β angle stator (tip span)</td>
<td>13</td>
<td>25</td>
<td>deg</td>
</tr>
<tr>
<td>β angle Rotor (mid span)</td>
<td>20</td>
<td>60</td>
<td>deg</td>
</tr>
<tr>
<td>β angle Rotor (tip span)</td>
<td>0</td>
<td>5</td>
<td>deg</td>
</tr>
<tr>
<td>η</td>
<td>0.88</td>
<td>0.92</td>
<td>-</td>
</tr>
</tbody>
</table>

The optimized angles provide a new velocity distribution, so the velocity triangles in the Rotor outlet were modified. The fig. 14 show the comparison between the velocity triangle before and after the optimization process.

8. Conclusion
Optimization process using evolutionary algorithm was applied in the axial turbine preliminary design, the techniques coupled two different software to handle the inlet blade angles at mid and tip span by the NSGAII. The results showed some feasible arrangement in the nozzle and rotor blades and carry out some improve in the efficiency. The evolutionary algorithm presents a powerful tool to turbomachinery optimization able to handle several design variables and couple some different software, this is important in the multidisciplinary field as so as turbomachinery design.

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10. References