Conceptual Design of Steam Turbine Labyrinth Seals Considering Thermal Compensation and Topology Optimization

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Abstract. Labyrinth seals (LS) are used in gas and steam turbines. These seals usually present thermal expansion in their fins, which can generate damages in the component with a subsequent increase of leakage. This problem can be explored and solved from the conceptual design stage in order to increase and optimize the seal performance. This work shows a methodology for the analysis and conceptual design of steam turbine labyrinth seals, considering thermal compensation and the topology optimization method (TOM). In this work, the TOM is applied as a tool for improving the seal thermal performance and it is implemented in the COMSOL CAE software. As result, several conceptual designs of optimized labyrinth seals for steam turbines are obtained and compared with a non-optimized seal. For the steam turbine optimized seal, designs with 44%, 76% and 50% reduction in the average radial displacement of the fins were obtained. In addition, it was determined that, due to thermal expansion wear, in a non-optimized steam turbine seal a 42% increase in leakage through the seal can occur.

Keywords: labyrinth seals, labyrinth seals design, labyrinth seals leakage, thermal compensation, topology optimization.

1 Introduction

Turbines convert energy within a fluid to mechanical energy. In these machines it is common to find sealing systems in different regions of it, and some of them are built with labyrinth seals (LS), which are a type of seals that allow free rotation of the moving shaft while separate two regions at different pressure, by means of a clearance space between the rotor and stator fins and surfaces. However, this clearance space prevents a full leakage sealing [1]. In steam turbines (ST), operation conditions of temperature and pressure reach relatively high values. These conditions, combined with the temperature increase in the flow through the seal, produce thermal expansion of the seal fins. As a result, there is a decrease in the clearance gap that can lead to an interference between components of the LS, which can produce excessive sealing material loss through the rubbing mechanism and, subsequently, an increase of the clearance. This permanent removal of material can result in a leakage increase [2].

In order to improve the sealing performance of the LS, the use of TOM is proposed in this work. Researchers have done works that use optimization strategies based on genetic algorithms, which is used to achieve an optimal configuration of a LS with squared cavities from a set of determined geometric configurations, with a subsequent simulation [3]. Also, other researchers have performed parametric optimization based on hybrid surrogate models [4], neural networks [5] and discrete variation of geometric parameters while observing the effects on fluid behavior [6], [7]. However, no studies have been found related to the optimization of LS using the TOM seeking for thermal compensation.

Several studies have addressed the effect of high temperatures on LS, where it has been found that due to thermal expansion of the seals, there is a reduction in their clearance and consequently a reduction in leakage flow [8], [9]. This effect could be a positive consequence in terms of leakage, but insufficient clearances in LS limit cooling flows, cause friction and interface damage, lead to overheating of downstream components, and limit the lifetime of such components [10]. The present research is oriented to apply an optimization strategy that allows obtaining the design of a LS with adequate performance. A methodology is proposed to study and then optimize the LS, with the objective of having thermal compensation, i.e., minimizing thermal expansion in the clearance spaces. The conceptual designs obtained allow having a general idea of what topologies or geometries the LS should have if they are to have thermal compensation, which is desirable from a leakage performance, maintenance and components replacement point of view. The set of fluid dynamics and thermo-structural simulations, as well as the optimization process were implemented in the COMSOL Multiphysics CAE software, version 6.0, with the finite element method (FEM).

In order to know the behavior of a labyrinth seal in real operating conditions, its application was selected in a 66 MW Alsthom Rateau steam turbine for power generation, with nominal working temperature of 510 °C. The unit operated in the Termobarranca plant of the Electrificadora de Santander, in Colombia, before its closure and dismantling. An application of an internal seal was selected as a case study, without losing generality in terms of the methodology. This case was also studied due to the physical availability of one of the annular segments of an SL belonging to this particular unit.

2 Methodology for numerical simulations and optimization

2.1 Fluid dynamics and thermo-structural model

Because high vorticity flow occurs in the LS, which is primarily responsible for the pressure loss in the seal, the k-ω Shear Stress Transport (SST) turbulence model was used [11], which has given good accuracy in predicting the size of vorticities and flow separation points [12]. It is a hybrid model that combines the strengths and superior performances of the models based on the RANS k-ε and k-ω equations. In validation studies of different numerical models for flow simulation in LS [13], it has been found that the SST turbulence model is suitable for modeling compressible flows with large velocity gradients, as is expected in flow through the seal.

Heat transfer in fluids and solids is simulated under the concept of conjugate heat transfer. Energy conservation is considered, and the fluid model becomes non-isothermal. On the other hand, heat transfer in solids is solved with the equation obtained by doing a heat balance. A cylindrical-axisymmetric geometry was assumed with small deformations. In the LS solid undergoing thermal expansion deformation occurs. Finally, the multiphysics model contains all coupled (physical) interfaces.

The problem is solved under stationary conditions, and the steam is assumed to be incompressible, in order to have more critical conditions of temperature, although steam is a compressible gas. The material of the solid LS is assumed to be AISI 403 stainless steel, because it is a representative material of steam turbine components [14], and its mechanical and thermal properties are evaluated with temperature. The mesh used for the solid and fluid domains is in convergence. The fluid pressure at the inlet is 8.63 atm, and the inlet temperature is 345 °C; the outlet pressure is 6.5 atm. All the external boundaries were assumed as adiabatic, except the fluid-solid interface where heat transfer occurs. The solid LS is assumed to be fixed in its base.

2.2 Topology optimization model

In order to achieve thermal compensation of the LS, the optimization problem is stated as:

$$\begin{aligned} &\underset{\rho_e}{minimize} \quad Q(\rho_e) = \sqrt{\left[\phi(\rho_e)^2\right]} \\ &subject\ to: \quad \sum_{e=1}^{N} v_e \rho_e \le V, \quad 0 < \rho_{mín} \le \rho_e \le 1, \quad e = 1, \ldots, N \end{aligned} \tag{1}$$

Where Q is the objective function, ϕ is a scalar value of the probe used to measure displacement, ρ_e is the (relative) density of the discretization finite element e, N is the total number of finite elements in the discretization, v_e is the amount of material (or volume) of the finite element, V is the amount of material available for design, and $\rho_{mín}$ is a minimum density value set to prevent any singularity in the equilibrium problem.

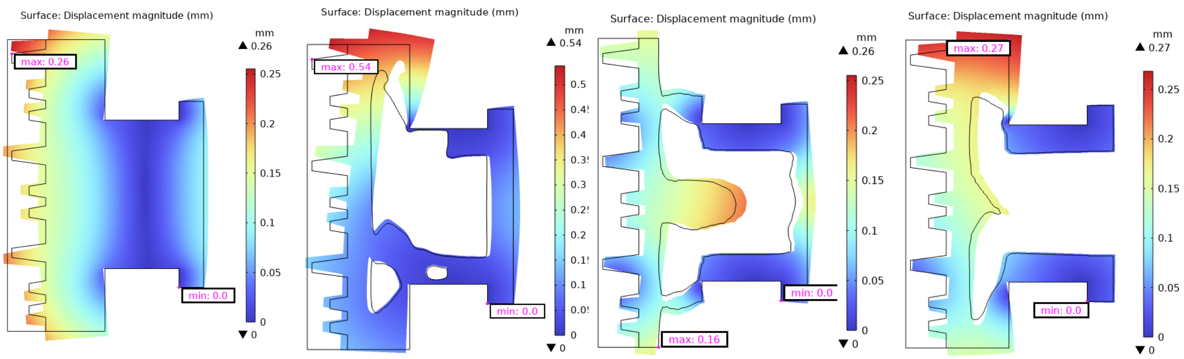
The input data for the pressure and temperature boundary conditions of the solid domain are obtained from the fluid dynamics and thermo-structural analysis, in the fluid-solid interface of the LS. The material model used is the SIMP model, and the regularization was achieved with the application of a Helmholtz filter. For the optimization algorithm the solver GCMMA was used combined with the adjoint method. Finally, a hyperbolic tangent projection was used over the solid optimized domain.

The scalar value ϕ was obtained in three different ways: in the C1ST case is the average displacement of all the fins of the seal in radial direction; in the C2ST case is the absolute displacement in the radial direction of the two more deformed fins in the thermo-structural analysis without optimization; and in the C3ST is the absolute displacement in the radial direction of the more deformed fin in the thermo-structural analysis without optimization. Also, different prescriptions of material regions were applied in the three different cases.

3 Results and discussion

To compare the performance of the different LS obtained by the TOM application, the optimized geometry for the C1ST, C2ST and C3ST cases was exported. These geometries were then subjected to fluid dynamics and thermo-structural analysis. Subsequently, the displacement results of the optimized seal were compared with the results obtained for the unoptimized labyrinth seal.

Fig. 1(a) shows that, due to thermal expansion, the central fins undergo the greatest displacement in the radial direction. In the optimized cases, it is observed that these same fins show smaller displacements, and even in the opposite direction due to the geometry produced by the application of the TOM.



(a) Non-optimized. (b) C1ST optimized. (c) C2ST optimized. (d) C3ST optimized.

Figure 1. Optimization results: Thermal compensation, total displacement magnitude (8:1 scale).

To quantify the thermal compensation in the optimized LS, the absolute value of the average radial displacement of the tip of the two highest and most displaced fins was measured in the non-optimized and optimized designs. The values obtained are shown in Table 1. For all cases there is a reduction of the tip displacement of the selected fins. The design with the greatest reduction is C2ST (see Fig. 1), with a value of 76% with respect to the unoptimized seal, while the smallest reduction is that of the C1ST case, equal to 44%. In the three cases evaluated, the reduction of the radial displacement value of the tip of the selected fins shows the significant improvement in the behavior of the LS, this at the operating temperature and, therefore, the thermal compensation of the conceptual design.

Table 1. Average radial displacement of the fins tip.

Case	C1ST	C2ST	C3ST
Non-optimized [mm]	0.1706	0.1706	0.1706
Optimized [mm]	0.0950	0.0403	0.0853
Reduction [%]	44	76	50

With thermal compensation of the seal, the stator fins reduce their deformation towards the rotor and the probability of interference and wear is reduced. In the absence of thermal compensation, the height of the fins can show wear. To determine the seal leakage performance, the value of the average mass flow magnitude at the outlet was measured for the non-optimized seal without fin wear (used as a reference value) and for the non-optimized seal with fin wear. This value was calculated by performing successive simulations modifying the height of the highest fins, since this is the place where the largest displacements occur. Table 2 shows the average mass flow at the exit of the SL for different magnitudes of wear at the tip of the highest fins. Also shown is the mass flow through the optimized seals for the C1ST, C2ST and C3ST cases. Here it is observed that only with 0.18 mm wear in the radial direction, which is the magnitude of the displacement at the fins in the non-optimized geometry, the leakage through the SL increases 42%. These values demonstrate the importance of implementing thermal compensation in the SL. It is also highlighted that the optimized seals do not present an increase in leakage, but produce reductions close to 5% with respect to the unoptimized and wear-free seal.

Table 2. Leakage behavior through the SL as a function of radial wear of the uppermost blade tips.

LS condition	Average mass flow [kg/s]	Change [%]
Optimized (C1ST)	0.2543	-4.2
Optimized (C2ST)	0.2521	-5.0
Optimized (C3ST)	0.2529	-4.7
Non-optimized (Without wear - Reference)	0.2655	0
Non-optimized (Fin wear of 0.18 mm)	0.3761	42

4 Conclusions

Heat transfer to the labyrinth seal induces thermal expansion in the radial and axial directions, which is manifested with greater magnitude in the fins of greater height in the radial direction. This thermal expansion causes the reduction of the clearance of the seal under study. This reduction may increase with increasing temperature in the regions of reduced clearance, which may eventually lead to friction between the moving and stationary surfaces.

Conceptual designs of steam turbine labyrinth seals obtained by the topology optimization method exhibit a reduction in the fin tip displacement. In the steam turbine seals, a reduction of the average radial displacement of the tip of the fins of 44% in the C1ST design, 76% in the C2ST design and 50% for the C3ST design was obtained.

The optimized labyrinth seals maintain the average mass flow at the outlet according to the initial geometry without deformation, i.e. without thermal expansion. Tip wear of the same magnitude as the thermal expansion, and without compensation, results in a 42% increase in leakage at the steam turbine seal.

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