Advanced simulation of coupled physics in thrust bearings

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Abstract. In hydro power units with very large reversible pump turbines, tilting pad thrust bearings may operate at the edge of the field of experience regarding sliding speed, contact pressure, size, and shape. Here, advanced numerical simulation methodologies offer the possibility to precisely predict the bearing performance and to safely reach guaranteed properties while minimizing the need for experimental investigations. Hence, objective of this work is to develop and validate an advanced method which fully resolves coupled physics in large thrust bearings of reversible pump turbine units. By applying this method, layout tools can be validated and calibrated for an extended design space. Moreover, a better understanding of physical phenomena and how they interact allows for the improvement of design standards. The present contribution introduces an accurate and robust coupling and solution procedure including finite element analyses of thermal and mechanical deformations of pad and thrust runner, mesh motion analyses, and conjugate heat transfer (CHT) analyses. CHT analyses account for flow and heat generation in oil film and groove as well as heat transfer in pad and runner. By applying the procedure to a large bearing investigated at a prototype-sized test rig, all analysis steps are verified and validated using accurate and extended measuring data.

1. Introduction

In the current hydro power market, a growing demand for large reversible pump turbines is observed. Mostly, such pump turbines are running at comparable high rotational speeds and under high heads. In addition, the available space for the thrust bearing may be subjected to several restrictions. An exemplary pad arrangement in a thrust bearing of a large pump turbine unit is shown in Figure 1. Altogether, advanced designs of tilting pad thrust bearings may involve operation at the edge of the field of experience regarding sliding speed, contact pressure, shape, and size. Especially size effects, see Ref. [1], and laminar-turbulent transition phenomena, see Ref. [2], may strongly affect the bearing performance. To design highly reliable and economic bearings under such conditions, extended knowledge and advanced tools are required. On the one hand, strongly coupled physics consisting of oil flow in gaps and grooves, heat transfer in fluid and solids, as well as solid deformations have to be fully understood. On the other hand, bearing layout tools need to be accurate to stay within safety margins, see Ref. [3], and to fulfill customer requirements. Hence, they have to be validated and calibrated for an extended design space. To gain this extended knowledge and such advanced tools, expensive and time-consuming experimental tests may be an option. However, the rapid development of simulation technology including multiphysics analyses and fluid-structure interaction (FSI), see Ref. [4], offers the possibility to investigate complex physical interactions in thrust bearings using a computational approach. Recent FSI applications to hydrodynamic lubrication with emphasis on thrust bearings are given in References [5] and [6] where computational fluid dynamics (CFD) and finite element analyses (FEA) are iteratively coupled in time domain.
The present contribution focuses on the development, application, and validation of an accurate and robust numerical simulation procedure to fully resolve coupled physics in large thrust bearings of reversible pump turbine units at steady operating conditions. Section 2 presents the different analysis steps to solve mesh motion, oil flow plus heat transfer, and solid deformations. Furthermore, the iterative coupling strategy is introduced. Section 3 deals with modeling, meshing, and numerical setup of a bi-directional bearing which was investigated at a prototype-sized test rig providing accurate and extended measuring data. In Figure 3, the main parts of a thrust bearing are explained. The measuring data from the test rig is used in Section 4 to compare coupled simulation results of two different operating conditions with experimental results. Finally, Section 5 draws the conclusion.

2. Coupled solution procedure

In order to obtain a robust and efficient numerical procedure for determining coupled physics of steady state operations in tilting pad thrust bearings, all analysis steps have to be stable, converging, and efficient. However, the usual FSI approach of coupling CFD and FEA at common surfaces of fluid and solids in time domain, as used in References [5] and [6], is quite time consuming and has to overcome severe stability and convergence problems. Hence, a different approach is developed based on static analyses of solid deformations followed by mesh motion analyses to define a new oil film geometry. Subsequently, conjugate heat transfer (CHT) analyses are performed on deformed meshes to obtain steady state solutions of flow and heat generation in oil film and groove as well as heat transfer in pad and thrust runner. This approach includes a volume coupling of temperatures, while surface coupling applies to pressure loads. To find the thermal and mechanical equilibrium for a given operating condition, multiple nested iteration loops are required.

2.1. Mesh motion analysis

By varying film thickness, tilting angles, or solid distortions, the oil film geometry changes, and the meshes of fluid and solid domains have to be adapted to the new geometry. This task is obtained by moving the mesh nodes of the previous analysis step to new positions using the mesh displacement capability of the commercial CFD solver ANSYS-CFX. Introducing intelligent expressions for the mesh stiffness, a stable procedure with good mesh quality even for severe geometry changes is reached, without the necessity of remeshing.

2.2. CHT analysis of oil flow and heat transfer

To analyze the flow in oil film, grooves, and considered parts of the oil tank, Reynolds-averaged Navier-Stokes (RANS) equations apply using the SST model for turbulence closure. To include heat generation and transfer, RANS equations are coupled with the energy equation which is solved in solid domains, too. Hence, heat fluxes between fluid and solids are an inherent part of the solution to a
single equation system and need not to be determined iteratively. Since oil viscosity strongly depends on temperature, the dynamic viscosity $\mu$ in Pa·s is calculated using the formula by Rost [7]

$$\mu = 0.00018 \cdot (\text{ISO-VG} \cdot \rho / 180)^{159.56 / (\vartheta + 95)} - 0.1819$$

with the ISO-VG viscosity class, the density $\rho$ in kg/m$^3$ and the temperature $\vartheta$ in °C, leading to a significant interaction of energy and momentum equations. To account for the rotation of the thrust runner, a solid motion model applies which extends the energy equation of the solid domain by a convection term, causing circumferential averaging of the temperature field. To solve all equations of the CHT analysis, the commercial CFD solver ANSYS-CFX is used, again.

Since cyclic symmetric geometry and physics are assumed, only a sector with a single pad is regarded using periodic boundary conditions. As a result of the symmetric pad shape of bi-directional thrust bearings, a low pressure region develops at the outlet edge causing negative pressure values if release of dissolved air and cavitation of oil are neglected. Therefore, the absolute pressure is clipped to zero before projecting fluid forces onto solid domains.

2.3. Finite element analysis of solid deformations

In order to determine thermal and mechanical deformations of pad and thrust runner, the commercial FEA solver ANSYS-Mechanical is used. Again, only a sector with a single pad is regarded, and both pad and runner sector are loaded with domain temperatures and with oil pressure at sliding surfaces. For the thrust runner, constraint equations enforce the cyclic symmetry, and for the pad, realistic support conditions apply depending on the type of pad support. Since deformations are small in relation to dimensions, linear static analyses are fully sufficient to obtain solid distortions.

2.4. Iterative coupling strategy

Aim of the coupled solution procedure is the determination of film gap geometry and corresponding temperature and pressure fields which fulfill the thermal and mechanical equilibrium for given thrust and speed. For this purpose, the above-mentioned analysis steps are coupled by multiple nested iteration loops, as shown in Figure 2. The innermost pad balancing loop varies tilting angles until tilting moments are balanced. The intermediate FEA-CHT coupling loop considers solid distortions and is repeated until pad reactions and temperatures reach a steady state. Within the outer load seeking loop, the film thickness is varied until the axial thrust from oil pressure coincides with the axial design load of the regarded operating condition.

![Figure 2. Coupled solution procedure with iterative coupling strategy to find thermal and mechanical equilibrium for stationary operating conditions.](image)

3. Modeling of a prototype-sized bearing investigated at a test rig

The developed solution procedure is applied to a tilting pad thrust bearing of a large reversible pump turbine unit. The bearing performance was investigated thoroughly at a prototype-sized test rig. The test rig measurements provide accurate and extended results of oil film thickness, oil film pressure, and pad temperature. Different operating conditions were studied imposing rotational speed and axial thrust with high accuracy. Hence, experimental test rig results offer a very good opportunity to reliably validate the coupled solution procedure.

3.1. Geometric modeling

From the test rig configuration, a simplified geometric model is deduced which is suitable for the coupled numerical simulation. The model includes a cyclic symmetrical bearing sector consisting of a single pad, the respective part of the thrust runner, and the oil domain which accounts for the inlet pipe geometry. The oil domain contains the lubricating film, the groove between adjacent pads, and a limited part of the oil tank at inner and outer diameter of pad and thrust runner. Considering the symmetry of the initial configuration without tilting and distortion, it is sufficient if the geometric model only comprises symmetric parts of all domains, as shown in Figure 3.

![Figure 3. Simplified geometric test rig model consisting of tilting pad (a), thrust runner sector (b), and oil domain (c) which accounts for the geometry of lubricating film (d) and inlet pipe (e). Shown is the symmetric part of the initial configuration to start the coupled simulation.](image)

3.2. Meshing of fluid and solid domains

Due to the comparably simple geometry, block-structured meshing applies to fluid and solid domains leading to purely hexahedral meshes of high quality with a good resolution of the lubricating film and of viscous and thermal boundary layers. For all domains, complete meshes are received by mirroring meshes of symmetric parts, ensuring equal surface meshes at periodic boundaries. In CHT analyses, hexahedral control volumes are used in conjunction with a high-resolution advection scheme, and in deformation analyses, 8-noded finite elements with enhanced strain formulation apply. In both cases, stable and second order accurate numerical schemes follow for the spatial discretization.

The numerical results presented in Section 4 are obtained on quite fine meshes consisting of approximately 3 million elements for the fluid domain, 0.3 million elements for the pad domain, and 0.6 million elements for the runner sector, as shown in Figure 4. On a Linux cluster with 64 cores, computing times of one to two days follow for the entire procedure when starting from scratch, i.e. with plane solid surfaces and roughly estimated tilting angles and gap thickness. However, even much coarser meshes, as used during the development phase, give reasonable results.
3.3. Physical modeling and boundary conditions

The viscosity class of the lubricating oil is ISO-VG 32. Pads and thrust runner are made out of steel, except a coating layer at the pad film surface for which the properties of Babbitt apply. At the inlet area of the inlet pipe, cooling flow rate and cold oil temperature are prescribed, while opening conditions with zero pressure apply at the outlet of the fluid domain. At fluid domain walls and solid surfaces being not part of a fluid-solid or periodic interface, either adiabatic conditions or appropriate heat transfer coefficients are defined.

To account for realistic support conditions of the pad which is situated on a single disk spring, a non-linear contact analysis of pad and spring is performed applying rated axial thrust. This analysis offers accurate values of the pad tilting stiffness to be used in the pad balancing loop and in the static deformation analysis in which the pad is supported by an appropriate distribution of linear springs without restraining thermal deformations unphysically.

4. Simulation results and comparison with test rig measurements

If a numerical procedure shall predict reliably the physical behavior of a complex technical system, verification and validation of the procedure is a crucial part of the development process. Hence, to check functioning, convergence behavior, and robustness of all analysis steps and to demonstrate the accuracy of computed bearing properties, two different operating conditions measured at the test rig are investigated numerically. On the one hand, operation at rated speed and thrust in turbine mode is chosen as the regular operating condition of the bearing. On the other hand, operation at increased speed and thrust is regarded. The rotational speed is increased by 11% and the axial thrust by 15%. In the following subsection, results obtained by coupled simulations and by test rig measurements are presented. Subsequently, the influence of operating condition on bearing performance is discussed, and finally, results from measurement and simulation are compared and evaluated.

4.1. Simulation and measurement results at rated and increased speed and thrust

After completing the coupled simulation for a given operating condition, fully resolved 3-dimensional result data is available for all variables including temperatures of solids and fluid, flow velocity and pressure, and solid deformations. Exemplarily, oil film thickness, pressure, and oil temperature are visualized in Figure 5 on the pad sliding surface for rated operation (top) and for increased speed and thrust (bottom). For all contour plots and diagrams, normalized scales are used in which minimum and maximum value of each quantity (across operating conditions) refer to zero and one, respectively. At the test rig, different pads are instrumented with sensors for film thickness, film pressure, and pad temperature close to the sliding surface. For each quantity, five sensors are located along a circumferential line. Therefore, Figure 6 present simulation results along this line together with measurement data for both rated operation (top) and increased speed and thrust (bottom).
Figure 5. Normalized contour plots of film thickness (left), oil pressure (center), and oil temperature (right) on the pad sliding surface, for rated operation (top) and for increased speed and thrust (bottom). The color scale is normalized using minimum and maximum value of each quantity.

Figure 6. Simulated and measured characteristics of film thickness (left), oil pressure (center), and pad temperature below the sliding surface (right) along a circumferential line, for rated operation (top) and for increased speed and thrust (bottom). Axes are normalized using minimum and maximum value of each quantity.
4.2. Influence of operating condition on bearing performance

By comparing oil film thickness, pressure, and temperature at rated operation with the results at higher speed and thrust, as given in Figures 5 and 6, the following can be observed. The bearing performance at increased speed and thrust is characterized by a slightly reduced minimum film thickness in conjunction with higher and more locally acting pressure and temperature loads. This behavior is caused by a combination of following effects. Due to increased thrust, pressure and temperature increase, while the film thickness decreases. In contrast, due to increased speed, averaged values of film thickness and temperature increase. Additionally, higher temperatures cause stronger thermal distortion leading to a reduced minimum film thickness and a higher peak pressure.

4.3. Validation of the simulation procedure by comparing numerical results with measurement data

In general, the comparison of measured and simulated bearing characteristics, given in the diagrams of Figure 6, reveals a very good agreement. For both operating conditions, equal observations can be made. The calculated pressure distribution and measured values match exactly, if minor deviations due to measurement tolerances are disregarded. An equally good agreement is found for the temperature characteristics, except for a single sensor located in the low pressure region close to the outlet edge. In this region, simulation results may exhibit some local inaccuracies since release of dissolved air and cavitation effects are not considered. Regarding the film thickness, small deviations are present at some sensor locations, but measurement tolerances of proximity probes are higher compared to pressure and temperature sensors. Altogether, by comparison with measurement data obtained at the test rig, the coupled simulation procedure is validated reliably.

5. Conclusions

The development, verification, and validation of an advanced procedure for analyzing fully coupled physics in large thrust bearings of hydro power units is executed successfully. By simulating different operating conditions of a bi-directional bearing investigated at a prototype-sized test rig, numerical accuracy, efficiency, and robustness are proven. Now, applying the procedure allows for

- gaining enhanced knowledge of strongly coupled physics in highly loaded thrust bearings without the need for costly and time-consuming experimental investigations,

- developing reliable designs which safely reach guaranteed properties even for very large bearings running at the limits of sliding speed and contact pressure,

- validating and calibrating layout tools and improving design rules for an extended design space.

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