A Study of Curved Labyrinth Seals for Steam Turbines

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Abstract: A Study has been conducted evaluate the structural behavior of newly designed labyrinth seals. Structural analysis was performed to understand, evaluate and compare new seals with a baseline straight seal that is typical of commonly used seals in steam turbines. New configurations of labyrinth seal knives were developed for use in steam turbines. The main objective of this study is to develop a better understanding of selected various labyrinth seals that may be configured to minimize the steam leakage and reduce seal interactions with the shaft. Computational fluid dynamic modeling of the various configurations, from a related study, and preliminary structural analysis led new designs to incorporate curvature into knife geometries including a sharp flat free-edge. Two-dimensional linear elastic static structural analysis was performed on a baseline straight labyrinth seal knife and seven different new configurations incorporating flexible geometries like curved seals, using finite element analysis software ANSYS®. Structural behavior of all new seals was evaluated in comparison with the results obtained for the baseline straight seal knife.

Keywords: Curved Labyrinth Seals, Steam Turbines, knife geometries, sharp flat free-edge.

1. INTRODUCTION

Steam and gas turbines are one of the primary means of producing electricity and power in the present day. But the energy efficiency of these turbines can be said to be an almost anti-thesis to the success with which they have been adopted to run the motor of the modern world. From day one of their inception for the production of electricity on a commercial basis, turbines have been posing an as yet unconquered challenge of achieving high efficiency. It has long been known that there exists a constant loss of working fluid from turbo-machinery. Stacker estimated that every 1% decrease in leakage flow through a high-pressure turbine seal would result in a 0.4% decrease in the specific fuel consumption. Based on Stacker's methodology and the jet fuel consumption figures in the US for 1998, a fuel savings of approximately 16 million barrels a year of jet fuel alone can be achieved. And with the ever increasing demand for fossil fuels, these figures would translate into much higher values in the present day scenario.

In the present thesis only steam turbines have been considered. So the mention of turbines, hereafter, refers only to steam turbines. A score of factors comprising the design constraints and the inherent science involved in their working can be blamed for the low efficiency rates of steam turbines. Albeit, one parameter has been identified as a prospective start point to improve the efficiency - the leakage of steam before it has performed useful work in the turbine.

A number of solutions have been sought for and adopted to overcome the loss of steam, with turbine seals leading the effort. The whole range of seals employed to date can be classified broadly into two categories – contact and non-contact types. Labyrinth seals form the class of non-contact type seals. These have been well documented as being used in steam and gas turbines and other turbo-machinery applications where a robust yet relatively simple seal is required between two differentially separated pressure zones

The labyrinth type seals boast of specific advantages like

- low maintenance
- simplicity of design
- negligible running torque
- lower wear of the shaft

One of the most important advantages of labyrinth seals is their long operational life. This is due to their non-contacting nature of operation. The labyrinth seals function by creating resistance in the flow of steam passing through the seal. This results in dissipation of the kinetic energy of steam in the form of turbulent vortices in the cavities of the turbine sections.

There are variations in the operation of the labyrinth seals by virtue of their geometry and construction. Based on the arrangement of the teeth they can be classified as teeth-on-rotor and teeth-on-stator type seals. There have also been models tested with teeth on both the rotor and the stator and have been termed as seals with interlocking teeth.

Based on the geometry of the steam flow passage, the seals can be convergent, divergent or straight-through labyrinth seals. Due to the possibility of variable cross-section for the flow passage, the teeth alignment can be either parallel to the rotor axis or straight-through or, can be stepped following the convergent or divergent nature of

the flow. There have also been models constructed with honeycomb stators and the teeth on the rotor.

Though there are various configurations of the labyrinth seal, both in industrial application and in the development, these seals suffer from relatively high steam losses compared to the contact-type seals. This can be attributed to the lack of a "mechanical seal" between the two pressure zones. Hence, any and all effort to enhance the performance of the labyrinth seal would have to be either on developing a new configuration or improving the existing designs. In either case the aim of the efforts would be to develop a seal that:-

a. has good dynamic sealing properties,
b. has higher compliance with the shaft,
c. is simple in geometry for ease of manufacture and maintenance, and
d. very long life cycle comparable to the existing seals.

2. REVIEW OF LITERATURE

The successful use of labyrinth seals in commercial steam turbines dates back to the starting years of the twentieth century, accompanied by a score of problems encountered with their operation and performance. Hence, a significant amount of research has been performed on developing theories to predict the leakage characteristics and performance of various seals including labyrinth seals. A study of the existing literature on the labyrinth seal revealed the strides taken towards understanding the leakage mechanisms and also a number of other questions like how to increase the dynamic sealing of the seal and so on, that have yet to be answered.

The first significant analytical effort on the problem of labyrinth seal can be attributed to Adolf Egli of the Westinghouse Electric Co. Egli made an attempt at formulating the problem by assuming the flow of steam through a labyrinth seal analogous to an orifice flow. He discussed the flow of steam through the labyrinth seal as the adiabatic expansion of steam through a series of throttlings.

The work of Bilgen and Akgungor tried to enhance the existing theories on the leakage and frictional characteristics of the seal by experimental verification. But the theory proposed made the assumption that the flow of steam can be approximated to Poiseuille flow due to the low clearance to diameter ratio. This resulted in large differences between the results obtained from the theory and the experiments.

A significant amount of research effort has been dedicated to model and theorize the flow through the seal but Wright has attempted at collecting the much needed data to understand the forces acting on the seal elements. Many parameters affecting the forces have been accounted for paving the way for developing theories to understand the forces acting on the seal. Subsequent research in this direction was done by Leong and Brown. They documented the lateral forces acting on the seal elements and attempted to develop a mathematical model describing the influence of the different aspects of the flow like the eccentricity in the rotation of the shaft, seal size and rotor speed on the total lateral forces.

A comprehensive effort to catalog the rotor dynamic coefficients of forces on the seal has been made by Childs and Scharrer. Though this is predominantly an experimental effort, it gave important insights into the flow patterns within the seal cavities influenced by such factors like pressure gradients, rotor speed and seal clearance.

The existent literature may broadly be classified into one half dedicated to minimizing the leakage flow in current designs of the seal and, the second half trying to improve the baseline seal configuration and alignment inside the turbines. While a lot of effort has been devoted to the first half, the second category, nevertheless, had some very promising prospects.

In the study undertaken by Michaud et al and Vakili new configurations for teeth-on-stator type seals have been evaluated. A study of the flow characteristics suggested improvements in the seal performance and as such new configurations have been studied.

3. NEED FOR NEW LABYRINTH SEALS

The application of labyrinth seals in the industry has a long track record owing to the various advantages of these seals over the continuously popular brush and other types of seals. The contact type sealing properties of the other seals is the main contributing factor for their popularity over the labyrinth seals. Due to a mechanical contact between the seal elements and the shaft, the leakage of steam can almost completely be eliminated. But the contact type seals have their set of disadvantages like:

- Due to the constant rubbing between the seal elements and the shaft, the wear on both is higher,
- The higher wear results in shorter operating life of the seal elements and hence, their frequent replacement and the associated costs and, the most important disadvantage being the wear of the turbine shaft which is most undesirable for the operation of a turbine.

Labyrinth seals, on the contrary, mitigate or totally overcome these disadvantages due to the absence of contact or rub between the seal elements and the turbine components. As a result, from this perspective, they are superior to the contact type seals. But as has already been stated, the labyrinth seals are not as effective in their sealing properties as the contact type seals.

4. SEALING MECHANISM IN A LABYRINTH SEAL

The labyrinth seals operate by making use of the flow characteristics of the steam through the seal cavities. Flow

visualization study and measurements in a baseline labyrinth seal indicated the following as the major mechanisms for energy loss:

1. viscous dissipation losses in the turbulent jet during throttling between the seal elements and the shaft
2. viscous losses in the form of turbulent vortices in the cavity chambers
3. viscous losses at flow stagnation areas and,
4. losses incurred due to the sharp changes in the direction of flow around the edges of the steps on the shaft and the edges of the seal elements.

The leakage of steam can be reduced by increasing the amount of energy lost through the various mechanisms of energy dissipation in the seal cavities - turbulence, circulation, flow-stagnation etc. The investigations of Michaud and Vakili led to the development of new configurations for the labyrinth seal. These new configurations were studied for their flow characteristics, and the results suggest that for improved sealing characteristics a good configuration for the seal should be able to dissipate the kinetic energy of the steam flow in the seal to the maximum by using many or all of the mechanisms cited above.

The shaft of a turbine is known to exhibit vibrations about its axis. As a result, there are documented instances of the impingement of the shaft on the labyrinth seal elements, thus permanently deforming them. The seal elements are designed to perform for maximum efficiency in their non-deformed condition. Hence, in addition to the lack of a mechanical sealing, the labyrinth seals also have to overcome the problem of lower performance due to permanent deformation upon impingement with the shaft. Thus, the main challenges associated with designing a labyrinth seal are:

- improving the sealing characteristics even though there is no mechanical seal

- designing the seal elements to exhibit high efficiency even in the case of large or permanent deformation upon impingement with the turbine shaft designing the seal elements such that they have high structural flexibility resulting in no or very small permanent deformation upon impingement with the turbine shaft at the same time not compromising the sealing efficiency at any instance of operation of the turbine. An ideal geometry of the seal element would not only cause the dissipation of the steam energy, thereby decreasing the leakage, but also perform at close-to-maximum design efficiency with or without deformation. Efforts have been made to achieve such a viscous dissipation losses in the turbulent jet during throttling between the seal elements and the shaft viscous losses in the form of turbulent vortices in the cavity chambers viscous losses at flow stagnation areas and, losses incurred due to the sharp changes in the direction of flow around the edges of the steps on the shaft and the edges of the seal elements. The practical difficulties in conceiving such a seal-geometry translated the efforts into striking a balance between the performance on the flow-containment front and mechanical strength front, consequently imposing a practical limit on the maximum efficiency possible to date.

Loss mechanisms in a labyrinth seal are depicted in Figure 1.
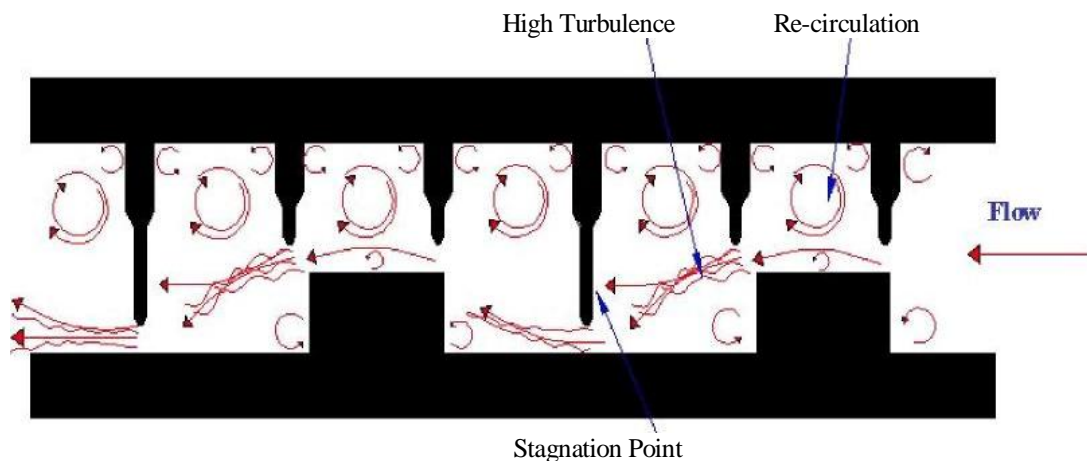
5. NEW CONFIGURATIONS OF LABYRINTH SEAL

As discussed, improved sealing characteristics may be achieved by creating as many sources of energy losses as possible in the flow of steam though the labyrinth seal. The leakage of steam through the seal has been found to be influenced by the following mechanisms:

- Stagnation of the flow on the knives and other solid boundaries.
- Generation and sustenance of highly turbulent vortices and other non-isentropic energy conversion processes.
- Curvature of the path taken by the leakage flow.

A study of the flow characteristics of steam through the vertical seal against the other configurations as discussed by

Michaud produced the following as the strategies to improve the seal design:

The leakage jet was found to be extending from one orifice of the seal assembly to the next orifice with minimal loss in its kinetic energy. To improve the sealing efficiency, the design should be able to direct the velocity vectors into either the rotor or the walls of the knives or the casing where flow stagnation would be facilitated.

The kinetic energy of the steam can also be attenuated by the creation of highly turbulent vortices in the cavity between adjacent knives of the seal. Hence the labyrinth design should be able to create such vortices in the seal cavities.

It is known that the steam flowing across the knives exerts a pressure on them. This was more pronounced in the case of the seal with slant knives wherein the steam impinged on the slant surface of the knives pressing them towards the shaft. Added to this is the fact that the shaft experiences vibrations about its axis thereby impinging on the seal knives and deforming them. Therefore, the knives are under the influence of two mutually opposing forces - steam pressure pressing them towards the shaft and the shaft forces forcing them towards the stator. As a result, the knives should be designed to be flexible and experience minimal deformation and/or damage due to these two forces.

Hence, a new configuration for the labyrinth seal should satisfy the following criteria to maintain a high sealing efficiency:

The seal knives should have good flexibility to minimize permanent deformation due to the shaft motion.
As was stated above, the knives are under the action of two mutually opposing forces. Hence, the configuration is not only designed to withstand the shaft forces alone but also to withstand the resultant of the two forces.

In the event of the impingement of the knives with the shaft there is every possibility of scouring of the shaft. In such a scenario, there should be the least amount of wear on the shaft. Therefore, the geometry, material and design of the knives have to be such that the shaft is left unharmed.

The knives may have to comply with the current operational constraints of maintaining the minimum required clearances and tolerances yet never compromising their operational efficiency.

Last but not the least is the long operational life and, the ease of maintenance of the seal and its components. Labyrinth seals are renowned for their simplicity and the ease of handling and assembling. Hence, the new configuration should possess similar features.

These criteria led to the design and study of the following new geometries for the seal knives:

1. Combination of C-shape and straight knives
2. Z-shape with flat edge knives
3. C-shape with sharp edge knives
4. C-shape with flat edge knives

6. CONCLUSIONS

The main objective of this study was to conduct the structural analysis of new configurations of labyrinth seals and compare them against a baseline labyrinth seal for structural viability purposes. To this end a static, steady 2-dimensional finite element structural analysis was performed on a baseline straight labyrinth seal, commonly in use in steam turbines, (referred to as the straight seal) within the elastic limit of its material. The material of the seal was common engineering steel. The results of the straight seal analysis show the need for new and improved seal configurations. The improved sealing of the new designs was supported by computational fluid dynamic studies of the straight seal and the new seals.

Comparison of the results of structural analysis between the straight seal and the new configurations indicated that three of the five C-flat seal configurations (CI, C2 and C3) exhibit higher flexibility than the straight seal. The higher flexibility has the added potential for installing seals with a smaller clearance distance from the shaft than the straight seal. Reduced clearance has the added advantage of reduced area of flow for steam, thus minimizing its leakage. Further, since the flexibility of the new seal is higher, the wear on it is expected to be minimal.

Two new seal configurations, C4 and C5, had very high load bearing capacity before reaching their elastic limits.
Two other configurations (CS1 and CS2) have more flexibility, making them a good choice for developing labyrinth seals with better sealing and contact performance.

A non-dimensional geometrical ratio was found to uniquely correlate flexibility of the different configurations. Though the data available was not exhaustive, this parameter appears to be a good indicator of the underlying relationship between the geometric variables of the knives and their flexibility.

7. RECOMMENDATIONS

The problem of the labyrinth seal belongs to the class of multi-physics encompassing the fields of fluid dynamics, heat transfer, structural and thermal stress analysis and material science leaving aside the study of the functioning of the turbine itself. The present study was a simplification of the actual problem. As a result, there are many areas for improvement and further research to gain a deeper understanding of the behavior of a labyrinth seal in operation.

The loads on the knives are time-dependent and not always within their elastic limit. Hence the foremost area

of improvement would be to perform a non-linear dynamic analysis.

The seal knives are subjected to vibrations due to the fluctuations in the operation of the turbine. Hence, a modal or vibration analysis would increase the understanding knife behavior.

Since the present study was a 2-dimensional analysis, a 3-dimensional analysis would be a giant leap in understanding the problem because of the fact that the shaft and steam forces are not always radial or tangential to the knives.

In a 3-dimensional analysis, the problem of contact stress gains significant importance. A study in this direction would be highly recommended. Also of importance are the frictional effects of the rubbing of the knife free ends on the turbine shaft.

The fluid dynamic effects of the flow of steam on the seals were not studied. This belongs to a class of problems called fluid-structure interactions. Such a study presents a holistic perspective of the problem from the fluid as well the structural side.

The CS1 and CS2 configurations exhibited more flexibility than the CI through C5 configurations. A further research into this particular type of geometry would be valuable. One of the most important recommendations would be the construction of a prototype for the ratification of the results obtained and to improve upon the fallacies and loop holes of the present study. Contact stress analysis would present deeper insights into the interactions between the shaft and the seal elements.

Also, failure or fracture analysis would help to predict the operating life of the knives.

The seal elements are constantly subjected to elongation and compression under the influence of steam and shaft forces. This can induce fatigue in the seal elements and eventually their failure. Fatigue analysis would provide grounds for better prediction of failure of the seal elements.

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