Tribology International 102 (2016) 580–599

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

# Pivot design and angular misalignment effects on tilting pad journal bearing characteristics: Four pads for load on pad configuration

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ARTICLE INFO

*Article history:*
Received 25 February 2016
Received in revised form
26 May 2016
Accepted 31 May 2016
Available online 7 June 2016

*Keywords:*
Tilting pad journal bearing
Misalignment
Tilt-pitch-yaw
Pivot design

ABSTRACT

This paper focuses on angular misalignment between tilting pad journal bearing (TPJB) and spinning journal. Three-dimensional (3D) TPJB numerical model is presented considering the tilt, pitch and yaw motions of the pad, pivot deformation, journal angular motion, and thermo-hydro-dynamic (THD) lubrication model. Cylindrical pivot is assumed to produce only tilting motion with a line contact, whereas the spherical pivot is to provide three angular motions with a point contact. Numerical modeling and simulation results are provided and discussed. Angular misalignment effects on bearing performance are predicted. Spherical pivot design produced invariant characteristics with varying misalignment ratio and phase, whereas the cylindrical pivot showed noticeable variation. Pad yaw and pitch motions led to the differential between the two pivot configurations.



## 1. Introduction

Rotor-bearing angular misalignment exists in nearly all rotordynamic systems. Potential causes of the misalignment are manufacturing tolerance, installation error and elastic deflection of a long rotor. The present study focuses on an angular misalignment between the TPJB and spinning journal, where the pad three angular motions exist depending on the pivot design. There have not been any researches about the TPJB misalignment with the consideration of the pad tilt, pitch and yaw motions. This study provides a 3D numerical model of the bearing-journal, and a numerical algorithm for the static equilibrium condition of the THD lubrication system. Misalignment effects were simulated and discussed with varying misalignment angle and phase.

### 1.1. Bearing-journal misalignment

There have not been many researches about the numerical modeling method or the test results of the bearing-journal misalignment since an axial variation of the rotordynamic system should be taken into account. The following are meaningful researches presenting the numerical approaches or the experimental results concerning the bearing-journal angular misalignment.

In 2002, Bouyer and Fillon [1] presented the experimental determination of the performance of a 100 mm diameter plain journal bearing submitted to a misalignment torque acting on the bush. According to the research, the maximum pressure developed in the bearing axial mid-plane was reduced with the misalignment, and the circumferential position of that was changed. The increased misalignment led to the increased temperature and oil flow rate. The minimum film thickness was measured and found to be reduced with the misalignment.

In 2004, Sun and Changlin [2] presented lubrication characteristics of a journal bearing taking account of the misalignment caused by spinning journal deformation. The journal deformation was induced by the load on the axial center of the long shaft. Film pressure distribution, the highest film pressure, the minimum film thickness and the misalignment moment were predicted. Axial variation of the film thickness was taken into account. Reynolds equation and finite difference method (FDM) were adopted to solve the fluid pressure. Thermal effects such as varying viscosity and thermal deformation were not considered. Noticeable change of the fluid pressure, the maximum pressure, film thickness distribution and minimum film thickness were observed with the varying misalignment angle. The load capacity, attitude angle, end leakage flow-rate and frictional coefficient were not sensitive to the misalignment.

In 2004, El-Butch and Ashour [3] analyzed the performance of the misaligned TPJB under a transient loading condition. The elastic and thermal deformations were predicted by the use of the FEM, whereas the lubricant pressure and the temperature were evaluated by the finite difference method (FDM). It is concluded that thermo-elasto-hydro-dynamic (TEHD) lubrication model improves the prediction in the case of the large bearing-shaft

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http://dx.doi.org/10.1016/j.triboint.2016.05.049
0301-679X/

**Nomenclature**

| | |
|---|---|
| $h$ | Film thickness |
| $\mu$ | Lubricant viscosity |
| $\boldsymbol{U}$ | Shaft surface linear velocity |
| $t$ | Time |
| $F_n$ | Nodal normal fluid force acting on the bearing pad and spinning journal |
| $e_x$ | $X$-Component of journal position |
| $e_y$ | $Y$-Component of journal position |
| $C_b$ | Bearing clearance |
| $p_n$ | Pad number |
| $n$ | Nodal position in circumferential direction |
| $m$ | Nodal position in axial direction |
| $N$ | Number of nodes in circumferential direction of the lubricant FE model |
| $M$ | Number of nodes in axial direction of the lubricant FE model |
| $O_J$ | Journal radial center |
| $\theta_n$ | Angular position of node $(p_n, n, m)$ |
| $J_{O_{tilt}}$ | Moment of inertia of the pad in $\eta$ axis |
| $J_{O_{pitch}}$ | Moment of inertia of the pad in $\zeta$ axis |
| $J_{O_{yaw}}$ | Moment of inertia of the pad in $\tau$ axis |
| $x, y$ | Local axis for the journal radial position |
| $z$ | Local axis for the journal angular position |
| $\eta, \zeta, \tau$ | Local axis for the pad angular position |
| $\delta_{tilt}$ | Pad tilt angle |
| $\alpha_{pitch}$ | Pad pitch angle |
| $\beta_{yaw}$ | Pad yaw angle |
| $p_{pvt}$ | Pivot displacement |
| $\theta$ | Circumferential nodal position |
| $z$ | Axial nodal position |
| $C_p$ | Pad clearance |
| $\theta_x$ | Journal angular position in $x$ direction |
| $\theta_y$ | Journal angular position in $y$ direction |
| $\theta_p$ | Pivot angular position |
| $R$ | Journal radius |

misalignment condition. The TPJB numerical model was limited to the cylindrical pivot design, and the pivot was assumed to be rigid. Two-dimensional (2D) energy equation was solved for the evaluation of the lubricant temperature, where axial heat transfer was ignored. Minimum film thickness was simulated under the mechanical unbalance. Transient rotor-bearing dynamic behavior was solved with the consideration of the pad flexibility, where the pad elastic deformation was assumed to be quasi-static. Time varying minimum film thickness under the non-zero unbalance was obtained. Flexible pad model predicted the increased minimum film thickness being compared to the rigid pad. Both misalignment and mechanical unbalance made effects on the fluid pressure and the minimum film thickness.

In 2010, Sun et al. [4] presented THD lubrication approach for the analysis of the misaligned plain journal bearing. Lubricant viscosity–pressure relationship, the surface roughness effect and the thermal effect were taken into account. Fluid film pressure, minimum film thickness and flow rate were predicted. Thermal effects such as lubricant temperature and the heat conduction in the spinning journal and bearing pad were simulated while the thermal deformation was ignored. In the case of the large misalignment angle and the large eccentricity ratio, the surface roughness and the surface pattern parameter was found to have influence on the lubrication performance.

In 2015, Xu et al. [5] presented static and dynamic characteristics of misaligned journal bearing employing the turbulent and THD lubrication model. Pressure distribution, film thickness and dynamic coefficients were provided with the varying misalignment angle. The fluid pressure developed on the bearing axial mid-plane was decreased with the increasing misalignment.

### 1.2. Tilting pad journal bearing

There have been a considerable amount of research papers about the TPJB. Pad tilt motion reduces the cross-coupled force terms leading to the stabilization of the rotordynamic system. In the case of the spherical pivot design, pad produces pitch and yaw motions. In this research, both cylindrical and spherical pivot configurations are compared and discussed. The following are references that have a great effects on the authors' current TPJB numerical model.

Lund's research paper in 1964 [6] provided the pad assembly method for the evaluation of the synchronously reduced force coefficients of the TPJB. Harmonic motions of the pad tiling and rotor whirling motions are assumed. Tieu's research paper presented in 1973 [7] provided a numerical algorithm and modeling method for the evaluation of the lubricant temperature adopting energy equation. Both iso-viscosity and varying viscosity cases were simulated and compared to each other. The iteration scheme provided in Tieu's research is the essential ground for the current research. Lund's research [6] was extended by Nilsson in 1978 [8]. 2D beam deformation was assumed for the analysis of the pad elastic bending under the fluid pressure. Pad flexibility was found to decrease the damping coefficients more than the stiffness terms. In 1990, Earles and Palazzolo [9] presented a TPJB numerical modeling method taking account of the pad flexibility. Single degree of freedom for the pad elastic deformation was assumed where only the pad radius curvature changes. In 1995, Desbordes et al. [10] calculated the journal orbiting under the several different mechanical unbalances with the consideration of the TPJB elastic deformation. The 3D elastic pad model predicted 40% lower minimum film thickness than the 2D approach under a large unbalance condition. In 2013, Wilkes and Childs [11] employed the same assumption of Earles and Palazzolo's [9] research where the pad surface remains full circular shape under the fluid pressure. In 2015, Suh and Palazzolo [12,13] presented a 3D TEHD TPJB lubrication model employing the FEM and nonlinear transient dynamic analysis method. Thermal distortion of the bearing pad and spinning journal, and elastic deformation of the bearing pad and pivot were taken into account. Bearing dynamic and static performance were predicted and compared to experimental results performed by other researchers. Employing the journal-lubricant-pad-pivot dynamic solver, the accurate pad elastic deformation could be predicted. The pad is supported only at the pivot location in their research, whereas earlier studies considered additional constraints to produce the pad tilt angle adopting the static pad deflection and tilt model. Taking account of the pad flexibility was found to be less important than the pivot elastic deformation to predict the TPJB performance. In the case of the typical pad thickness, the pad flexibility did not produce a noticeable difference between the rigid and flexible pad models.

In current research, THD lubrication model is employed since the TEHD analysis does not make a big difference in the case of the normal pad thickness as discussed by Suh and Palazzolo [12,13]. Generalized Reynolds equation, 3D energy equation, bearing-journal thermal-dynamic model, misalignment model, bearing