A 2D AXISYMMETRIC APPROACH FOR LOW PRESSURE TURBINE TIP SEALING DESIGN

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ABSTRACT

Low pressure turbine tip sealing design plays a key role in the overall turbine aerodynamic design, since it is responsible for a majority of performance loss. Meanwhile, given the complexity of its geometrical features from labyrinth seal configuration as well as the corresponding CFD modeling, design of such component in the purpose of reducing turbine leakage flow necessitates specific expertise from human expert. In the present study, instead of performing expensive 3D RANS simulation based design optimization, we address the tip sealing design of a low pressure turbine stage via a 2D axisymmetric approach. We show at first the consistency between 2D axisymmetric RANS simulations and their 3D counterpart in terms of flow characteristics within sealing and leakage mass flow. The 2D axisymmetric sealing design, which is parametrized considering geometrical constraints regarding mechanical and manufacturing feasibility, is optimized via a classification based genetic optimizer. 3 designs are accordingly derived from the optimization process and analyzed via 3D CFD simulation with turbine main flow in a RANS context. The effectiveness of the 2D design optimization is demonstrated by 3D validation. Furthermore, the effect of the tip sealing design on the main flow behavior is revealed from 3D simulation results.

INTRODUCTION

Sealing, which serves to reduce the leakage flow over the tip of blades, is key for modern turbomachines. The leakage flow is considered as a main source of aerodynamic losses according to previous studies (Denton et al. 1993, Gier et al. 2005, Peters et al. 2005). The losses can be effectively mitigated by reducing the tip gap. However, thermo-mechanical and manufactural constraints limit the reduction of this gap. Therefore, minimizing aerodynamic losses related to tip sealing given a certain gap value is an important problematic for modern turbomachinery design.

With the rise of computational capacities, Computational fluid dynamics (CFD) is not only used to reveal the aerodynamic loss mechanisms related to sealing design (Timothy et al. 2015, Timothy et al. 2016, Granovskiy et al. 2019), but also applied for sealing design optimization. Schramm et al (Schramm et al. 2004) applied the simulated annealing method to reduce the mass flow rate through a three-finned, stepped labyrinth seal. The step position and the step height are assumed to be parameters. Wlodzimierz et al (Wlodzimierz et al. 2010) applied the Goal-Driven optimization scheme to find a new design of the labyrinth and cavity geometry for the rotor tip seal with a honeycomb land. Recently, as machine learning techniques gain popularity within the turbomachinery community, data-based metamodels are also utilized for sealing design. In Sebastian et al (2017), metamodel-based optimization is compared with Goal-Driven optimization to design a two-finned labyrinth. In (Wlodzimierz et al. 2018), metamodel is used to reduce leakage flow through a straight-through labyrinth seal with a honeycomb and alternative land configurations. Meanwhile, the aforementioned design optimization work does not consider turbine configuration including 3D blade profiles. In the present study, design optimization is performed based on 2D axisymmetric CFD simulations, in which the main flow is taken into consideration. We present a parametrization approach to describe a two-finned labyrinth sealing design, based on which mechanical and manufacturing constraints are imposed.
A genetic optimizer, which is based on classification discriminating good solutions from bad ones, is utilized to solve the constrained optimization problem. The efficacy of the applied optimization is empirically benchmarked with the classic Bayesian Optimization technique on an analytical problem. An optimal design is obtained from the optimization process aiming at reducing the leakage mass flow. In addition to the optimal and baseline designs, 3D CFD simulation is performed also on another design, which is derived from the optimal one by increasing 0.1mm of the fin tip gap, to illustrate the effect of the gap value on turbine performance. We show the consistency between 2D and 3D simulations in terms of leakage mass flow prediction.

The remainder of the paper is organized as follows. Firstly, technical details concerning the 2D, 3D CFD simulations as well as design optimization are presented. After introducing the 2D optimization results, detailed analysis derived from 3D CFD calculations is presented. Based on the observations, we draw some conclusions and perspectives in the end.

**TECHNICAL DETAILS**

There is commonplace in turbomachinery to have labyrinth seals and their sealing principles for a variety of configurations. In the scope of turbine design, the decrease in turbine efficiency associated with an increase of leakage mass flow of blade tip labyrinth seal, which is caused by the pressure difference between the suction and pressure side of the blade as well as the relative wall movement (Raymond et al. 2006). Hence, the potential payoff of reduced leakage validates the continuing search for improved labyrinth seals.

The cell-centered, coupled, finite volume solver for compressible Navier-Stokes equations of the commercial software StarCCM+ is applied for the CFD simulations in the present study. 3D steady RANS simulations are performed for design validation, while 2D axisymmetric simulations are used for design optimization. The 2D axisymmetric model is illustrated in Figure 1. While the non-axisymmetric flow around the airfoil cannot be counted, part of turbine main flow is added into the shroud labyrinth seal model as inlet and outlet chambers allowing observation of interaction between main and leakage flow.

The main airflow path and 3D blade profiles are derived from an in-house low pressure turbine design, which includes a Turbine Frame (TF). TF serves to guide flow from High Pressure Turbine (HPT) to LPT. The actual TF design consists of a multibody vane row, where long-chord struts replace some of the vane airfoils. The bulky struts provide access for oil and cooling air supply lines. In the present study, the TF is considered in the 3D CFD simulations. For the sake of confidentiality, the main airflow path profile and the TF configuration cannot be communicated here. It is worth mentioning that the 3D simulations are conducted on the whole turbine model, which comprises three stages, to ensure the representativity of the present study. The sealing of the first stage is addressed. We show only the 3D CFD result of the first stage to be consistent with the corresponding 2D axisymmetric simulations and also for the sake of confidentiality. Total pressure and static pressure are imposed on respectively inlet and outlet of the turbine model. Different designs are compared at same inlet boundary condition and same stage total pressure drop.

The hexa-dominant unstructured mesh was generated by StarCCM+ for 2D simulations, as shown in Figure 1, whereas, structured hexahedral mesh prepared by AutoGrid was used for 3D design validation. In order to build high quality 2D mesh, 5 prism layers near sealing walls together with layer stretch 1.1 for whole computation domain are constructed. $y^+$ of the resulted mesh is less than 1 to take the wall shear stress into consideration, and to capture the vortex development in seal cavities.

Besides, more strictly mesh criterion is applied for 3D mesh of turbine main flow integrated with tip sealing, which is used to derive high accuracy solutions for turbine aerodynamic characteristics including mass flow, total-to-total efficiency, kinds of losses and flow field details etc. Therefore, wall $y^+$ less than 1 is required which is the same with 2D mesh, and expansion ratio of 1.2 for domains near blade surface along blade-to-blade direction is defined while
expansion ratio of 2 is kept for whole fluid domain. Besides, aspect ratio for flow near blade area is constructed to be less than 300 while the value for extended turbine inlet and outlet is less than 680, the maximum value for tip sealing zones is 160. In terms of skewness angle, the minimum value is 16 degree.

The κ-ω shear stress transport turbulence model of Menter (κ-ω SST) is applied in the current study for both 2D and 3D simulations. Airfoil suction separation bubble is a typical loss mechanism for LPT (Engber and Fottner 1984). γ-Reθ transition model (Jolan et al. 2018) is accordingly utilized in 3D simulations to capture the transition phenomenon in the main flow. Meanwhile, for the 2D axisymmetric simulation, the transition model is exempted, since flow around airfoil is not considered.

While the combination of κ-ω SST turbulence model and γ-Reθ transition model is shown in the literature to lead to accurate prediction of main flow characteristics, turbulence model selection for flow modelling within shroud labyrinth seal is less tractable. In the present study, limited by the capacity of StarCCM+ solver, we apply one turbulence model for both main flow and flow inside the cavity in 3D simulations.

For 2D axisymmetric simulations, we apply total pressure and total temperature on the inlet and static pressure on the outlet, the values of which are derived from the corresponding 3D simulation of the baseline design. A rotation speed is considered as well. For 3D CFD simulations, total pressure and total temperature are imposed on the first stage LPT inlet and the static pressure is imposed on the turbine outlet. The same rotation speed as the 2D simulations is applied on the rotating rows.

Based on the criterion defined, the structural hexahedral mesh was obtained and shown in Figure 2. The y+ value of the 3D mesh is less than 1. The first stage of turbine with a big struct frame in nozzle is illustrated in Figure 2. Mixing plane is used between the interface of stator and rotor, as well as the second fin tip connecting faces. The later mixing plane interface was built to eliminate the interface setting between main flow and sealing flow interaction planes, which forms an inseperable fluid domain in shroud sealing inlet and outlet with main flow. Although values were different from 2D simulation, profiled total pressure, profiled total temperature at inlet and static pressure at outlet were imposed on the fluid domain according to the turbine working conditions in 3D simulations. Second-order implicit time integration and second-order upwind spatial discretization were used for the solver. The convergence criterion for residuals was defined to be less than 10^{-4} for both 2D and 3D simulation with the help of pre-load initial pressure, temperature and velocity fields into the computation domain, which speeds up the convergence significantly.

![Flow direction](image)

**Figure 2 3D mesh illustration.** (a) illustration of the row of TF and the row of the rotor blade; (b) illustration of the rotor tip sealing.

**Parametrization**

Due to the axisymmetric characteristic of shroud labyrinth seal, the parametrization is able to be performed in 2D space. 13 parameters are selected to describe the structure design of labyrinth seal. For the sake of confidentiality, only part of detailed parameters is shown in Figure 3 and Table 1. It should be noted that the symbol “-” means that the direction changed to left, similarly, the symbol “+” means that the direction changed to right in Figure 3. The range of optimized variables are not shown here for confidentiality reasons.

It is worth mentioning that in the present study, we would like to reduce the leakage mass flow for a given sealing gap (C). Consequently, the sealing gap (C) is not addressed in the design optimization process. We illustrate the effect of the sealing gap in the validation phase, the details of which will be given in the next section.
Figure 3 Parametrization of tip labyrinth seal

Table 1 Design parameters

<table>
<thead>
<tr>
<th>Variables</th>
<th>Meaning</th>
<th>Unit</th>
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<tbody>
<tr>
<td>C</td>
<td>Sealing gap</td>
<td>mm</td>
</tr>
<tr>
<td>SD</td>
<td>Relative step axial location</td>
<td>mm</td>
</tr>
<tr>
<td>$\theta_1$</td>
<td>First fin angle</td>
<td>degree</td>
</tr>
<tr>
<td>$\theta_2$</td>
<td>Second fin angle</td>
<td>degree</td>
</tr>
<tr>
<td>KP</td>
<td>Pitch change</td>
<td>mm</td>
</tr>
<tr>
<td>RAT</td>
<td>Ratio of pitch changing</td>
<td>/</td>
</tr>
<tr>
<td>CL</td>
<td>Point movement on the right side</td>
<td>mm</td>
</tr>
<tr>
<td>CR</td>
<td>Point movement on the left side</td>
<td>mm</td>
</tr>
<tr>
<td>RA1</td>
<td>First fin rotation</td>
<td>degree</td>
</tr>
<tr>
<td>RA2</td>
<td>Second fin rotation</td>
<td>degree</td>
</tr>
<tr>
<td>LR</td>
<td>Line movement on the left side</td>
<td>mm</td>
</tr>
</tbody>
</table>

Design optimization

Figure 4 Optimization process. The geometrical design is firstly assessed by the predefined constraints. If the constraints are satisfied, then CFD evaluation will be carried out on the geometrical configuration. Otherwise, a big leakage mass flow will be associated with the design. The design data as well as the corresponding leakage mass flow will be processed by the optimization algorithm implemented via the ‘zoopt’ library.
The overall design optimization process is described in Figure 4. The design space is constrained taking mechanical and manufactural considerations. From a mechanical point of view, the distance between the two fins should be as small as possible and the fins should be centered approximately in the axial direction on the stacking line of the rotor blade as illustrated in Figure 5. Threshold values are imposed on the gap and axial center of the fins, which are calculated with the designated design parameters, to ensure that mechanical property of the rotating system is not jeopardized. In terms of manufactural consideration, firstly, keep tip width of 1mm as the minimum fin tip manufacturing capability, although the thinner tooth can mitigate heat propagation through the cavity into the blade with a sharp leading edge and restrict more primary flow (Raymond et al. 2006). Secondly, the short distance from the step on the sealing stator to the sharp fin (defined as Relative step axial location, i.e. SD) is limited by turbine rotor axial movement as well as honeycomb installation spacing requirement. Hence limitations are imposed on the two SD distances for the two fins in the sealing design.

![Figure 5 Constraints from mechanical consideration](image)

A classification-based optimization algorithm RACOS (Yang et al. 2016) is applied for design optimization. In each iteration, the algorithm discriminates the ‘good’ and ‘bad’ solutions according to an evolving threshold and samples based on the trained binary classifier. As the threshold value decreases during the optimization process, the algorithm converges progressively to the global optimum. We refer to (Yang et al. 2016) for more details and theoretical bases of the algorithm. In the present study, as previously explained, mechanical and manufactural constraints are considered in addition to the objective function, i.e. leakage mass flow. In practice, at each iteration, the generated solution is evaluated at first with the constraint functions. If the constraints are not respected, an empirical large value with respect to the baseline leakage mass flow is returned to the algorithm as the objective function value and the corresponding CFD simulation is exempted, so that the algorithm can directly classify this solution as ‘bad’. The applied analytical constraint functions divide the design space into feasible and unfeasible regions. Assigning big objective value to unfeasible samples forces the algorithm to search within the feasible region.

An empirical comparative study is performed on a 20-dimensional Ackley function to illustrate the effectiveness of this approach with respect to the classic Bayesian Optimization technique. The Ackley function is subjected to a constraint, which is described as follows:

\[ f = -a \cdot \exp \left(-b \cdot \sqrt{\frac{1}{D} \sum_{i=1}^{D} x_i^2}\right) - b \cdot \exp \left(\frac{1}{D} \sum_{i=1}^{D} \cos(c \cdot x_i)\right) + a + \exp \left(1\right), \]  

\[-1 \leq x_i \leq 1, \sum_{i=1}^{5} x_i \leq 2.0\]

Expected Feasible Improvement is applied as acquisition function for Bayesian optimization (Jones et al. 1998, Jin et al. 2021). Gaussian process is utilized as surrogate model. For this 20-dimensional problem, an initial Design of Experiment (DoE) is constructed with 90 samples and 10 subsequent optimization iterations are performed. For RACOS, as explained, the constraint is considered by assigning a big objective function value to unfeasible samples. To be comparable with Bayesian Optimization, totally 100 iterations are performed. We conducted repetitively 10 runs for each approach to be statistically representative, the results of which are illustrated in Table 2.

<table>
<thead>
<tr>
<th>Table 2 Comparison between RACOS and Bayesian Optimization on the empirical analytical problem</th>
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</thead>
<tbody>
<tr>
<td>Best solution</td>
</tr>
<tr>
<td>RACOS</td>
</tr>
<tr>
<td>Bayesian Optimization</td>
</tr>
</tbody>
</table>

It is can be seen that for this relatively high dimensional problem, RACOS outperforms Bayesian Optimization. This observation is consistent with the results on non-constrained high-dimensional optimization problems in the literature. Meanwhile, for classification-based optimization algorithm, the efficacy is strongly impacted by the so-called ‘Error-Target-Dependence’ (Yang et al. 2016), which characterizes the dependence between the classification error and the target region. If the problem optimum is located too close to the feasible region border, the optimization performance will strongly depend on the classification precision, which will have an unfavorable effect on the constrained problem resolution. The overall applicability of the applied practical approach will be further assessed with more benchmark problems in the future. In the implemented process, only the feasible solutions are recorded.

**Results and analysis**

The optimization process via 2D axisymmetric simulation is illustrated in Figure 6(a). As explained, only the designs satisfying the predefined constraints underwent CFD simulation. The overall computational time for the optimization via 2D simulation is about 10 hours with 25 cores, Intel Xeron Gold 5118 @ 2.30GHz, 256 GB memory based on the help of pre-load initial pressure, temperature and velocity fields into the computation domain. The design, that leads to the lowest leakage mass flow in 2D evaluation, is selected as the optimal design in the present study. The optimal design has more inclined fins compared to the baseline, as illustrated in Figure 6(b). This trend is consistent with previously reported designs in the literature (Wlodzimierz et al. 2018).

2D axisymmetric CFD results of the optimal and baseline designs are described in Figure 7. In addition to the optimal and baseline designs, another design is generated by increasing the sealing gap of 0.1mm of the optimal design to illustrate the effect of sealing gap. 3D CFD validation simulations are performed on these three configurations. It can be seen in Table 3 that the 3D simulations confirm the trend predicted by 2D simulations in terms of leakage mass flow over main mass flow. With the leakage mass flow reduction, the stage total-total efficiency is accordingly increased from the baseline to optimal design. Furthermore, the design bigger sealing gap leads to more important leakage mass flow compared to the other two, which demonstrates the primordial role of sealing gap value in leakage mass flow control.
Table 3 Results comparison between baseline and optimum

<table>
<thead>
<tr>
<th></th>
<th>2D leakage mass flow/main mass flow</th>
<th>3D leakage mass/main mass flow</th>
<th>Stage total-total efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline design</td>
<td>1.34%</td>
<td>0.84%</td>
<td>91.73%</td>
</tr>
<tr>
<td>Optimal design</td>
<td>1.27%</td>
<td>0.75%</td>
<td>92.0%</td>
</tr>
<tr>
<td>Optimal design with bigger gap</td>
<td>/</td>
<td>0.93%</td>
<td>91.71%</td>
</tr>
</tbody>
</table>

Figure 8 gives the relative Mach number distribution on a 2D section of the 3D CFD simulations. It is obvious that the exit vortex induced by optimized sealing is stronger than the original one as highlighted by the streamline description, which leads to a higher flow resistance and traps more leakage flow in it. Hence the leakage mass flow is reduced although sealing gap keeps the same for both cases. Furthermore, the area underneath the sealing exit where the relative Mach number is smaller than elsewhere in the main flow is reduced thanks to stronger exit vortex. For the design that has bigger sealing gap, despite an apparent increase in leakage mass flow, the inclined fins render the exit vortex stronger, which mitigates the impact of leakage flow on main flow. That is why, as given in Table 3, the optimal design with bigger sealing gap leads to similar total-total efficiency compared to the baseline design, which has small gap.

Figure 8 Relative Mach number distribution. In the highlighted area, the streamline description is overlapped on the relative Mach number distribution, which is given on the addressed section and the exit section.

Discussion

Different turbulence models, e.g. Realizable κ-ε (Granovskiy et al. 2019), Standard κ-ε (Porreca et al. 2008) and κ-ω SST (Jie et al. 2012), are used to describe the flow development within sealing. In the present study, the combination of κ-ω SST turbulence model and γ-Reθ transition model is applied. Such combination demonstrates its effectiveness in describing the profile loss mechanisms in low pressure turbine (Jolan et al. 2018). However, the transition model is not commonly used for sealing flow modelling in the literature to our best knowledge. As explained, stronger vortex within sealing prevents leakage flow from interfering the main flow. Application of transition model may lead to an underestimation of the vortex intensity, which influences the leakage mass flow assessment. A dedicated study for transition modelling application on sealing flow simulation, especially on the interaction between leakage and main flow, will be an important route for our future work.

In the present study, only the first stage simulation result is presented. In reality, the first stage sealing has impact not only on the first stage but also on the second stage stator. In steady RANS simulations, the stage-stage interface is represented by a mixing plane, which does not allow to fully describe the effect of the periodic wake. Therefore, sealing impact on the subsequent stage will be considered in the future through transient CFD simulations.

Conclusion

In the present work, we propose a 2D axisymmetric approach for tip sealing design of a low pressure turbine stage. The tip sealing is described by 13 design parameters, on which mechanical and manufactural constraints are defined. A
A classification-based genetic optimization algorithm is utilized for the constrained optimization problem resolution. We show consistency between 2D axisymmetric simulation and its 3D counterpart in terms of leakage mass flow prediction. The optimized design reduces the leakage mass flow by roughly 10% compared to the baseline design and increases 0.3% stage total-total efficiency. Our future work mainly consists in deepening the understanding of tip leakage loss mechanism by further investigating the applicability of different turbulence models and extending the study to transient phenomena.

REFERENCES