Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition
GT2019
June 17-21, 2019, Phoenix, Arizona, USA

GT2019-90504

COMPUTATIONAL ANALYSIS OF THE EQUALIZATION BEHAVIOR OF THRUST BEARINGS WITH REGULAR AND MODIFIED LEVELING PLATES

Seckin Gokaltun*
Research Scientist, Member of ASME
Kingsbury, Inc.
10385 Drummond Road
Philadelphia, Pennsylvania 19154
Email: sg@kingsbury.com

Scan DeCamillo
Research Manager,
Kingsbury, Inc.
10385 Drummond Road
Philadelphia, Pennsylvania 19154
Email: scan@kingsbury.com

ABSTRACT

In this work, a Finite Element Analysis (FEA) model has been developed that represents the interaction between the thrust bearing components under the influence of a misaligned rotor. The FEA model represents the contact between bearing components such as the pads and leveling plates and calculates the forces and moments created, as well as capturing the elastic deformation caused by the load imposed by the runner. The current analysis excludes the existence of the fluid film between the runner and the pads; therefore, the loads and misalignments created represent a static loading condition. It was observed that the bearing equalization system is still functional for design modification cases such as material removal at the outer diameter of the lower leveling plates, while the equalization performance is reduced slightly.

NOMENCLATURE

FEA Finite Element Analysis
LLP Lower Leveling Plate
ULP Upper Leveling Plate
α Misalignment angle (degree)
m modified
r regular (unmodified)
Z Axial dimension

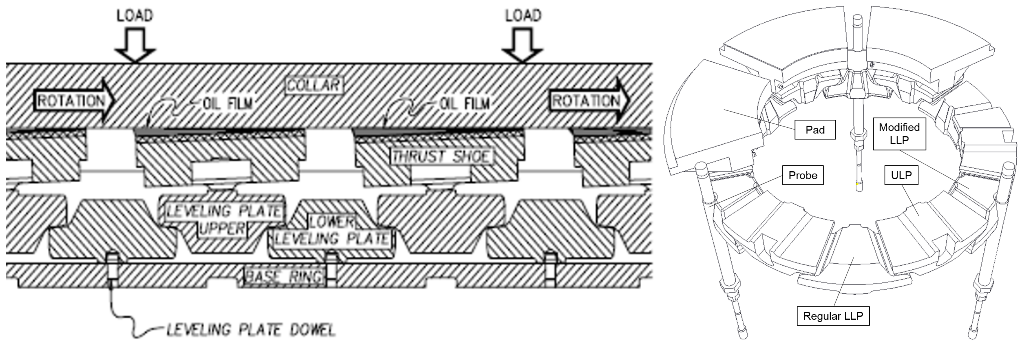
*Address all correspondence to this author.

INTRODUCTION

The operation of tilting-pad thrust bearings is affected significantly by the orientation of the rotor with respect to the plane of the pad surfaces. Misalignment leads to unequal load distribution among the individual thrust pads and can be classified as static or dynamic depending on the cause of misalignment. The shaft can be statically misaligned due to bearing and housing manufacturing tolerances, while dynamic misalignment can occur during the operation of the machine if the housing distorts under mechanical and thermal loading. Leveling plates are used in tilting-pad thrust bearings in order to compensate for the load imbalance due to static and some minor dynamic misalignment [1].

As depicted in Fig. 1(a), the bearing pads are supported by the Upper Leveling Plates (ULPs) that are resting on the Lower Leveling Plates (LLPs) at the wing surfaces. Any extra load imposed on one or more of the pads due to misalignment creates a moment imbalance on the LLPs and makes them tilt. This results in the opposite pad(s) being raised towards the collar surface, which increases the load carried by the opposite pads and improves the load distribution among the pads.

Understanding the equalization behavior of the leveling plates is an important aspect of tilting-pad bearing design, especially when structural modifications to the LLPs are necessary to monitor the conditions of the collar or other bearing components. A common modification involves a probe inserted through a hole or slot in the lower leveling plate as shown in Fig. 1(b). The



(a) (b)

FIGURE 1: (A) SCHEMATIC OF BEARING COMPONENTS. (B) SCHEMATIC OF BEARING INSTRUMENTATION PLACED THROUGH THE LOWER LEVELING PLATES. (THE COLLAR, THE BASE RING AND SOME OF THE PADS ARE HIDDEN FOR CLARITY.)

location of the hole or the slot can be at the center of the LLPs or at the wings of the LLPs and/or the rocking strip as shown in Fig. 2, as dictated by the bearing design and rotor monitoring application requirements. It is crucial to evaluate the effect of the modifications to the LLPs on the equalization performance during misalignment conditions, which is the goal of the study presented here.

The equalizing system in tilting pad bearings has drawn some attention in literature where the operating principles of leveling plates have been presented [2, 3, 4]. It was mentioned that unequal load pressure among the pads can lead bearings to fail at pressure less than the design loads and cause fatique-induced mechanical failure at the shaft ends [2], which has been noted elsewhere [4]. Kislov and Sudarev (1992) represented the leveling plates as two-dimensional elastic beams varying in cross-section and curvature, and solved for the deformations using finite difference method to get the fluid film geometry which was fed into their Reynolds Equation solver [3].

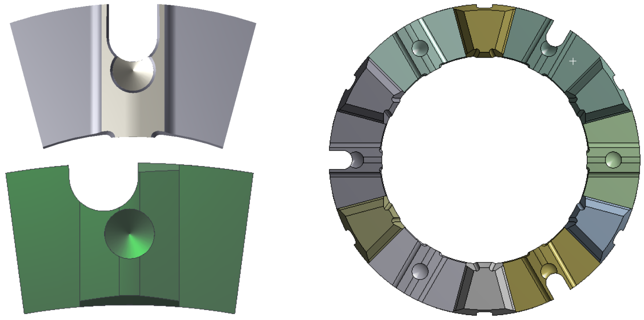
The topic of shaft misalignment in thrust bearings has also been studied widely. Heshmat and Pinkus modified the definition of the film thickness used in their Reynolds Equation solver with collar misalignment angles and studied the effect of misalignment for 6 to 12-pad tapered-land thrust bearings [5]. Viet et al. [6] developed a numerical model to model the performance of a 6-pad thrust bearing under misaligned and starved conditions. San Andres has studied the effect of misalignment numerically for a hydrostatic/hydrodynamic bearing [7]. Li et al (2012) have conducted experiments using a 10-pad equalizing thrust bearing with modified lower leveling plates and have shown that the leveling plates were able to balance the load among the pads evenly during start and stop conditions [8]. The effect of the leveling plates on the start-up characteristics of tilting-pad thrust bearing was also studied by Wang et al. [9] numerically with experimental validation, and it has been concluded that the bearing had a 10% load imbalance among the pads when the leveling plates were not used. The leveling mechanism aided in reducing the friction torque during the start-up as well as in reducing the tolerance requirements during manufacturing.

In this work, a finite element analysis (FEA) of a thrust bearing is developed in order to evaluate the effect of misalignment on the load distribution among pads in the bearing. The fluid film is not included in this study and the misalignment is caused by rotating and translating the shaft which is initially in contact with all the thrust bearing pads. The FEA analysis allows for the three-dimensional tracking of the contacts between the structures and the solution of the mechanical deformations of the leveling plates. To the best of our knowledge, this kind of analysis of the leveling plates in a thrust bearing is the first such work in the literature.

The rest of the paper is organized as follows: first, the FEA model developed for conducting the virtual static misalignment tests is shown. The geometry, material properties and boundary conditions are described. Next, the test conditions of the virtual static tests are presented for validating the model for a bearing with unmodified leveling plates, and the parameters used for conducting the misalignment tests with the modified leveling plates are given. Finally, comparison between the unmodified and modified leveling plates is presented for the misaligned cases.

FINITE ELEMENT MODEL

The FEA model used in this work was built using ANSYS® Mechanical Products, Release 17.1. The components included in the linear and static structural analysis were a self-equalizing, 6-pad, center-pivoted, tilting-pad thrust bearing, the base ring and the dowel pins holding the lower leveling plates from moving sideways, and a trimmed shaft with the integral collar as shown in the exploded views on Fig. 3. The base ring was hidden on the



(a) (b)

FIGURE 2: (A) EXAMPLE FOR LOWER LEVELING PLATE MODIFICATIONS. (B) BOTTOM VIEW OF A SET OF LOWER AND UPPER LEVELING PLATES WHERE EVERY OTHER LOWER LEVELING PLATE IS MODIFIED.

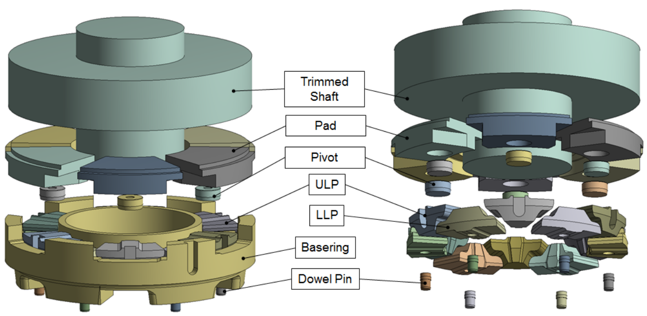
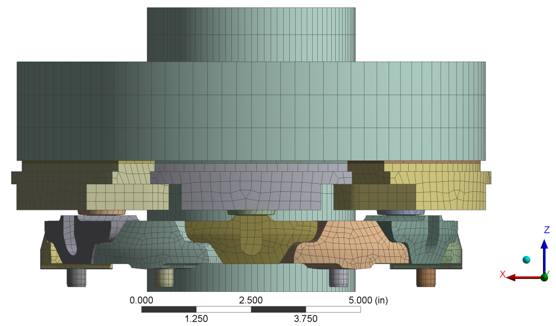


FIGURE 3: EXPLODED VIEWS OF THE KINGSBURY TILTING-PAD THRUST BEARING FROM TOP AND BOTTOM VIEWS SHOWING THE COMPONENTS INCLUDED IN THE FEA MODEL.

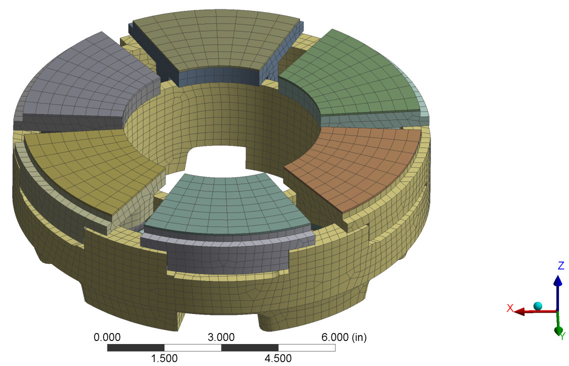
view from the bottom to view the leveling plates better. There is also a thin babbitt layer which is hidden from these views to improve the visualization of the components. The inner diameter of the pads is 5.5-in and the outer diameter is 10.5-in, which corresponds to a test bearing used at the high-speed thrust bearing test rig at Kingsbury Inc.

The mesh used to discretize the solid bodies is shown in Fig. 4 and was constructed with 229,888 nodes and 79,138 elements that were mostly hexahedral. The geometry of the modified leveling plate model was chosen based on previous experience at Kingsbury, Inc. for bearing assemblies which employed modified leveling plates.

The modified leveling plate model considered three aspects: the depth of the slot from the outer diameter of the modified lower leveling plate, the number of modified plates, and the arrangement of them in the base ring. The depth of the slot extends into the dowel pin hole for the heavily modified case, while the number of modified plates vary from one to three. The distribution of the modified plates in the base ring depends on the requirements for the sensor locations and can be equally spaced or clustered towards one side of the bearing.



(a)



(b)

FIGURE 4: (A) SIDE VIEW OF THE FEA MESH EXLUDING THE BASE RING.(B) INCLINED VIEW OF THE FEA MESH EXCLUDING THE SHAFT AND THE COLLAR.

Four different geometries for leveling plates were used in this study which included:

1. no modified LLPs,
2. single modified LLP,
3. three modified LLPs with a small hole (38% reduction in rocking strip area, 7% reduction in LLP volume) and
4. three modified LLPs with a deep hole (50% reduction in rocking strip area, 13% reduction in LLP volume).

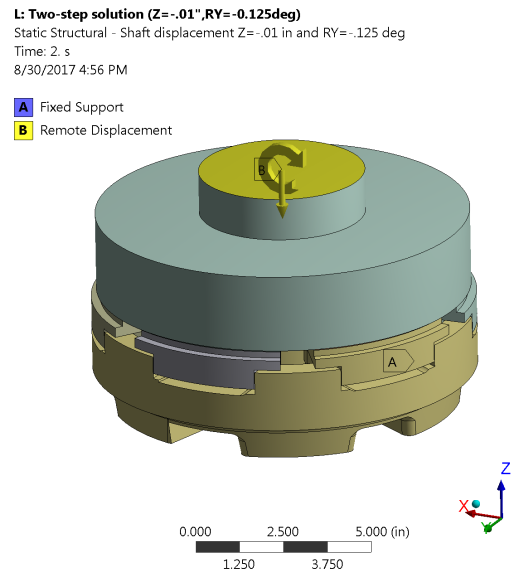
The only two boundary conditions used in the model were a fixed boundary condition for the bottom surfaces of the base ring and a remote displacement boundary condition at the top surface of the shaft in order to create loading and misalignment on the pad surfaces (Fig 5). The forces induced in the model due to the displacement of the shaft are transmitted into the internal components via the contact surfaces. Frictional contact, with a frictional coefficient of 0.2, is imposed at contacting surfaces where a sliding or rolling motion is expected, e.g., the pad pivot, leveling plate, and base ring interfaces. The shoe pivots were assumed to be bonded to the pads. A frictionless contact is assigned between the collar and the pad surfaces to eliminate forces in the plane of the collar surface during misalignment.

Steady-state solutions were obtained using a multi-step loading profile where a uniform displacement was assigned on the shaft in the negative Z direction to create uniform pressures in the contact areas. The misalignment step was created by rotating the shaft with respect to the X axis for misalignment on a single pad or the Y axis for misalignment between two pads. The displacements of the shaft and the collar in the X and Y directions are restrained to zero to prevent the collar from sliding off the pad surfaces during the misalignment. A final adjusting step is carried out by lifting the shaft back in the positive Z direction to match the applied load.

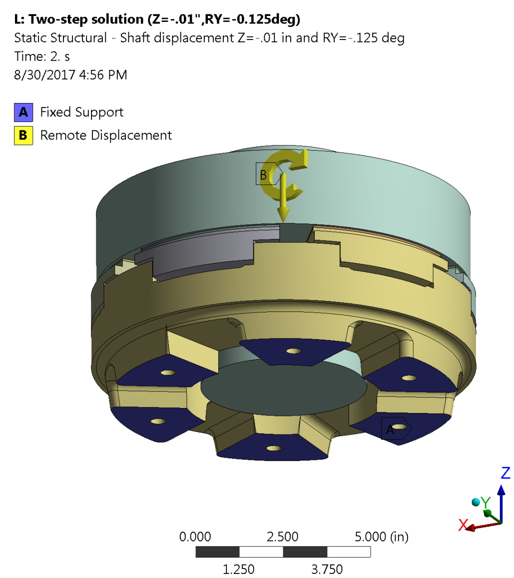
All the components in this model, were assumed to be of structural steel, which is the default material in ANSYS Mechanical, and the properties of which are listed below in Table 1.

TABLE 1: MATERIAL PROPERTIES OF THE STRUCTURAL STEEL USED IN THE FEA MODEL.

Density (lbm/in)^3	0.2836
Young's modulus (psi)	2.9008×10^7
Poisson's ratio	0.3
Tensile yield strength (psi)	36,259
Tensile ultimate strength (psi)	66,717



(a)



(b)

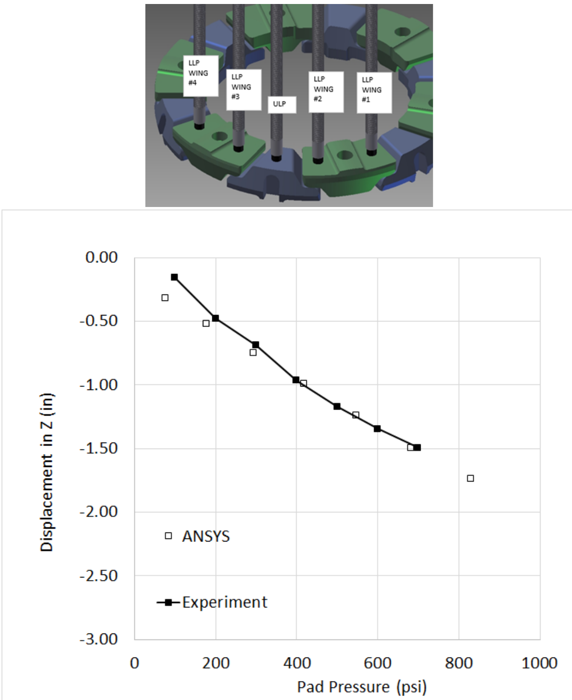
FIGURE 5: (A) REMOTE DISPLACEMENT BOUNDARY CONDITION IMPOSED AT THE TOP END OF THE SHAFT. (B) FIXED BOUNDARY CONDITION AT THE BOTTOM SURFACE OF THE BASE RING.

RESULTS

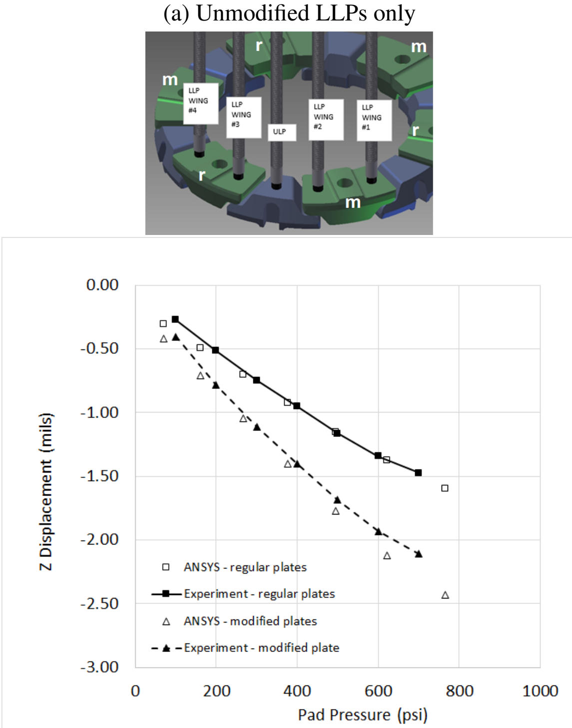
The structural analysis of the leveling plate mechanism is conducted in two parts: First, the FEA model was used to simulate a so-called 'static loading' test where a uniform load was applied to all the pads in the axial direction. The purpose of this was to validate the results of the FEA model against experimental data conducted at Kingsbury, Inc. This was repeated for unmodified and modified leveling plates. Next, the misalignment cases were simulated for a bearing with unmodified and modified leveling plates under various loading conditions.

Static tests

The first test case simulated using the FEA model was a static loading scenario where no misalignment was applied on the bearing. The shaft was moved in the axial direction to apply a force on the thrust pads that transmitted that force to the LLPs via the ULP wings. The result is deformation of the wings and a penetration of the LLPs into the base ring at the rocking strip and penetration of the pad supports into the ULPs. The axial displacement of the LLP wings was monitored with respect to the amount of pressure created on the pads due to the squeezing motion of the collar. Figure 6 shows the normalized displacement



(a) Unmodified LLPs only



(b) Modified and Unmodified LLPs

FIGURE 6: COMPARISON OF UNMODIFIED AND MODIFIED LEVELING PLATE WING DEFORMATIONS OBTAINED FROM THE FEA MODEL AGAINST STATIC TEST RESULTS.

profile of the wings at increasing pressures for a bearing with unmodified LLPs and one with both unmodified and modified LLPs.

The same static loading condition was created in an experimental set-up for the actual bearing and the wing displacements were tracked by proximity probes. Figure 6 shows the arrangement of the proximity probes used during the experiments. Four of the probes utilized pointed at the bottom surfaces of the wings of two LLPs separated by an ULP. The displacement results for both the unmodified plates and the modified plates were normalized using the initial position of each proximity probe. Figure 6(a) indicates that the FEA model is capturing the displacement of the wings very well in comparison to the experimental data. The FEA results shown here are average values of 12 LLP wing displacements while the experimental data is the average of four LLP wing displacements.

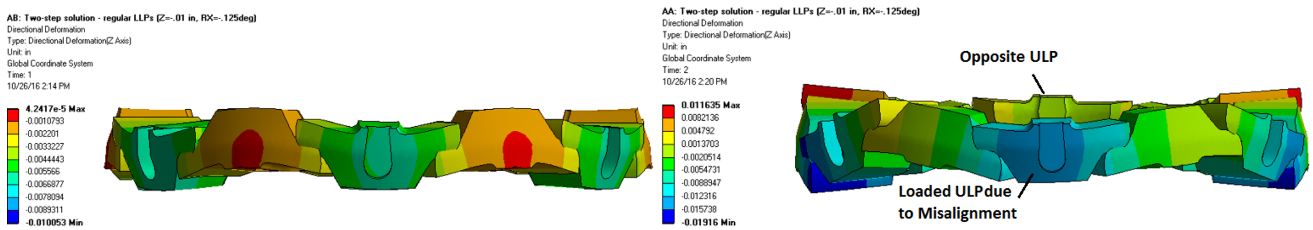
The comparison of the FEA model with the experimental results for a bearing with both modified and unmodified LLPs was also found to be in good agreement as shown in Fig. 6(b). The arrangement of the modified LLPs and the unmodified LLPs is shown in the top picture of Fig. 6(b), where every other LLP was modified. The loading method is again a static type for this test, where no misalignment was applied. The results show that the modified plates deform more than the unmodified plates due to the removal of material.

Based on the static tests of the modified and unmodified LLPs with no misalignment, it was concluded that the FEA model was successfully validated for the displacements of the lower leveling plates obtained in a bearing.

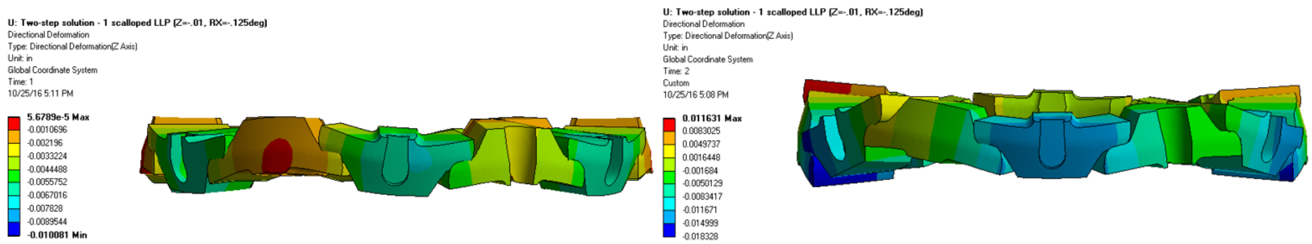
Misalignment tests

After the FEA model was validated for a static loading scenario, the next step was to investigate the behavior of the leveling mechanism for various dynamic cases where the leveling plates would tilt due to the misalignment of the collar. As described in Section , the misalignment load was applied in three steps: 1) Uniform loading step 2) Misalignment step 3) Readjustment step. The uniform loading step is a static loading case as shown previously. Here the shaft is pushed onto the pads in the negative Z direction at a given displacement. The amount of displacement is set to induce the desired amount of pressure on the pads. After that step, the translation of the shaft is stopped and a rotation is created. This corresponds to the misalignment step where the collar pushes on one side of the bearing while releasing pressure from the opposite side. The misalignment axis is oriented to create a misalignment loading on a single pad as indicated in Figure 7(a) and Figure 8(a).

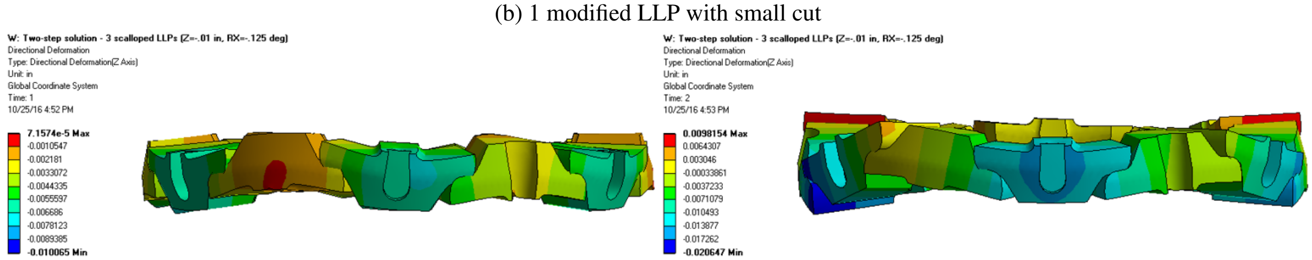
Figures 7 and 8 present the deformation of the leveling plates at the end of the uniform loading step shown on the left column and at the end of the misalignment step shown on the right column. The load applied uniformly on the pads at the end of



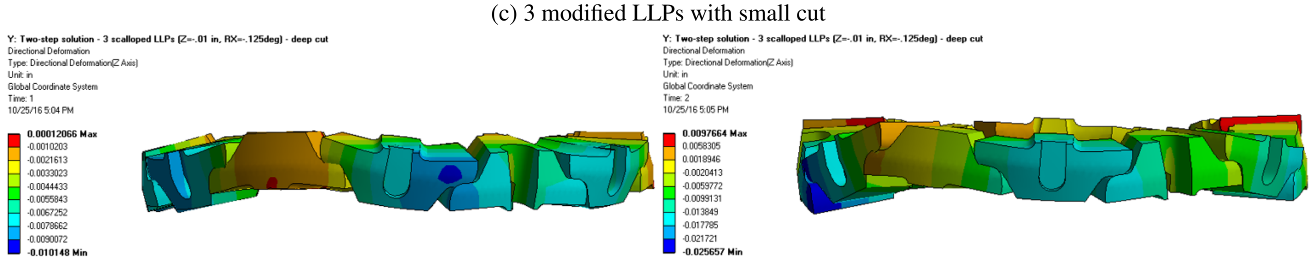
(a) Unmodified LLPs



(b) 1 modified LLP with small cut



(c) 3 modified LLPs with small cut



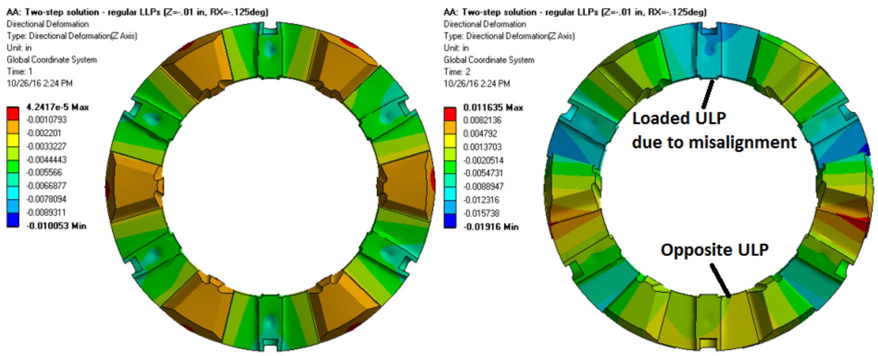
(d) 3 modified LLPs with deep cut

FIGURE 7: SIDE VIEW OF DEFORMED LEVELING PLATES AFTER THE STATIC LOADING STEP OF 1000 PSI (LEFT COLUMN) AND AFTER THE $\alpha = 0.125°$ MISALIGNMENT STEP (RIGHT COLUMN). COLORS INDICATE DEGREE OF DEFORMATION IN THE AXIAL DIMENSION.

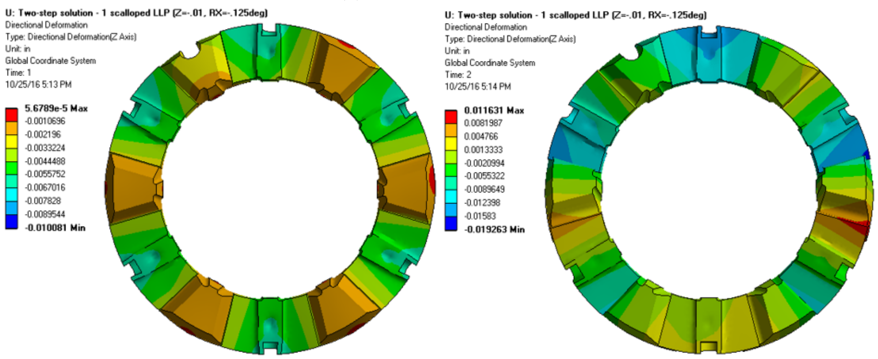
the static load step corresponded to 1000 psi, after which the rotor was misaligned by $\alpha = 0.125°$ towards the ULP (centermost plate in Fig. 7). What is evident is that the modified leveling plates deform more when the same amount of 1000 psi load is applied on them. This is indicated by the maximum deformation value observed in the left column of Figs. 7 and 8. The leveling plate mechanism weakens as more modified LLPs are used or as the cut deepens in the LLPs.

Evolution of the results of misalignment indicate that the leverage mechanism is slightly reduced for a modified leveling plate system, which is difficult to discern from the plots shown. The analysis indicates that using three modified LLPs with a small cut reduced the displacement of the pad opposite to the misaligned pad by 1.18% compared to 2.12% for the case with three modified LLPs having a deeper cut. Figure 9 presents the pressures induced on the pad surfaces due to a 0.125° misalignment of the shaft on a single pad at 1000 psi load. Three cases are shown: no modified plates, three modified plates that are equally spaced, and three heavily modified plates that are equally spaced. It can be seen that utilization of modified plates does not have a significant influence on the load distribution for the 6-pad bearing under 1000 psi load and 0.125° misalignment.

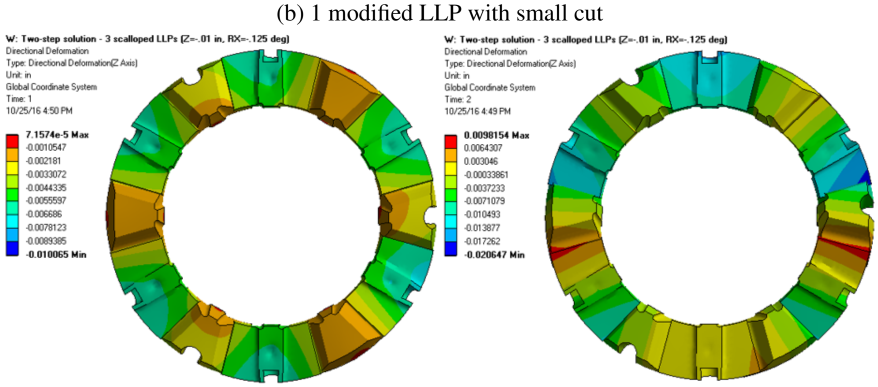
Up to this point, the FEA model parameters were for a high load value, which represents a worse case scenario compared to



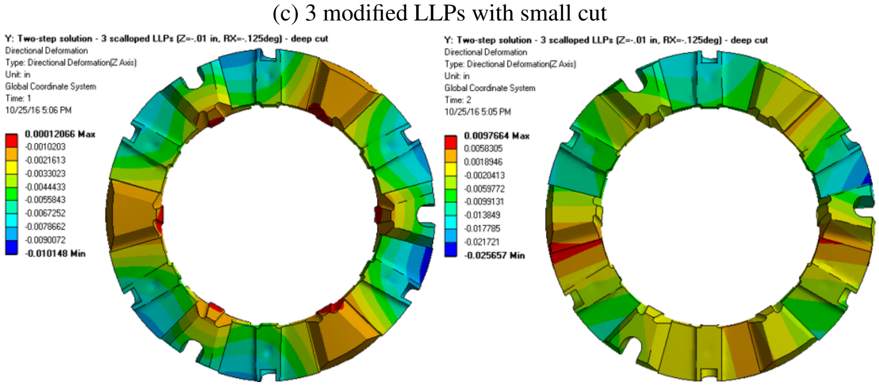
(a) Unmodified LLPs



(b) 1 modified LLP with small cut

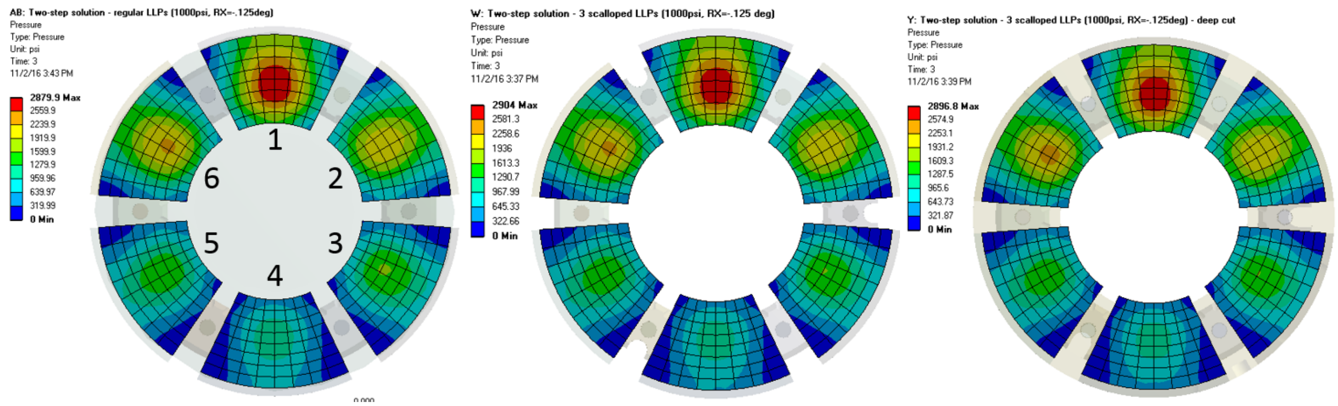


(c) 3 modified LLPs with small cut



(d) 3 modified LLPs with deep cut

FIGURE 8: TOP VIEW OF DEFORMED LEVELING PLATES AFTER THE STATIC LOADING STEP OF 1000 PSI (LEFT COLUMN) AND AFTER THE α=0.125° MISALIGNMENT STEP (RIGHT COLUMN). COLORS INDICATE DEGREE OF DEFORMATION IN THE AXIAL DIMENSION.



(a) Unmodified LLPs (b) 3 modified LLPs with small cut (c) 3 modified LLPs with deep cut

FIGURE 9: PRESSURE INDUCED AT THE FRICTIONLESS CONTACT BETWEEN THE PAD SURFACE AND THE COLLAR AFTER A 0.125° MISALIGNMENT AFTER THE PADS ARE LOADED TO 1000 PSI.

the loads expected in the field when the bearings are in operation. In order to evaluate the effect of modified leveling plates on the operation of the leveling mechanism and the load distribution on the pads, a new set of calculations have been generated using the FEA model at lower loads. Additional FEA simulations were conducted to obtain results with unmodified LLPs compared against a case where all of six LLPs were modified with a small cut.

The average pad loads generated by pushing the runner down on to the pads were 300 psi and 500 psi, while the misalignment angle imposed by rotating the runner towards a single pad were 0 and 0.1. It was observed that when all six of LLPs were modified with a small cut, the load carried by Pad 1 increases since the leveling mechanism effectiveness is reduced; however, this reduction is small, where an 8% increase in Pad 1 pressures is observed at 300 psi, and an 6% increase is observed at 500 psi when modified LLPs are used.

It is noteworthy that the ratio of the load carried by the misaligned pad ($P1$) is reduced when the load is increased from 300 psi to 500 psi for a misalignment angle of 0.1.This suggests that the leveling mechanism works more effectively as the load is increased.

CONCLUSIONS

In this work, a computational model of major components of a thrust bearing leveling system were investigated in order to assess the effect of rotor misalignment on the equalization capability of a tilting-pad thrust bearing utilizing leveling plates that are modified for instrumentation purposes. The FEA model was validated by comparing it against experimental data obtained for a bearing under axial loading, which confirmed that the computational model represents the component displacements well. Displacements obtained due to misalignment of the rotor were then used to predict the effectiveness of the leveling plates and influence of some lower leveling plate modifications and configurations.

Our analysis at relatively large loads (1000 psi) and misalignment angles indicates that the modifications and configurations presented slightly diminished the ability of the leveling plates to transfer the displacements to the neighboring upper leveling plates and did not significantly influence the load distribution.

A more significant influence on load distribution was predicted at lower unit loads, approximately 8% increase on the misaligned pad at 500 psi, and 6% at 300 psi for a 0.1° misalignment. The study suggests that the leveling mechanism works more effectively at higher loads.

Based on this study it was concluded that the bearing equalization system is still functional for the lower leveling plate modifications and configurations analyzed, although the equalization performance is reduced slightly.The modification introduced in the leveling plate mechanism of a tilting-pad center-pivot thrust bearing does not jeopardize the operation of the bearing in terms of pressure imbalance caused among the bearing pads.

ACKNOWLEDGMENT

The authors would like to thank the Kingsbury Inc. for permission to publish this paper. Special thanks go to Dr. Neil Jenkins and Joe Wilkes who have provided valuable support during the execution of this work.

REFERENCES

[1] Kingsbury, Inc., 2015. A general guide to the principals,

operation and troubleshooting of hydrodynamic bearings. https://www.kingsbury.com/pdf/universe_brochure.pdf.

[2] Kovarskii, K. E., Golinkin, S. L., and Volynskii, M. M., 1964. "Constructional Features of a Thrust Bearing with Pivoted Shoes". *Teploenergetika,* ***11***(5), pp. 57–62.

[3] Kislov, N. A., and Sudarev, A. V., 1992. "Calculation of Thrust Bearings with Lever-Type Leveling Devices". *Tyazheloe Mashinostroenie (Russian Journal on Heavy Machinery),* ***5***, pp. 6–10.

[4] Arafa, H. A., 2006. "Mechanical Design Pitfalls". *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* ***220***(6), pp. 887–899.

[5] Heshmat, H., and Pinkus, O., 1987. "Misalignment in Thrust Bearings Including Thermal and Cavitation Effects". *J. Tribology,* ***109(1)***(86), pp. 108–114.

[6] Viet, T. T., Maspeyrot, P., and Frene, J., 1996. "Behaviour of a misaligned and starved hydrodynamic thrust bearing". *Tribologia(Finland),* ***15***(4), pp. 16–41.

[7] San Andrés, L., 2002. "Effects of Misalignment on Turbulent Flow Hybrid Thrust Bearings". *Journal of Tribology,* ***124***(1), p. 212.

[8] Li, P., Zhu, Y., Zhang, Y., Chen, Z., and Yan, Y., 2012. "Experimental study of the transient thermal effect and the oil film thickness of the equalizing thrust bearing in the process of start-stop with load". *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology,* ***0***(0), pp. 1–8.

[9] Wang, Z., Ying, L., Fei, G., Xiangfeng, L., and Yuming, W., 2018. The influence of the equalizing beam structure on the tilting-pad thrust bearing during start-up and shut-down. Poster presented at ASME Turbo Expo 2018, Lillestrøm, Norway.