

# Aerodynamic Optimization Strategies in Gas Path Systems: A Turbine Design Exploration

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## Abstract

One of the steps in the complex design of aircraft propulsion system consists of designing an efficient turbine gas-path. Gas-path geometry affects how the stators, rotors and duct will be designed. For this reason, the optimization of the gas-path needs to be done early in the development process of an engine. This is the concept of Preliminary Multi-Disciplinary Optimization (PMDO). At this stage of the design process, as many configurations as possible should be analysed. Due to the size of the design space to be explored thousands of configurations have to be considered. Consequently, each of these configurations needs to be simulated rapidly. To meet this requirement, an in-house 1D meanline code based on a correlation loss model is used.

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The optimization is done with a combination of direct optimization and design exploration. A simple direct optimization is used to generate a first version of the gaspath. Design exploration is achieved with an in-house Framework for Design Exploration (FDE). This framework includes Design of Experiment (DOE) and Surrogate Assisted Optimization (SAO) workflow. SAO is executed to find a global optimum configuration within user defined limitations. These design limits are defined according to a set of predefined limitations on factors (input parameters) and constraints on responses (output parameters). Furthermore, any responses can be set as an objective to be minimized, maximized or to be targeted for a specific value. To obtain such an optimized gas-path, a robust parametrization has to be developed. An

efficient parametrization will limit the number of nonphysical gas-path configurations in the design space without excluding any optimal configurations.

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This work focuses on optimizing the turbine gas-path to achieve one of three possible objectives. For most of the cases, the objective is maximizing efficiency. Another possible objective consists of minimizing the total length of the turbine while achieving a specific efficiency. Finally, this optimization tool can be used by turbine aerodynamicists to quickly analyse different stage configurations such as two versus three Power Turbines (PT). Iterating on the number of PT stages becomes much faster when the entire optimization process is automated.

## INTRODUCTION

The propulsion system of the future will be more efficient, more reliable, more compact and lighter. In order to meet these criteria, which are often contradictory, compromises must be made. For example, is increasing the isentropic efficiency by 1% of the entire engine still profitable if the reliability of the engine is affected? Several research projects aim at increasing the reliability of gas turbines (Mohammadi and Montazeri-Gh, 2016) to reduce the costs related to the maintenance of an aircraft engine. At the end it is probably an economic argument that will decide the decision to favour certain criteria at the detriment of others. Such decisions must be made as early as possible in the development cycle of a new propulsion system in order to avoid making major changes during development. This kind of unforeseen changes can be avoided by using a robust optimization system (Ghisu *et al.*, 2011, Herrera *et al.*, 2017).

Considering that the development of an aircraft engine involves experts in several fields such as the aerodynamics, combustion, secondary flow, performance, thermal analysis, etc., all these groups need to work together. These groups often work

sequentially and iteratively until there is convergence on a design that satisfies all the experts involved in this development process. Additional delays are thus added in the process of developing an aircraft engine. Moreover, one of the main challenges faced by engineers is to continually increase the efficiency of



each component of the engine while reducing development time.

In this research work, the preliminary design of an axial turbine is studied. In order to reduce design time without compromising design quality, new methods are being considered. Through the years, several in-house design tools have been developed. These tools range from simple spreadsheets to 2D and 3D numerical analyses. It is natural to think that a 3D CFD analysis is more accurate than a preliminary 1D analysis, but the latter, once well calibrated, can give results in agreement with experimental tests. For example, some studies show recent advancements in statorrotor stagger angle optimization that can reduce the computation time of a CFD analysis by up to 20% (Asgarshamsi *et al.*, 2015). Also, work on a 3D detailed analysis has shown how optimization can lead to profile loss and secondary loss minimization (Song *et al.*, 2018). On the other hand, the development of these detailed 3D optimization methods should not be done to the detriment of the development and optimization of the preliminary design tools (Dye *et al.*, 2007).

Such preliminary numerical design tools have always been used at Pratt & Whitney Canada (P&WC) to determine the key features of a turbine before moving to the advanced design stage. These tools must be able to determine the number of stages, the number of blades, the work done by the fluid in each stage and especially the geometry of the gas-path in addition to several other parameters. The work currently underway at P&WC aims, among other things, to integrate and centralize these tools and to reduce from a few months to a few days the preliminary design process of a turbine (Moradi *et al.*, 2015; Moret *et al.*, 2016; Twahir *et al.*, 2016). This work focuses on the preliminary design of the gas-path of an axial turbine. More precisely, the hub and tip radii (stator and rotor) of each of the stages are to be determined including the number of airfoils for each stator and rotor. At this point, only the basic information of the airfoils is established such as velocity triangles and throat area for stators and rotors. Although the RPM and total work are already fixed by the design of the compressor, the work done by each stage of the turbine is still unknown. The distribution of the enthalpy variation is established in order to improve the performances of the stages and to minimize the losses. In order to determine these preliminary design parameters, a code based on the quasi-1D theory is required to perform the analyses. This code (also referred as meanline) includes a

complete loss model adapted to a turbine (Kacker and Okapuu, 1982). In summary, the loss model used in this work includes profile losses, secondary flow losses, trailing edge losses and tip clearance losses (with or without a shroud). This meanline tool can be calibrated from an existing engine to reduce discrepancies between experimental and meanline data. Since code execution only takes a few seconds, several thousand designs can be done in a matter of hours. With an appropriate optimization method, it is now possible to improve the preliminary design of a multi-stage axial turbine while reducing the time required in achieving it.

The main advantage of a preliminary design code is that the calculation time is only a few seconds long unlike advanced design tools. Thousands of designs can be explored in less than 12 hours. Despite the impressive amount of points that can be tested, the storage space required for this data remains less than the disk space required for a single CFD solution. Furthermore, the optimization method is more efficient than proceeding by trial and error. Given the large number of parameters to vary in order to explore the design space, manual gas-path optimization is often reserved for an experienced engineer. The possibility of automating, in part, this traditional approach may allow engineers with less experience to contribute to the design and optimization of the gas-path of an axial turbine. One way to automate the optimization process is by using Surrogate models (Zhang *et al.*, 2016). Surrogate modelling has already been used for optimization and a review is provided by (Diaz-Manriquez *et al.*, 2016). Although optimization can be applied to several facets of aircraft engine design, the present work aims to focus on optimizing the gas-path of an axial turbine. Other types of optimization analysis are also possible once the gaspath is defined such as dynamic and structural analyses (Pugachev *et al.*, 2015).

In this paper, the methodology is presented describing the type of design of experiment (DOE) used as well as the surrogate assisted optimization (SAO) workflow. The parameterization for the unshrouded and shrouded stages is described. Next, three different types of analysis are presented that can influence the development of a turbine. The first analysis consists of optimizing the isentropic efficiency of a multi-stage turbine. The second analysis is aimed at adding a stage and studying the impacts on the overall efficiency of the turbine. In the third analysis, the objective is to minimize the total

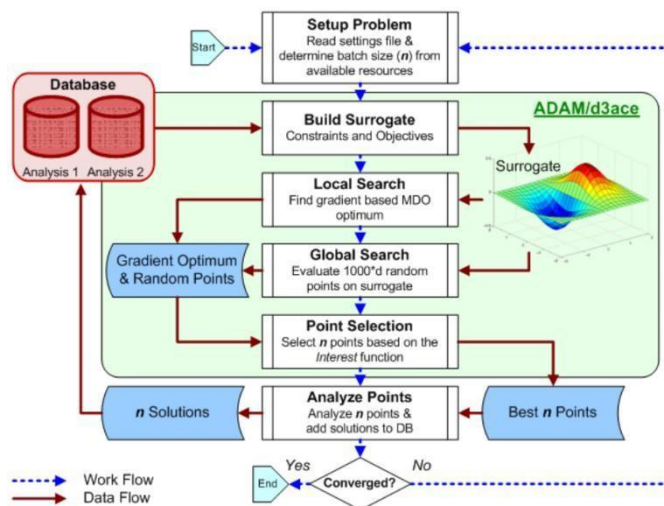
length of the turbine while achieving a target efficiency.

**METHODOLOGY**

Several optimization techniques are available. In this work, a combination of DOE and SAO is used. DOE methods are mostly used when a small number of learning points are available to define the design space, as is the case when an optimization analysis starts with an empty database. From an initial point, a series of points to be analyzed is thus generated according to the type of DOE selected. In this case, a Latin-Hypercube Sampling (LHS) algorithm is preferred. LHS is an advanced version of the Monte Carlo sampling method. The main disadvantage of DOEs in engineering applications is that they are effective in exploring only a limited area of the design space. In these engineering applications, the proposed points may represent nonphysical combinations or simply point in a direction recognized as irrelevant by an experienced engineer. To overcome this problem, the use of an SAO allows to focus on a smaller area of the design space while allowing to stay centered around the optimum point in the database. Whenever a local exploration detects a new optimum the future exploration area will centre around this new optimum and so on for the whole optimization process.

**SAO Workflow**

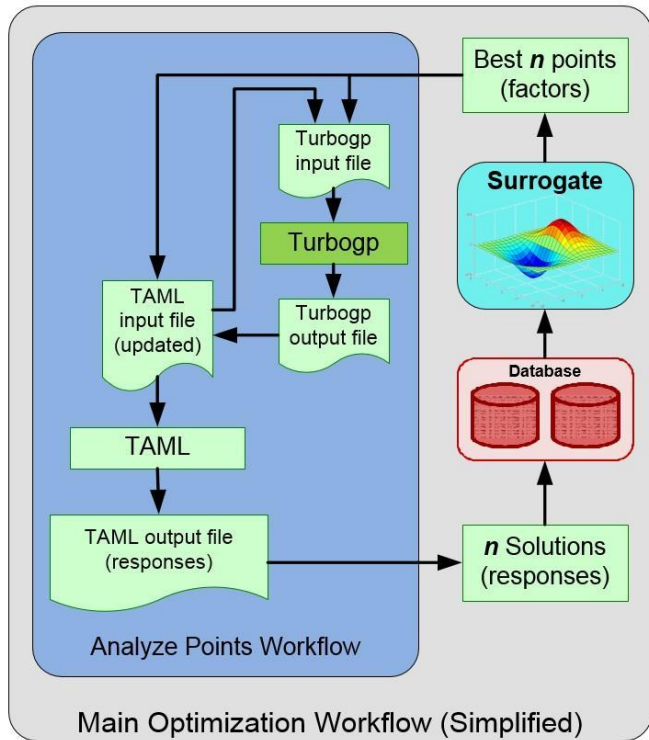
The workflow presented in Figure 1 allows a simplified visualization of the optimization process. The schema is used to analyse the workflow and dataflow of the optimization process. The first step of the workflow is to read the user's settings. It includes, among others, the number of learning points ( $n$ ) that are analysed at each optimization cycle until convergence is reached. The second step is to build the surrogate model for each constraint and objective. Once the surrogate models are built the optimum is located. In addition, 1000 points are sampled for the next optimization cycle. Of these 1000 points, the  $n$  best points are selected based on a function of interest. The purpose of this function is to intelligently explore the design space to converge as quickly as possible to a physically acceptable solution. Once the  $n$  points are selected, those points will be analysed by the turbine meanline tool. To determine if there is convergence, a criterion must be defined. If after  $m$  optimization cycles the optimum remains unchanged (within a tolerance) then convergence will be assumed.



**Figure 1 – Optimization Workflow**

**Analysis Workflow**

From the point of view of the optimization workflow, each of the  $n$  points considered may be seen as a black box. This black box can represent any analysis. In this case, the analysis represents the preliminary turbine design tool based on the meanline. This means the optimization workflow provided inputs parameters (factors) to the meanline and once the analysis is completed outputs (responses) are read by the optimization workflow. Figure 2 shows the different steps of the analysis workflow performed at each optimization cycle. When factors are generated, the first step is to generate the full meanline input file. The factor conversion to meanline input file is done by a tool called Turbogp (see Figure 2) which will be detailed in the next section. Once this input file is created the preliminary design tool is executed. The turbine meanline code is used to iterate and solve the 1D governing equations and loss models.



**Figure 2 – Analysis Workflow within the Optimization Workflow**

**Gas-Path Parametrization**

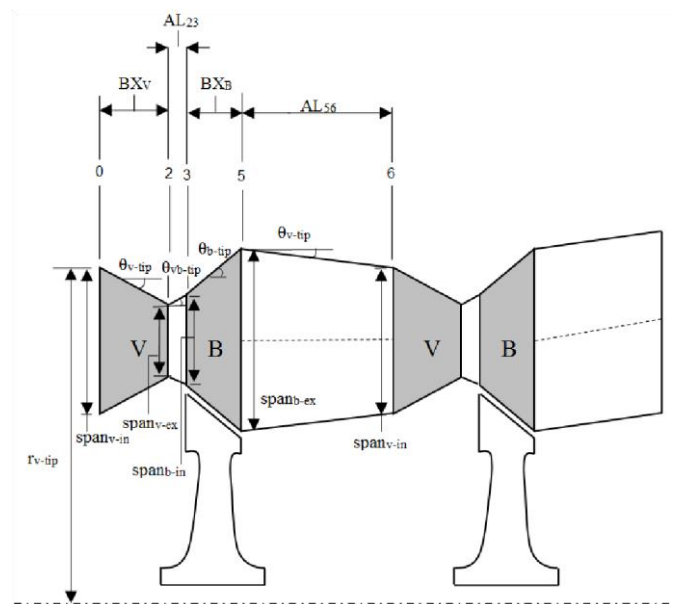
This section details the system inputs (factors) that need to be provided by the surrogate to the analysis workflow to generate the output (responses) that will be sent to the database. The execution of the meanline only lasts a few seconds, but several thousand points are needed to identify the optimal design of the turbine. The time required to optimize a 1-stage turbine may take several hours and more than one day in the case of a multi-stage turbine. This is due to the number of factors to be varied to find the optimal design. One aspect that can be exploited to reduce the calculation time is the parameterization of the system to be optimized. The goal is to have as small a design space as possible while being careful not to exclude optimal designs. For example, parametrizing the inlet of the first stator can be done by using a hub radius and a tip radius. Consequently, the span can be defined as

$$span = r_{tip} - r_{hub}$$

which becomes negative for some combinations of tip and hub radii. To limit non-physical cases an appropriate parameterization is sought. A more efficient parameterization is to use the tip radius and the span as factors to calculate the hub radius which become a response in

$$r_{hub} = r_{tip} - span$$

where the tip radius and the span may be imposed a maximum or minimum value. These limitations applied to the factors make it possible to avoid many nonphysical gaspath configurations and thus reduce the design space without excluding optimal configurations. In the case of unshrouded rotors, the parameterization consists of a series of flare angles and axial lengths (duct and chord) as illustrated in Figure 3 where two stages are shown. Another advantage of this parameterization is that the overall radial position of the gas-path is controlled by only one factor, the tip radius at the inlet of the first stator. Thus, the gas-path can vary significantly in the radial direction without causing geometric distortions.



**Figure 3 – Parameterization for Unshrouded Blades**

The second type of rotor found in a turbine is characterized by a shroud to reduce aerodynamic losses. These turbine stages often used as LPT or PT, operate at a lower rotational speed and are subjected to lower temperatures than unshrouded stages. Therefore, this module of the turbine is more compact which allows a more advantageous parameterization than the one used for the unshrouded stages. This new parameterization uses a spline to model the meanline. As shown in Figure 4, this spline is composed of three control points regardless of the number of stages. The slopes for the first and last control points of the meanline spline are calculated from the adjacent duct. Subsequently, cross-section area ratios must be provided (factors) to determine the span at the exit of each stage. Once the spans are calculated, two splines are added to define the gas-path at the hub and the shroud. At this point, only the slopes at the exit of the

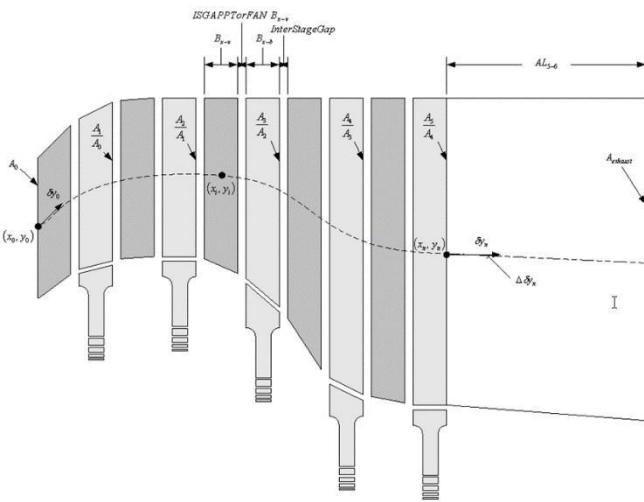
rotors are determined. To determine the stator and rotor input radii, the points of intersection between the splines and the LE / TEs are used. This ensures a smooth gas-path while reducing the number of factors provided to generate the shrouded stages of the turbine. Finally, the axial parameters (factors) of this module of the turbine are the axial chords of the components and the axial lengths of the ducts between components. With the complete parameterization established, it is now possible to optimize the gas-path of the turbine.

- 1) A maximum Equivalent Conical Duct Angle (ECDA) is imposed on each inter-spool duct.
- 2) A maximum flare angle is also imposed on the interspool duct.
- 3) Limits for flares angles are imposed on sides of the gaspath for each stage.
- 4) Minimum and maximum Zweifel coefficients are also imposed for each stage.
- 5) Limit for  $AN^2$  parameter (stress).

In all the test cases presented, RPMs are held constant as well as the enthalpy changes (work) across each spool. All these test cases are an initial research exercise to evaluate the potential of this optimization methodology. For an actual design, more constraints would be applied than in this work.

**Efficiency Optimization: Test Case 1**

Engine A has two spools with the first spool consisting of one unshrouded stage and the second spool consisting of two shrouded stages. In this test case, all turbine stages are optimized for efficiency. It is expected that in this specific case the design space is larger than in a real case where the inlet of the first stator should be constrained by the exit of the combustion chamber. In the original design, the stator and rotor of the CT (first spool) operate in a choked regime which results in high losses. The optimized design shifted the CT outward (see Figure 5) and therefore increased the crosssectional area and reduce the work ratio  $\Delta H/U^2$ . As a result, the Mach number decreased in the CT rotor to become subsonic. The reduction in the Mach number reduces the losses significantly and is responsible for increasing the efficiency by 4.45% in the first spool. Note that the constraint of ECDA in the inter-spool duct has been reached. The Mach number was also reduced through the two stages of the PT which helped increase the efficiency of the second spool by 1.42%. The overall increase in turbine efficiency is 2.79% (see Table 1). Note that due to increases in the crosssectional area, the  $AN^2$  parameter increased but did not reach the constraint value.



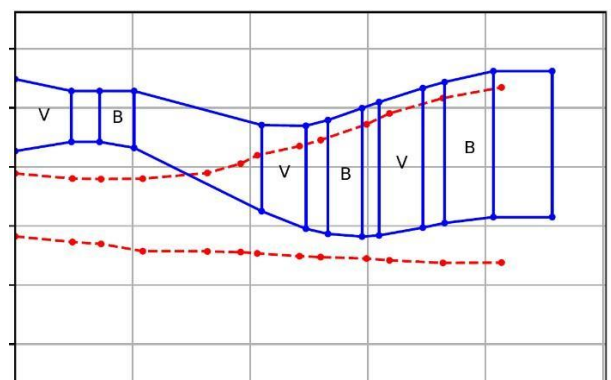
**Figure 4 – Parameterization for Shrouded Blades**

**RESULTS AND DISCUSSION**

Four test cases are analyzed using two engines (A & B) with different configurations. Engine A has two spools with the first spool consisting of one unshrouded stage and the second spool consisting of two shrouded stages. Engine B has two spools with the first spool consisting of one unshrouded stage and the second spool consisting of either one or two shrouded stages, depending on the case. For test case 1, Engine A is selected and all turbine stages are optimized for efficiency. For test case 2, Engine B with one shrouded stage is selected and only the power turbine is optimized for efficiency. For test case 3, Engine B with two shrouded stages is selected and only the power turbine stages are optimized for efficiency. For test case 4, Engine B with one shrouded stage is selected and only the power turbine is optimized for length. The isentropic efficiency of the initial configuration is held constant and the length of the turbine is minimized.

**Constraints for all Cases**

All cases have the same basic constraints;



**Figure 5 – Gas-path Visualization where dash line represents the original gas-path and the solid line**

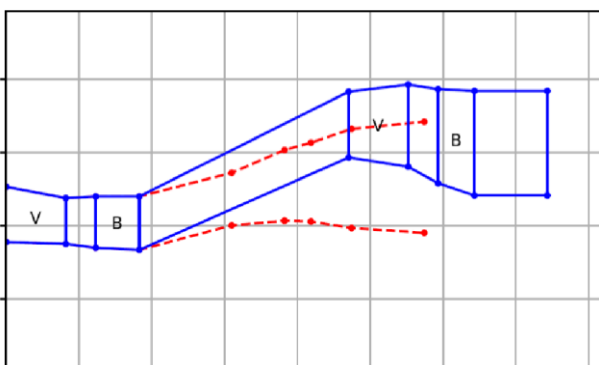
**represents the optimized gas-path.**

**(Engine A) Table 1 – Isentropic Efficiency Improvement (Engine A)**

	Spool 1	Spool 2	Total
Opt. eff.	+Δ4.57%	+Δ1.42%	+Δ2.79%

**Efficiency Optimization: Test Case 2**

Engine B has two spools with the first spool consisting of one unshrouded stage and the second spool consisting of one shrouded stage. This test case aims at only optimizing the PT stage of the turbine. As in test case 1, the optimization was achieved by increasing the cross-sectional area which allowed the Mach number to decrease and reach a subsonic regime in the stator of the PT. As shown in Figure 6, the optimal point was reached at the upper limit allowed for the inter-spool duct rise angle based on Market Feedback Analysis (MFA). This maximum duct rise angle provides a lower work ratio  $\Delta H/U^*$ . With the reduction of the Mach number comes a reduction in aerodynamic losses in the rotor which results in an increase in efficiency of 2.47% for the second spool and 1.04% for the entire turbine (see Table 2). For a real engine, more constraints would be applied than in this work. For example, the increase in PT tip radii would imply an increase of the outside diameter of the nacelle and therefore create an additional drag. In addition, the parameter  $AN^2$  has increased by 20% indicating that the stresses in the rotor blades will become more important. In addition, the stage reaction increased which implies the static temperature of the rotor must be closely monitored.



**Figure 6 – Gas-path Visualization. Efficiency Optimization of a Single PT Stage Turbine**

**(Engine B) Table 2 – Isentropic Efficiency Improvement after Optimizing a Single PT Stage Turbine. (Engine B)**

	Spool 1	Spool 2	Total
Opt. eff.	+Δ0%	+Δ2.47%	+Δ1.04%

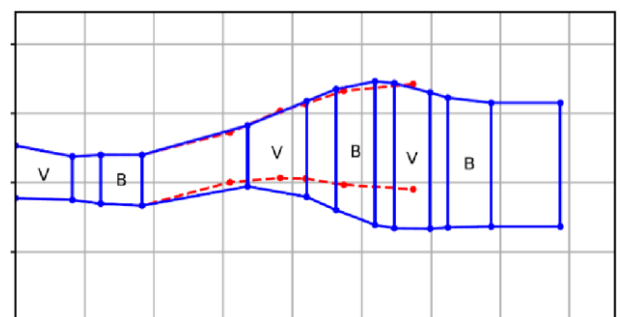
Opt. eff.	+Δ0%	+Δ2.47%	+Δ1.04%
<b>Stage Count Optimization: Test Case 3</b>			

**Stage Count Optimization: Test Case 3**

For test case 3, Engine B with two shrouded stages is selected as shown in Figure 7. Only the power turbine stages are optimized for efficiency. The first observation is that each stage does less work and consequently has a better work ratio. Also, the two stages of the second spool are in the subsonic regime. This is explained by the fact that the throat area is increased. Indeed, the  $AN^2$  parameter has increased by about 50%. As mentioned in the constraints section, the enthalpy change of each spool is conserved. However the split of the enthalpy change of the PT spool between the two stages is allowed to vary in the optimization process. At the optimal design, the split of the enthalpy change was 47% in stage 1 and 53% in stage 2 of the PT. This result implies lower rotor temperatures than the original design of the test case 2. In the end, an increase in the efficiency of the turbine of 1.19% compared to the single stage case is observed (see Table 3) which also represents an increase of 0.15% compared to the optimized case with a single stage PT (test case 2).

**Table 3 – Isentropic Efficiency Improvement after Optimizing the Two PT Stages Turbine (Engine B)**

	Spool 1	Spool 2	Total
Opt. eff.	+Δ0%	+Δ2.82%	+Δ1.19%

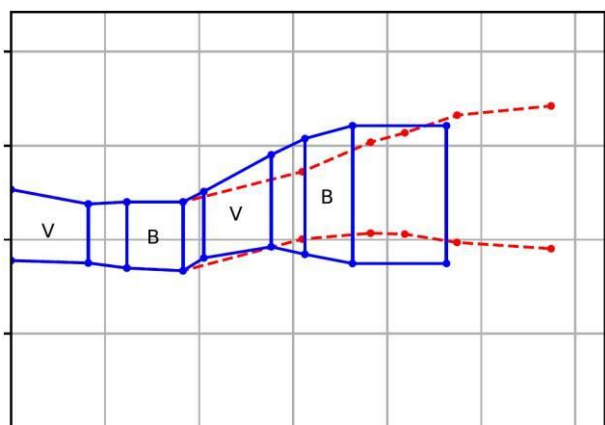


**Figure 7 – Gas-path Visualization. Efficiency Optimization of a Two PT Stages Turbine (Engine B)**

**Turbine Length Optimization: Test Case 4**

For test case 4, Engine B with one shrouded stage is selected and only the power turbine is optimized for length. The efficiency of the turbine is maintained while minimizing the length of the turbine. The main challenge in this case is to reduce the different axial dimensions of the turbine components without affecting the efficiency of the turbine as shown in

Figure 8. It is therefore necessary to avoid having large flare angles that could cause the separation of the boundary layers. In addition, to maintain the initial efficiency, it is necessary to limit the range in cross-section areas of the gas-path to avoid large increases in the Mach number and, therefore, the aerodynamic losses. Moreover, throats areas were held constant. The most limiting constraints were the Zweifel coefficients which prevented further reduction of the axial chords of the stator and the rotor. In the end, the optimized length represents a reduction of almost 25% of the initial length (see Table 4).



**Figure 8 – Gas-path Visualization. Length Optimization with the Efficiency Held Constant for of a Single PT Stage Turbine (Engine B)**

**Table 4 – Length Reduction with Constant Isentropic Efficiency of the PT (Engine B)**

	<i>Efficiency</i>	<i>Length</i>
Opt. gas-path	+ $\Delta 0\%$	$0.76L_{initial}$

**CONCLUSION**

Research done in recent years has allowed Pratt & Whitney Canada to develop its own optimization tools and apply these to different modules of an aircraft engine. This work presented the methodology developed to optimize the gas-path of an axial turbine. Other parameters such as the number of blades, stage reaction, etc. are also included in this optimization process. Several exploration methods have been developed and the one used in this work is a combination of DOE and SAO. To minimize the design space without excluding optimal designs, a parameterization using a combination of flare angles and spans is used for unshrouded stages. For shrouded stages, the use of a spline with three control points to define the meanline considerably reduces

the number of degrees of freedom of the gas-path. Fewer degrees of freedom imply a surrogate model that is simpler to calculate and represents significant savings in calculation time.

In this work, four test cases are studied. For all these research cases, the imposed constraints do not reflect all the constraints of a real engine design. The first test case with Engine A consists of an overall optimization of the three stages of the turbine. In this case, only basic geometric constraints were used which allowed greater flexibility in the exploration of the design space. Therefore, an increase in isentropic efficiency of 2.79% is observed globally. The goal of the second test case with Engine B is to optimize the efficiency of the power turbine only. An improvement of 1.04% is obtained. The third test case uses the same design as the second test case (Engine B) but with an additional PT stage. This configuration, once optimized, allowed an efficiency increase of 1.19% compared to the initial case or an increase of 0.15% compared to the optimized configuration with one PT. The last test case also uses the same design as the second test case (Engine B) as the initial point. In this case, the purpose of the analysis is to maintain initial efficiency while minimizing the total length of the turbine. The result shows a turbine 25% shorter than the original design while having the same isentropic efficiency.

The current meanline has a loss model which is continuously improved. An improvement concerning the losses in the duct is already developed and validated. Future work includes implementing this duct loss model in the meanline code which would allow removing the duct angle constraint in the optimization process. Optimization is becoming more and more important in modern engineering. It is natural to want to incorporate more optimization methods into the development of preliminary and detailed design tools. Artificial intelligence may become an indispensable component in optimization tool. It is expected to reduce the time needed to achieve optimal design for each module of an aircraft engine. At present, many preliminary design tools are incorporated into optimization methods. The compressor, fan, and combustion system are all modules that can benefit from the use of the latest technologies in terms of optimization.

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