AUTOMATION OF A TURBINE TIP CLEARANCE PRELIMINARY CALCULATION PROCESS

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ABSTRACT
An aeronautical gas turbine engine design is a multidisciplinary iterative process requiring an efficient interaction between each discipline tool and process in order to find the best compromise satisfying all the conflicting domains involved. The gas turbine engine design traditionally has two main stages: the pre-detailed design and the detailed design phases. During the first phase of the design, time is the main concern and the fidelity of the results may be impacted. This may compromise the engineers’ ability to thoroughly explore the envelope of potential designs and thus lead to the selection of a sub-optimal system concept. Considering the time-consuming analysis and resources-intensive tools used during the detailed design phase, it is extremely difficult to correct an unsatisfactory concept at that stage of an engine’s design. The use of Multidisciplinary Design Optimization techniques at a preliminary design phase (Preliminary MDO or PMDO) allows correcting this. PMDO system implementation requires bringing as much knowledge as possible in the early phases of the design where the freedom to make modification is at a maximum. This imposes the use of higher fidelity tools that communicate effectively with each other. Considering the impact of the turbine tip clearance on an engine’s efficiency and on preventing blades wear, an accurate tool to predict the tip gap is a mandatory step towards the implementation of a full PMDO system for the turbine design. Tip clearance calculation is a good candidate for PMDO technique implementation considering that it implicates various analyses conducted on both the rotor and stator. As a third and final step to the development of such tip clearance calculator satisfying PMDO principles, the present work integrates the results of the turbine rotor and housing thermal and stress analyses presented in two previous papers. These processes’ integration leads to the automatic calculation of a turbine stage’s closure during a given mission and the computation of the cold build clearance. Compared to a regular preliminary tip clearance calculation process, the proposed conceptual system offers a considerable increase in the accuracy of results and a time reduction. The system being automated and faster than the one of a regular pre-detailed design phase, it was possible to run optimisation loops in order determine the worst mission in terms of throat closure. The proposed system also allowed running a sensitivity analysis of the tip clearance leading to the identification of parameters that should be focused on when optimizing a turbine’s tip clearance. Finally, by requiring fewer user inputs this system decreases the risk of human errors while entirely leaving the important decisions to the designer.

INTRODUCTION
The design of a gas turbine engine is a multidisciplinary and iterative problem in which the best compromise has to be found between the conflicting disciplines involved: thermal, structural, aerodynamics, manufacturing, cost, weight, etc. The design of aero-engines traditionally follows two main stages: pre-detailed design and detailed design. At the pre-detailed stage, only a few groups are involved having their own set of specialized tools and methodologies, and the process is thus even more segmented within the groups to form sub-disciplines’ specialists. Panchenko et al.
(2002) explain that even though knowledge increases during the design process, the freedom to modify any part of the design decreases as shown in Figure 1, and/or induces major delays in the planning and a rise of design costs. It is consequently difficult to correct a bad concept at a detailed design phase. To correct this, Panchenko et al. (2002) suggest the use of Multidisciplinary Design Optimization (MDO) at the preliminary design phase, since it is at that stage that the biggest influence on the final product configuration can be made. As explained by Martins and Lambe (2013), the concept of MDO has been widely studied during the past 50 years. However, there is a lack of information in the literature about using this methodology during the early stages of design. Referring to Panchenko et al. (2002), NATO Science and Technology Organisation (2006) and Korte et al. (1998), the following steps are required to implement a PMDO system:

1. Develop a robust tool base: design tools based on parametrized CAD models, and advanced physics analysis tools which includes the development or improvement of correlations;
2. Apply single discipline optimization to individual analytical tools;
3. Create an integration framework, i.e. a software architecture enabling integration, communication and execution of several tools;
4. Implement multidisciplinary optimization with a clear statement of the design objectives, constraints and variables, and an appropriate selection of the algorithms.

A collaborative program was initiated between Pratt & Whitney Canada and the École de Technologie Supérieure to implement an MDO system for designing turbines at the predetailed design phase (PMDO). As part of this collaborative program, the development of a tip clearance calculation system is a mandatory step and a perfect example for the implementation of a PMDO methodology considering that it requires the design and analyses (thermal, structural and aerodynamic) of several turbine components as described in Figure 2. Lattime and Steinetz (2004) show that the prediction of a turbine’s tip clearance through a typical flight mission is essential in order to maximize an engine’s efficiency and its service life. Indeed, an increase of the tip clearance implies that the engine has to augment the turbine inlet temperature to develop the same thrust. If the disk temperature reaches its upper limit, the engine must be removed for maintenance. If the gap between the rotor and the shroud segments is larger than 1% of the blade’s height, an increase of 1% in tip clearance produces a drop of about 1% in efficiency (Hennecke, 1985). Based on this, a process predicting the tip clearance variation during a flight mission and calculating the cold build clearance necessary to avoid any rub is mandatory in an integrated turbine design system.

Figure 1: Knowledge vs. design freedom during the design process (NATO, 2006)

In order to develop a tip clearance calculator at the preliminary phase using PMDO principles, three steps can be identified: (1) the prediction of the rotor’s thermal and centrifugal growth (work published by Moret et al., 2017); (2) the prediction of the static components’ thermal growth (work submitted by Moret et al., 2018); and finally (3) the calculation of the radial gap between the blade tip and the shroud segment (subject of this paper).

This work is structured as follows: the methodology used to implement the proposed solution is first presented. This is followed by a chapter developing how the tip clearance is calculated and what is the mechanism of the gap size’s variation during a flight mission. This same chapter also develops how the cold build clearance can be determined. Finally, the paper concludes with a presentation of the main results obtained using the process introduced in this work. These results show the possibility to use this process to run iteration loops in order to calculate the cold build clearance. This final chapter also presents the first results obtained when running a targeted sensitivity analysis, thus demonstrating the optimization capability of the tool. These results finally allowed validating the proposition made in this work by exceeding the stakeholders’ criteria in terms of time gain and accuracy of the results.

METHODOLOGY

Based on the definition of Wieringa (2009), this work is a practical problem as opposed to a knowledge problem. Therefore the goal of this work is to identify the requirements of the industry regarding the research problem,
to propose a new process in response to those requirements, and to implement that proposal. The initial requirements were to improve the pre-detailed design process by proposing a more flexible, robust and adaptable design and analysis system. This means that the new system has to allow more rotor and stator configurations to be modelled while requiring limited number of input from the user. Based on standard design practice it is usually accepted for a regular pre-detailed phase to be about 30% off when compared to the detail design phase results. The new process aims at reducing the gap between pre-detailed and detailed design processes, and it should therefore improve as much as possible this 30% accuracy. Finally, the whole design and analysis process should not be slower than the current process.

As it has been developed previously by Moret et al. (2017) and Moret et al. (2018), and is summarized here for the reader’s benefit, tip clearance calculation over an entire flight mission implies the determination of the transient radial growth, due to temperature and rotational speed (for the rotor), of the turbine’s rotor and static components. Figure 3, first introduced by Moret et al. (2017), shows the architecture of the tip clearance calculation process being developed in this work, where each arrow represents data exchange. As one can see and as mentioned in the Introduction, the creation of a rotor and a stator analyses system are the two first steps toward the implementation of a tip clearance calculator. For reminder, these steps were published by Moret et al. (2017) and submitted for publication by Moret et al. (2018).

The integration of all the sub-systems shown in Figure 3 is handled by the use of a common and centralized data structure, and by means of Object-Oriented Programming (OOP) to create a framework repeated through all parts of the system.

**TIP CLEARANCE CALCULATION**

As introduced here above, the tip clearance variation during a specific mission can be calculated based on the growth of the rotor and stator components. These allow calculating two parameters: the transient closure of the gap between the airfoil’s tip and the shroud segment, and the initial value of the clearance, also called cold build clearance.

\[
\delta s = (r_{stator} - r_{rotor}) + (\delta r_{stator} + \delta r_{rotor}) = s_{cold} + \delta c
\]

where \( r_{stator} \) and \( r_{rotor} \) are respectively the initial radius of the shroud segment and airfoil tip, \( \delta r_{stator} \) and \( \delta r_{rotor} \) are respectively the radial growth of the shroud segment and airfoil tip, \( s_{cold} \) is the cold build clearance and \( \delta c \) is the gap closure. The closure is here defined as a negative value considering that the rotor’s growth is larger than that of the stator. The reason why the closure is defined as a negative value is that it is clearer when graphically representing the tip clearance variation. The clearance starts at its cold build value, and gets closer to 0 as the gap between the rotor and stator closes (i.e. the closure becomes more negative). The tip clearance graph is therefore a vertical translation of the graph of the closure, up by the value of the cold build clearance.

![Figure 3: Tip clearance calculation methodology (Moret et al., 2017)](image-url)
To calculate the tip clearance, locations need to be chosen where the radial position of the rotor tip and of the stator surface are to be evaluated. For the rotor, the node (from the finite element model) of the airfoil tip that experiences the maximum radial displacement through the entire flight mission was selected. Similarly for the stator, the radial position is measured at the node of the shroud segment gas-path surface that experiences the minimum growth through the same mission. This solution is conservative considering that the maximum growth of the rotor is compared to the minimum growth of the stator, which leads to the most severe closure value.

**The Physics of Tip Clearance Size Variation**

As seen in several references such as Lattime and Steinetz (2004), Howard and Fasching (1982) or Olsson and Martin (1982), many loads are acting on the turbine components and thus affect the tip clearance. These loads can be separated into two families: the engine loads and the flights loads. The engine loads include thermal, centrifugal, internal pressure difference and thrust loads; while flight loads include inertial, aerodynamic (external pressure) and gyroscopic loads. Some examples of these loads’ effect on the engine are shown in Figure 4. All these loads can be either axisymmetric or asymmetric, and their effect on the engine is presented in Figure 5. As demonstrated by Lattime and Steinetz (2004) and Olsson and Martin (1982), the axisymmetric loads with the most influence on the turbine clearance’s variation are the thermal and centrifugal loads. The two first part of this work published by Moret et al. (2017) and submitted by Moret et al. (2018) develop the transient growth analysis process of the rotor and static components due to these main loads. As developed later in this paper, the main asymmetric loads are accounted by considering their 3D effects on the engine when calculating the cold build clearance.

**Determination of the Cold Build Clearance**

The cold build clearance is the size of the tip clearance when the engine is not running. As explained by Lattime and Steinetz (2004), the cold build clearance is set by the most severe transient engine operation in terms of loads in order to avoid any rubs between the airfoil and the shroud segment during these critical manoeuvres. For that reason, aircraft acceptance tests include flight missions susceptible of producing such loads.

Figure 6 presents the engine rotational speed and the high pressure turbine tip clearance variation during a certain flight mission profile selected by Lattime and Steinetz (2004) for its high potential in terms of engine loads. As one can observe, two pinch points, i.e. points of maximum closure, are identified. The first one occurs during start-up, when the radial growth of the airfoil due to the thermal and centrifugal loads is maximal while the thermal expansion of the stator has just started. The second pinch point corresponds to a re-acceleration to take-off, also called re-slam, after a certain time at ground idle, called dwell time. This second pinch point can be more severe than the first one because the thermal and centrifugal expansion of the airfoil is maximal while the housing is still contracting around the rotor due to its cooling during the dwell time at ground idle. In particular, Howard and Fasching (1982) developed that this dwell time characterizes the severity of a re-slam manoeuvre. Based on this, one can conclude that an “optimum” must be found for the dwell time that leads to the “worst” re-slam possible. And this worst re-slam, if leading to the most severe pinch point, allows calculating the cold build clearance. To determine this “optimum” dwell time, iterative runs of the growth transient analyses of the rotor and housing assembly need to be executed.

Figure 7 shows the transient growth of the airfoil tip and of the shroud segment gas-path side, and the transient closure of the gap between them. This graph was obtained using the process described in this work for one of the test case that will be introduced later in this paper. As absolute values cannot be disclosed for proprietary reasons, the units of the Y-axis were normalized using the airfoil tip leading edge initial radius. In Figure 7, one can clearly observe the differences in response time of the rotor and stator for a change in throttle condition. It is these differences in response time that leads to the pinch points of critical closure.

![Figure 4: (a) Engine mounts and load paths, (b) Closures due to aero loads, (c) Closures due to thrust loads (Lattime and Steinetz, 2004)](image_url)

![Figure 5: (a) Effect of axisymmetric loads, (b) Effect of asymmetric loads (Lattime and Steinetz, 2004)](image_url)

![Figure 6: HPT tip clearance variation in function of time (Lattime and Steinetz, 2004)](image_url)
Figure 7: Rotor and stator transient growths and closure

Depending on the case, the re-slam manoeuvre may not always be the worst scenario during a flight, and this is why the entire flight mission needs to be simulated. This mission has to include specific steady-state and transient manoeuvres such as take-off, climb, cruise, shut-down in flight or re-slam, in order to capture all possible pinch points.

Once the closure is calculated for all these manoeuvres based on the centrifugal and thermal loads, 3D effects must be added to account for the asymmetric loads as explained by Lattime and Steinetz (2004). Some of the main 3D effects to be considered are due to the inertia loads (gravity), aerodynamic loads, engine bending due to the thrust loads, thermal growth of the seals, or to the gyroscopic loads. These 3D effects are measured during tests on the engine for specific conditions and used as reference by new concept engines of similar build. Table 1 shows an example from Lattime and Steinetz (2004) where some 3D effects are added to the axisymmetric loads to get the total closure for several flight manoeuvres. Considering that it might sometimes be complicated to measure all the 3D effects’ contribution separately, they can be grouped together as it is the case here with the flight load closure.

Table 1: Axisymmetric and asymmetric loads contribution to total closure (Lattime and Steinetz, 2004)

<table>
<thead>
<tr>
<th>Event</th>
<th>Asymmetric (speed &amp; thermal)</th>
<th>Asymmetric</th>
<th>Thrust</th>
<th>Thermal</th>
<th>Total closure (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climb (pitch)</td>
<td>-0.051</td>
<td>-0.006</td>
<td>-0.005</td>
<td>-0.004</td>
<td>-0.004</td>
</tr>
<tr>
<td>In-flight reverse</td>
<td>-0.009</td>
<td>-0.022</td>
<td>-0.011</td>
<td>-0.002</td>
<td>-0.042</td>
</tr>
<tr>
<td>Throat reverse</td>
<td>-0.014</td>
<td>-0.008</td>
<td>-0.001</td>
<td>0.000</td>
<td>0.043</td>
</tr>
<tr>
<td>Hard turn</td>
<td>-0.053</td>
<td>-0.007</td>
<td>-0.001</td>
<td>-0.005</td>
<td>-0.016</td>
</tr>
<tr>
<td>Airplane stall</td>
<td>-0.051</td>
<td>-0.008</td>
<td>-0.002</td>
<td>-0.007</td>
<td>-0.044</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

As introduced previously, the processes used to calculate the rotor and stator growths, which were developed by Moret et al. (2017) and Moret et al. (2018), have been integrated to calculate the gap closures during typical flight missions. The whole tip clearance calculation process being automated, it is possible to use it to run iteration loops. In the future, the objective is to use it, along with other similar systems dedicated to other disciplines, to run multidisciplinary optimization studies on the whole turbine design.

The tip clearance calculator was used on the first stage of the high pressure turbine of three different engines to validate its output and to produce the results presented in the following subchapters of this paper. Those engines are of different configurations: a turboshift is used as test case 1, a turboprop as test case 2, and a high-bypass ratio turbofan as test case 3.

Dwell Time Iterations

As explained earlier, one of the most critical manoeuvre in terms of tip clearance is the re-slam after a specific duration at idle. Iterative runs need to be executed in order to find the most severe dwell time for the stage’s tip clearance. These iterations aim at finding the “worst” dwell time possibly leading to the global pinch point. If the effect of the dwell time on the re-slam closure is ignored, the global pinch point might be missed as shown in Figure 8 (obtained for test case 2). Indeed, in Figure 8 the maximum closure for the first dwell time happens at the slam acceleration; but if the dwell time is increased, as for the three other curves, the maximum closure occurs at the re-slam. The closures were normalized using the airfoil tip leading edge initial radius.

Figure 8: Effect of the dwell time at idle on the mission’s global pinch point for test case 2

Figure 9 was obtained by measuring the closure at re-slam for various dwell times for the three test cases. Considering that actual values of closures or dwell time cannot be disclosed due to proprietary reasons, the closures were normalized using each test case’s respective maximum closure and the dwell times were normalized using the engines’ respective response time for the cooling air to pass from its value at take-off to its value at idle. In Figure 9 the values of closures are positives because of this normalizing of the Y-axis. The curves of the three test cases do not end at the same time due to the differences in their respective response time used to normalize the X-axis.

As one can see in Figure 9, the maximum closure does not occur at the same instant for the three test cases. However, the closure at re-slam follows the same trend for the three test cases: a non-symmetrical bell curve with a steep slope before the maximum and a flatter slope after this point. One can conclude that the closure will always have one unique optimal value for the dwell time and that this “worst” dwell time can therefore always be identified.

Figure 9: Re-slam closures depending on the dwell time
Sensitivity Analysis

Many parameters have an impact on a turbine stage’s tip clearance, but every one of them influences the tip clearance differently. However, when designing a turbine all these parameters cannot be modified to satisfy the analyst trying to optimize the tip clearance. Indeed, some parameters are set by performance requirements or by physical limitations for example. Figure 10, Figure 11 and Figure 12 show the difference, in percent of the reference value at re-slam of the detail design study used as target, between the closures at re-slam for different input and the reference value. The zero in the Y-axis therefore shows the detail design reference value.

Figure 10 shows the results of a sensitivity analysis done on the first test case for various parameters. As one can see, the airfoil size or the turbine inlet temperature have major impacts on the tip clearance. But as explained previously these parameters cannot be altered by an analyst for tip clearance optimization purpose. In the case of the airfoil size, the reason is that varying it will change the stresses the airfoil experiences and therefore its life, and will also have a major impact on its aerodynamic properties leading to a variation of the whole turbine’s efficiency. For the Turbine Inlet Temperature (TIT), the reason is that it is set by the combustion chamber to meet stages performance requirements. The airfoil cooling temperature has a significant effect on the tip clearance, but similarly to the TIT it cannot be modified to optimize the tip clearance. Indeed, the cooling temperature is controlled by the compressor stage at which the air is extracted. The disc bore width on the other hand has a limited impact on the tip clearance. This is expected considering that it is the bottom of the disc, which therefore does not grow much during a mission. However, this parameter (as well as the other parameters of the disc design) is controlled by the rotor lifting requirements.

This discussion leads to the question of identifying the parameters that can be modified by a tip clearance optimization program and that would lead to significant impact. Based on several previous designs, these parameters are:

- The cooling scheme of the housing and shroud segment assembly
- The total amount of cooling flow injected in the housing and shroud segment assembly
- The thickness of the housing
- The housing material

One can notice that these parameters are all affecting the static components, and that none impact the rotor. The reason is that the tip clearance prediction falls under the responsibility of the analysts designing the housing and shroud segment assembly. One of the main reasons justifying this is that, as it was introduced here above, the rotor’s design is affected by more constrains (centrifugal stresses, vibrations, aerodynamic of the airfoil, internal cooling of the blade, etc.) than the static components. The rotor being one of the most critical parts of the turbine, it is logical not to add an extra constraint on the rotor side, but to control the tip clearance through the static components’ design.

The cooling scheme can hardly be optimized by a program as it requires an analyst’s input to select where to put holes to allow cooling flows to affect certain areas. A program can however study the impact of varying the amount of certain flows or varying the total amount flow used to cool down a stage to see their impact on the tip clearance. As one can see in Figure 10, Figure 11 and Figure 12, the amount of flow used to impinge the shroud segment has a significant impact on the tip clearance. As it was demonstrated by Moret et al. (2018), increasing the impingement flow leads to a colder average temperature of the shroud segment and the housing. Having the temperature of the housing closer to the cooling temperature means a slower response of the whole stator, and therefore an improvement of the closure as the motions of the rotor and stator tend to be more in phase. This is explained by the fact that the disc has a large thermal inertia, and is usually slower to respond than the housing. Slowing down the housing therefore reduces the difference in response time between the rotor and stator.

As can be seen in Figure 10, Figure 11 and Figure 12, the total amount of cooling flow has an effect on the tip clearance which is very similar to the one of the impingement flow. This is explained by the fact that impingement cooling is the most efficient way to control the stator’s temperature. And it comes from this that the effect observed in Figure 10, Figure 11 and Figure 12 of varying the total cooling flow mainly comes from its direct effect on the impingement flow. The impingement flow is of course directly dependent on the total amount of flow available for a stator stage. Both the impingement flow and total amount of flow used have their lower limit set to nearly 0 and are limited to a maximum value by engine efficiency requirements. Indeed, the cooling air is extracted at the compressor and therefore corresponds to a loss from the entire engine point of view. As it is shown in Moret et al. (2018), the effect of the impingement flow on the housing temperature (and therefore on its radial growth) does not change significantly passed a certain value. This means that limiting the study of the effect of the impingement or total cooling flows to a maximum value does not impact much the results shown in Figure 10, Figure 11 and Figure 12.

The housing thickness is limited to a minimum value set by containment (i.e. structural integrity) requirements, and to a maximum value set by the weight of the engine. One can observe that, in the tolerable range within which the thickness can vary, this parameter has a limited influence on the tip clearance.

The materials considered for this study vary mainly in their thermal expansion coefficient. Three commonly used materials were compared and their impact on the tip clearance is shown in Figure 10, Figure 11 and Figure 12. As can be observed, these have the largest influence on the tip clearance when compared to the other parameters that a tip clearance optimizer should be allowed to modify. For the first test case, the reference material leads to the lowest re-slam closure value as its thermal expansion coefficient is the highest of the three materials considered. This explains why there is no value under 0 for test case 1. For the second and third test cases it is the opposite: the reference is the material
having the smallest thermal expansion coefficient leading to the highest re-slam closure; which explains why there are no values above 0.

![Figure 10: Sensitivity analysis of various parameters for test case 1](image)

![Figure 11: Sensitivity analysis of various parameters for test case 2](image)

![Figure 12: Sensitivity analysis of various parameters for test case 3](image)

**Speed and Accuracy Improvements**

In a regular process, analysts have to manually run thermal and stress analyses on the rotor and stator in order to get the tip clearance closure. Moreover, these analyses must be executed iteratively in order to find the “worst” dwell time. This can be a long procedure considering the time required to set up and run these analyses. It was demonstrated by Moret et al. (2017) and Moret et al. (2018) that the proposed system considerably reduces the time required to run these analyses. By executing the same cold build clearance study using the industry current process and using the process proposed in this work, it was found that the proposed system takes 25% of the time that is needed with the current process. Moreover, this system is executed on the click of a button where the regular process requires manual modification of input files which in turn could lead to human error.

As mentioned in the Methodology, the objective of this work was to improve as much as possible the estimated 30% accuracy of the current pre-detailed design process. The accuracies described in this section where calculated using Equation (2).

\[
\text{Accuracy} = \frac{(s_{\text{cold}} - s_{\text{cold,ref}})}{s_{\text{cold,ref}}} \tag{2}
\]

When comparing the cold build clearance calculated by this work with the final design value for the three test cases using Equation (2), it is found that the tip clearance calculator delivers output with an average accuracy of about 6% and with a standard deviation of 1.93%, as shown in Table 2. This means that by using this work’s proposed process, results can be produced with a considerably improved accuracy compared to the industry current process. This accuracy of about 6% is indeed a great improvement that outshines the currently accepted pre-detailed accuracy of 30%.

<table>
<thead>
<tr>
<th>Test case 1</th>
<th>Test case 2</th>
<th>Test case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>6.03</td>
<td>3.74</td>
</tr>
<tr>
<td>Average</td>
<td>6.08</td>
<td></td>
</tr>
</tbody>
</table>

Moreover, it is accepted that at a detailed design level the cold build clearance required to avoid rubs during the engine operation is predicted with an accuracy of 0.2% of the blade height. For the three test cases considered in this paper, this 0.2% of the blade height is equal to an average difference between the accepted prediction and the final designs of about 11% as shown by Equation (3). One can therefore conclude that this work’s system produces results with an accuracy level that is not only acceptable at a pre-detailed design stage, but also has potential for detailed design standards.

\[
\text{Eq. (2)} \Rightarrow \left( s_{\text{cold,ref}} \pm 0.2\% h_{\text{blade}} \right) - s_{\text{cold,ref}} \Rightarrow 0.2\% \times \frac{h_{\text{blade}}}{s_{\text{cold,ref}}} \approx 11\% \tag{3}
\]

**CONCLUSION**

It was demonstrated that the proposed system can automatically determine the “worst” dwell time at idle prior to a reacceleration to a take-off condition. Obtaining this time is important in the identification of a flight mission’s maximum closure which is a mandatory step in the calculation of the turbine stage’s cold build clearance. It was also showed that the closure at the re-slam manoeuvre for increasing dwell times follows a bell-shaped curve with one unique maximum meaning that the optimum dwell time can always be found.

The influence of various parameters on the tip clearance was studied through a sensitivity analysis. It was however found that only a limited number of parameters that have an impact on the tip clearance can actually be modified by the analyst in charge of optimizing the tip clearance. Prior to running the sensitivity analyses on three test cases, an
informed choice was made in order to limit the number of the studied parameters to the ones that could be useful to the study. These identified parameters are, by order of importance, the housing material, the total amount of flow used to cool the stator, closely followed by the impingement flow, and finally the housing thickness. This last parameter has a minor influence on the tip clearance because it is limited by containment and mass requirements. This targeted sensitivity analysis allowed giving guidelines for analysts by identifying the parameters worth being studied during a tip clearance analysis.

The study of the dwell time and the sensitivity analyses also showed the optimization capability of this system. These studies indeed highlighted the possibility of using the tools developed in this work to run iterative loops for a set of design variables. This process is therefore ready to be integrated in an optimizer along with other systems calculating more turbine output (efficiency, mass, life, etc.), and to run PMDO studies.

It is expected from the implementation of a PMDO system to improve the quality of pre-detailed level results considering that more knowledge is being injected early in the design process. It is also anticipated that such system would lead to an increase of productivity through the reduction of the overall design time. In this work it was proved that, when using a PMDO system, the time required to deliver a pre-detailed prediction of the tip clearance is reduced by 75% due to improvements in the process efficiency and to the integration of all the sub-systems required to run this study.

When compared to a current preliminary design phase process, it was found that the proposed system delivers results with an accuracy improved by 80%. The pre-detailed results are indeed passing from an accepted 30% accuracy to an average of about 6%, therefore exceeding the expectations set for this work. Finally, it was demonstrated that the accuracy of the proposed process is not only better than what was initially anticipated for such pre-detailed design system, but that it also passed the accuracy requirements for detail design results of about 11%.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CAD = Computer-Aided Design</td>
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</tr>
<tr>
<td>c = Gap closure</td>
<td></td>
</tr>
<tr>
<td>δc = Transient gap closure</td>
<td></td>
</tr>
<tr>
<td>hblade = Blade height</td>
<td></td>
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<tr>
<td>NATO = North Atlantic Treaty Organization</td>
<td></td>
</tr>
<tr>
<td>PMDO = Preliminary and Multidisciplinary Design Optimization</td>
<td></td>
</tr>
<tr>
<td>rRotor = Initial airfoil tip radius</td>
<td></td>
</tr>
<tr>
<td>rShroud = Initial shroud segment radius</td>
<td></td>
</tr>
<tr>
<td>δrStator = Transient radial growth of the shroud segment</td>
<td></td>
</tr>
<tr>
<td>δrRotor = Transient radial growth of the airfoil tip</td>
<td></td>
</tr>
<tr>
<td>Scold = Cold build clearance</td>
<td></td>
</tr>
<tr>
<td>δs = Transient tip clearance</td>
<td></td>
</tr>
<tr>
<td>tGroundIdle = Dwell time prior to re-slam</td>
<td></td>
</tr>
<tr>
<td>tCool = Cooling air response time</td>
<td></td>
</tr>
<tr>
<td>TIT = Turbine inlet temperature</td>
<td></td>
</tr>
</tbody>
</table>

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REFERENCES


