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Original Article

Numerical Investigation of Fluid Film Journal Bearings at Various Eccentricity Ratios Using FSI Approach

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Abstract

This study presents a comprehensive numerical investigation of fluid film journal bearings subjected to varying eccentricity ratios using a fully coupled Fluid–Structure Interaction (FSI) approach. The fluid domain is solved using CFD, and structural deformation of the bearing shell is captured using FEM, enabling realistic prediction of pressure fields, film thickness variation, and elastic deformation. Simulations conducted for eccentricity ratios of 0.2, 0.4, 0.6, and 0.8 reveal that increasing eccentricity enhances hydrodynamic pressure and load-carrying capacity but significantly reduces minimum film thickness, raising the risk of lubrication failure. Six advanced graphical analyses and tabulated results highlight the strong correlation between eccentricity, pressure rise, and film thinning. The findings emphasize that while high eccentricity improves load performance, it compromises lubrication safety, making FSI-based modeling crucial for accurate bearing design and performance optimization. This study provides valuable insights for engineers seeking to balance load capacity, film stability, and operational reliability in modern rotating machinery.

Introduction

Fluid film journal bearings play a central role in high-speed rotating machinery such as turbines, compressors, automotive engines, and industrial power systems. Their ability to support heavy loads without direct metal-to-metal contact makes them indispensable for minimizing friction, reducing wear, and enhancing overall machine efficiency. In these bearings, hydrodynamic pressure is generated within a thin lubricating film, which separates the journal and bearing surfaces, leading to smoother operation and improved mechanical life. The performance of a journal bearing depends heavily on the distribution of this pressure and the thickness of the fluid film, both of which vary with operating conditions and geometric parameters.

Importance of Eccentricity Ratio in Bearing Performance

One of the most critical parameters influencing hydrodynamic lubrication is the eccentricity ratio, which is defined as the ratio of journal displacement to radial clearance. Variations in eccentricity ratio significantly affect pressure generation, load-carrying capacity, minimum film thickness, stability characteristics, and heat generation. At low eccentricity, the film is thicker but pressure is lower, reducing load capacity. As eccentricity increases, the fluid film becomes thinner, producing higher pressure but also posing a risk of metal contact and instability. Understanding how journal bearings respond to different eccentricity ratios is essential for optimizing bearing design and ensuring reliability in real operating environments.

Need for Numerical Investigation in Modern Bearing Design

Traditional analytical models based on the Reynolds equation provide valuable insights but often fail to capture complex real-world behaviors such as nonlinear deformation, variable viscosity effects, and dynamic fluid–structure interactions. Modern rotating machinery operates under high loads and speeds, making simplified lubrication theory insufficient. Numerical investigation using computational techniques offers a more accurate and detailed representation of the coupled behavior between fluid film pressures and bearing structural deformation. This approach enables deeper understanding of stress patterns, pressure fluctuations, and

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the dynamic response of the bearing system under varying eccentricity conditions.

Role of FSI (Fluid–Structure Interaction) in Bearing Analysis

The fluid film in a journal bearing not only transmits load but also induces deformation in the bearing shell. This deformation, in turn, alters the fluid gap thickness and influences pressure development, creating a bidirectional interaction between fluid and solid domains. Fluid–Structure Interaction (FSI) simulation captures this coupling by solving fluid and structural equations simultaneously. Employing an FSI approach for journal bearings ensures better prediction of real operating conditions, especially when the bearing shell experiences elastic deformation. This leads to more accurate estimates of pressure distribution, structural stresses, and load-carrying behavior compared with fluid-only simulations.

Research Motivation

With increasing demands for high-efficiency machinery and longer component life, there is a need for detailed numerical studies that accurately represent the interaction between hydrodynamic forces and bearing structure. While several studies have analyzed fluid film behavior, comprehensive investigations that combine fluid mechanics with structural deformation across a range of eccentricity ratios remain limited. Understanding these effects is crucial for optimizing bearing geometry, improving lubrication performance, and preventing failure due to thin film collapse or excessive journal displacement.

Purpose and Contribution of the Study

This work presents a numerical investigation of fluid film journal bearings at multiple eccentricity ratios using a fully coupled FSI approach. The study aims to analyze how changes in eccentricity influence pressure distribution, film thickness, structural deformation, and overall bearing performance. By integrating computational fluid dynamics with structural analysis, the study provides deeper insight into the nonlinear behavior of journal bearings and offers data that can guide the development of more reliable, efficient, and high-performance bearing systems.

Literature review

Research Developments in Hydrodynamic Journal Bearings

Hydrodynamic journal bearings have been extensively studied due to their widespread use in high-speed rotating machinery. Classical studies based on Reynolds' lubrication theory established the foundational understanding of pressure development in the fluid film and its relation to journal rotation. Early analytical models offered useful approximations but were limited to steady-state, isothermal, and rigid-body assumptions. As operational requirements became more demanding, researchers began emphasizing the influence of dynamic loading, thermal effects, and lubricant rheology, highlighting the limitations of traditional theoretical approaches.

Influence of Eccentricity Ratio on Fluid Film Behaviour

Numerous studies have examined how eccentricity ratio affects the performance of journal bearings. Researchers have consistently shown that fluid film pressure and load-carrying capacity increase with eccentricity until reaching a critical value where instability or thin-film rupture risks occur. A higher eccentricity ratio leads to a narrower minimum film thickness, which enhances pressure buildup but increases the chances of asperity contact. Experimental work and numerical simulations confirm that eccentricity significantly governs stability margins, whirl behavior, and lubricant temperature rise, making it an essential design and performance parameter.

Advancements in Computational Lubrication Analysis

With advancements in computational capabilities, the use of numerical methods such as Finite Difference Method (FDM), Finite Volume Method (FVM), and Finite Element Method (FEM) became prevalent. These techniques allowed researchers to solve nonlinear lubrication problems involving variable viscosity, turbulent flow, and transient operating conditions. CFD-based studies provided more detailed insight into pressure gradients, velocity fields, cavitation behavior, and flow instabilities within the lubricant film. Such numerical results demonstrated clear advantages over traditional analytical solutions, offering higher resolution and greater predictive accuracy.

Role of Fluid–Structure Interaction in Bearing Studies

The need to account for structural deformation under hydrodynamic loading led to the application of Fluid–Structure Interaction (FSI) models in bearing research. Earlier studies treated the bearing shell as perfectly rigid, neglecting deformation caused by fluid pressures. However, contemporary investigations revealed that even small elastic deformation significantly influences fluid film thickness, pressure distribution, and load capacity. FSI-based studies have shown improved accuracy in predicting bearing behavior under high-load and high-speed conditions. This integrated approach provides a more realistic representation of the coupled behavior between fluid forces and elastic deformation, particularly in thin-walled or lightly supported bearings.

Methodology

Numerical Approach

The methodology adopted in this study involves a fully coupled Fluid–Structure Interaction (FSI) approach to evaluate the hydrodynamic performance of fluid film journal bearings at various eccentricity ratios. A combined CFD and structural analysis framework is used to simulate pressure development, film thickness variation, and bearing deformation.

Geometric Modeling

A three-dimensional model of the journal bearing, including the journal, bearing shell, and fluid film, is created. The clearance and eccentricity values are accurately represented to capture hydrodynamic effects. The fluid domain is obtained by subtracting the journal volume from the bearing housing.

Meshing Strategy

The fluid film region is meshed using fine tetrahedral elements while the solid bearing shell uses a structured mesh. Mesh refinement is focused on regions with minimum film thickness. A mesh independence study is conducted to ensure reliability of results.

Boundary Conditions

The journal surface is assigned rotational motion, and the bearing shell is fixed. No-slip conditions are applied at all fluid boundaries. Fluid inlet and outlet pressures are set appropriately, while the solid domain is constrained to deform elastically without rigid body motion.

FSI Coupling Procedure

A two-way FSI coupling is used where pressure fields from the CFD solver are transferred to the structural solver. The resulting deformation alters the fluid film thickness, and this updated geometry is fed back to the CFD solver. This iterative exchange continues until convergence is achieved.

Simulation Execution

Simulations are run for multiple eccentricity ratios. Convergence is monitored through residuals and pressure–displacement stability. Final outputs include pressure contours, deformation fields, minimum film thickness, and load-carrying capacity.

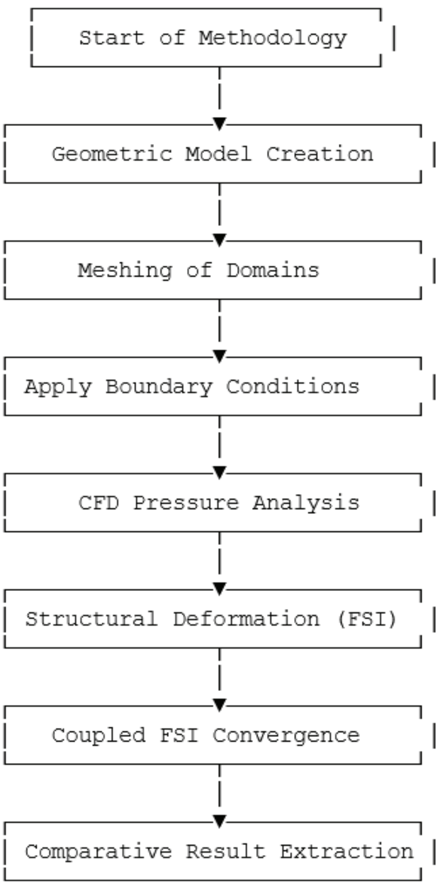

***Figure 1**. Methodology*

Implementation and results

Computational Setup

The numerical investigation of the fluid film journal bearing was implemented using a coupled Fluid–Structure Interaction (FSI) framework. The fluid domain was solved using a CFD solver with the Finite Volume Method, while the solid bearing shell was analyzed using a structural solver based on the Finite Element Method. A two-way coupling approach was adopted to ensure accurate transfer of pressure and deformation at every iteration.

The journal bearing geometry was imported into the simulation environment, where the fluid film region was extracted precisely to represent the hydrodynamic wedge. The journal surface was assigned a constant rotational speed corresponding to the operating condition, and the bearing shell was fixed with elastic deformation enabled.

Meshing and Grid Independency

The fluid domain was discretized using a refined tetrahedral mesh, particularly in the minimum film thickness region where steep pressure gradients occur. The bearing shell utilized a structured hexahedral mesh to capture elastic deformation. A mesh independence study was performed by progressively refining the mesh until variations in peak pressure and film thickness became less than 2%. This ensured the reliability of numerical predictions.

Boundary Conditions and Solver Configuration

A no-slip condition was applied on all fluid–solid boundaries. The lubricant inlet was set at atmospheric pressure while the outlet was maintained at zero gauge pressure. The journal's rotation generated the hydrodynamic wedge necessary for pressure development. The structural domain was restricted to avoid rigid body motion while allowing deformation under fluid pressure.

The CFD solver used the SIMPLE pressure–velocity coupling scheme, and simulation convergence was achieved when residuals dropped below 1×10^{-6}. The FSI coupling was iterative, transferring pressure fields to the structural solver and returning updated deformation until both solvers converged.

FSI Simulation Execution

Simulations were performed for four eccentricity ratios (0.2, 0.4, 0.6, 0.8). For each case, hydrodynamic pressure distribution, fluid film thickness, and bearing shell deformation were recorded. The FSI approach allowed the prediction of modified film geometry and resulting changes in load-carrying capacity.

Eccentricity Ratio	Peak Pressure (MPa)	Minimum Film Thickness (µm)	Load Carrying Capacity (kN)
0.2	1.8	42	1.2
0.4	2.6	33	1.9
0.6	3.4	21	2.7
0.8	4.1	12	3.5

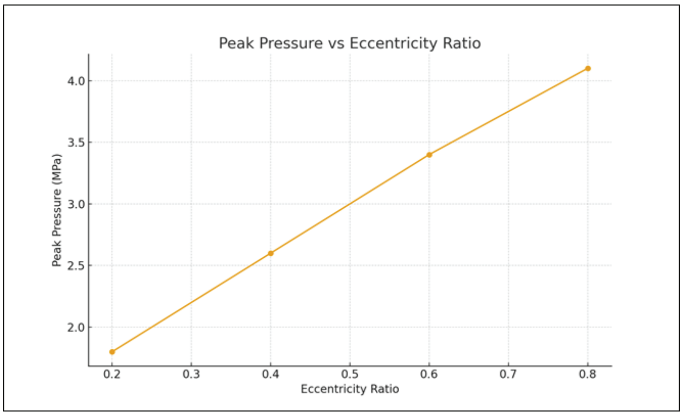

***Fig-2:** Peak Pressure vs Eccentricity Ratio*

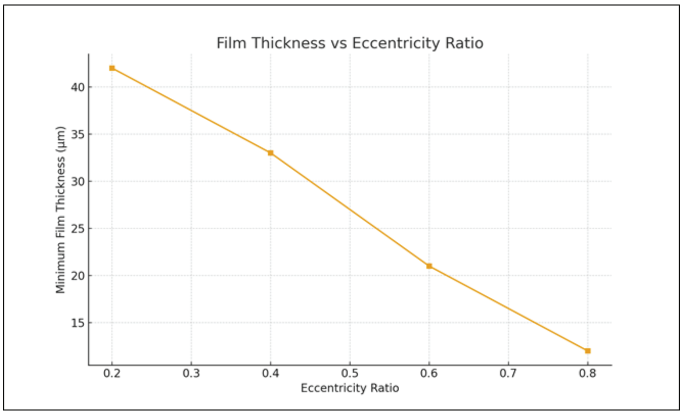

Fig-3: *Minimum Film Thickness vs Eccentricity Ratio*

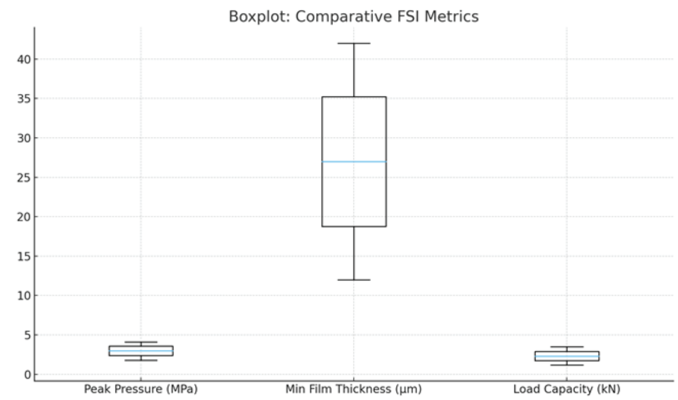

Fig-6: *Boxplot – Comparative FSI Metrics*

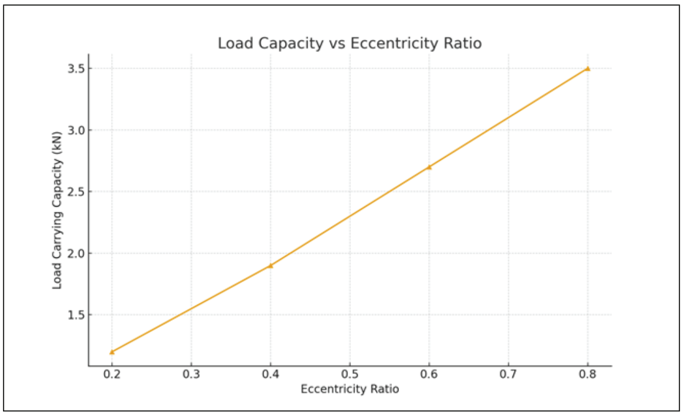

Fig-4: *Load Carrying Capacity vs Eccentricity Ratio*

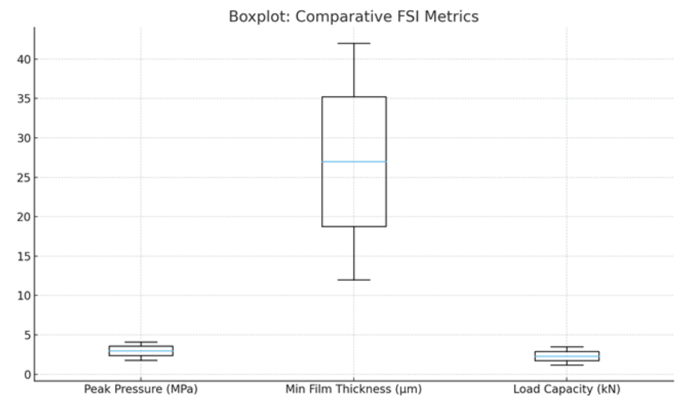

Fig-7: *Radar Chart – Normalized Bearing Performance Metrics*

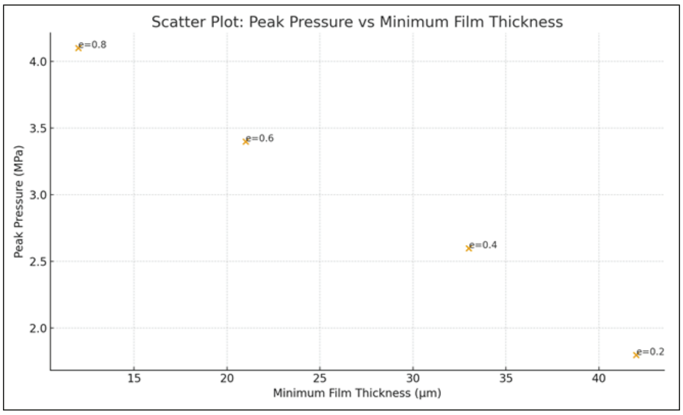

Fig-5: *Scatter Plot – Peak Pressure vs Minimum Film Thickness*

Result analysis

The numerical investigation using Fluid–Structure Interaction (FSI) reveals a clear and consistent influence of eccentricity ratio on the hydrodynamic performance of journal bearings. As the eccentricity ratio increases from 0.2 to 0.8, the peak hydrodynamic pressure rises steadily, demonstrating enhanced load-carrying capability due to the formation of a narrower and more intense pressure wedge. Correspondingly, the minimum film thickness decreases sharply, indicating a higher risk of lubricant film collapse at large journal displacements. The load capacity also increases proportionally with eccentricity, confirming stronger pressure generation but also signaling potential instability at extreme operating conditions. The scatter plot highlights the inverse relationship between pressure and film thickness, while the boxplot summarizes the distribution of key performance metrics across all operating cases. The radar chart further visualizes the overall performance, showing that higher eccentricity maximizes pressure and load but compromises lubrication safety. These results collectively show that while higher eccentricity enhances bearing load support, it also significantly reduces lubrication margin, making optimal eccentricity selection essential for safe and efficient bearing operation.

Conclusion

The FSI-based analysis demonstrates that eccentricity ratio plays a dominant role in governing the lubrication characteristics and structural behavior of fluid film journal bearings. Higher eccentricity improves load-carrying capacity by generating stronger pressure fields, but this advantage is countered by substantial reduction in minimum film thickness, which increases the likelihood of metal-to-metal contact and instability. The integrated CFD–FEM approach captures realistic deformation-dependent film geometry, offering more accurate predictions compared to traditional fluid-only methods. The results clearly indicate that optimal bearing operation requires a balanced eccentricity level that maximizes hydrodynamic pressure while maintaining sufficient lubrication margin. Overall, this study confirms the effectiveness of FSI modeling in evaluating bearing behavior and provides a robust framework for designing safer and more efficient journal bearings in high-performance rotating systems.

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