Influence of eccentricity ratio on stability performance of hydrodynamic conical journal bearing

A. K. Gangrade¹, V. M. Phalle ², S. S. Mantha ³, A. N. Siddiquee ⁴

¹ Research student. Department of Mech. Engg., VJTI, Mumbai, and Faculty, K. J. S. C. E., Vidyavihar, Mumbai, India
² Associate Professor, Department of Mechanical Engineering, VJTI, Mumbai, India
³ Ex-Professor, Department of Mechanical Engineering, VJTI, Mumbai, India
⁴ Professor, Jamia Millia Islamia (a Central University), New Delhi, india

¹Corresponding Author: akgangrade@somaiya.edu

Abstract. Due to growing need of conical journal bearings for combined axial and radial load application, efforts are being made to explore suitability of various shapes of hydrodynamic conical journal bearings. The combined load carrying ability of conical journal bearings appear as a better option to employ in rotary-machines and added applications. Thus, in this research work, efforts have been made to explore the stability performance of hydrodynamic conical journal bearing by finite element analysis. The bearing performance have been examined for semi-cone angle (γ = 5°, 10°, 20°) and eccentricity ratio (ε) up to 0.6 for rotor speed (v = 2.6, 5.2 m/s). Results are presented for axial and radial load capacity, stiffness and damping constants and rotor threshold speed. Load carrying capacity is improved with semicone angles and journal operating speed. Stability performance of bearing as a threshold speed (ωth) decreases with increase of semi cone angle. Hence, selection of journal operating speed and semi-cone angle is significant for dynamic stability of conical journal bearing.

1. Introduction

Hydrodynamic conical journal bearings are successfully utilised for supporting the rotors in micro mechanical systems and turbines in hydro-electric application of very high capacity around 100 MW. Hydrodynamic conical journal bearings comprise low expenses, ease of making and compact size as related to two separate bearings presently working in turbo-machines and other applications [1, 2]. Hydrodynamic conical journal bearing has a capability to sustain radial and axial loads. Thus, stability behaviour of hydrodynamic journal bearing is an important and interesting task for its correct development. The stability behaviours of hydrodynamic journal bearing are essential to ensure the harmless setup of rotor-bearing system. Thus, an analysis has been proposed and carried out for stability of conical hydro-dynamically lubricated journal bearing for variation in eccentricity ratio and other operating parameters. Gangrade et al. [3-5] in their parametric study and experimental work on test-rig observed that dynamic performance of hydrodynamic conical journal bearing depend on relative eccentric position, variation in radial load and semi cone angle. In further study Korneev [6]
recommended a diverse database to plot the rotors trajectory and determined the stability of conical hydrodynamic bearings for geometric limitations and other operating situations.

Yousif and Nancy [7]: presented numerical and experimental work and found that mixing of solid additives in the lubricating fluid improve the performances of conical bearing as per mass transfer theory. They have resolved, additives present in lubricating oil also improve the load carrying capacity. Gamal and Al-Hanaya [8] solved the equation of pressure distribution and calculated the fluid flow on conic surfaces by using average clearance technique. Numerical results have been presented with standard charts for combined axial and radial load capacity. Hong et al. [9] have considered linear damping and stiffness constants for hydrodynamic force to assess the stability of journal bearing. They have confirmed by numerical study along with experimental work and concluded that for small eccentricity ratio hybrid conical journal bearing has better stability in practice. Korneev and Yaroslavtsev [10] evaluated the damping and stiffness constant by using the empirical formulas for oil lubricated grooved conical journal bearing (which researchers have named multi-pad bearing). Kim et al. [11] derived the generalized Reynolds equation by using meridian and angular coordinates and calculate the stability performance of conical bearing by numerical formulation. In 2016, Sharma and Awasthi [12] considered the effect of aspect ratio on the performance of fluid film journal bearing by numerical methods. Sharma et al. [13] developed the code for dynamic and static performance analysis of hybrid conical journal bearing in spherical coordinate system by using Reynolds equation.

The result established in the study of Luis San Andres [14] presented the improvement of stability performance with increase of eccentricity ratio in hydrodynamic journal bearing. In his work, hydrodynamic journal bearing found stable for eccentricity ratio 0.75 and above. Stability performance of hydro-dynamically lubricated journal bearings were also explored by few researchers [15-17]. Gangrade et al. [18] presented CFD analysis of water lubricated conical journal bearing for various operating conditions and Phalle et al. [19] studied the stability performance characteristic of oil lubricated conical journal bearing using numerical method. In this study code developed in Fortran is used to evaluate the effect of eccentricity ratios on stability of conical hydrodynamic journal bearing. The stability performance of conical journal bearing is studied for variations in eccentricity ratio (ε) up to 0.6 for rotor speed (v = 2.6, 5.2 m/s). The numerically computed results have been examined for semi-cone angle (γ = 5°, 10°, 20°) of conical hydrodynamic journal bearings for aspect ratios (λ = 1.0) for axial and radial load capability, stiffness constants, damping constants and rotor threshold speed of journal bearing. The main objective of this work is to develop an understanding for selection of conical journal bearing in combined radial and attend the constant axial load for randomness in rotating machines.

2. Analysis

Hydrodynamic conical journal bearing model is expressed in spherical coordinate system and analysed in steady state equilibrium condition by using modified Reynolds equation. Finite element method is used to formulate the fluid flow in the clearance space of a hydrodynamic conical journal bearing. Four noded isoperimetric elements were used for modeling and simplification of the solution. Schematic interpretation of a bearing model sustained by lubricating film is shown in Fig. (1). Time-dependent equation governing the hydrodynamic conical journal bearing has recommended by Sharma et al. [13] as follows:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r}{h^3} \frac{\partial p}{\partial r} \right) + \frac{1}{sin \gamma} \frac{\partial}{\partial \phi} \left( \frac{h^5}{12 \mu r} \frac{\partial p}{\partial \phi} \right) - \frac{\omega}{2} \frac{\partial h}{\partial \phi} + \frac{\partial}{\partial t} h = 0
\]

(1)

Where \( r, \gamma, \omega, \mu, p \) and \( h \), are represents the journal radius at mid-plane, semi-cone angle, journal speed, viscosity of fluid, pressure around the circumference of bearing and minimum fluid film thickness, respectively. The Reynolds equation (1) is expressed in non-dimensional form for further study as follows.
\[
\frac{\partial}{\partial \beta} \left( \sin^2 \gamma \right) + \frac{\partial}{\partial \alpha} \left( \frac{h^3}{12\mu} \frac{\partial \rho}{\partial \alpha} \right) = \frac{\Omega}{2} \frac{\partial \bar{h}}{\partial \alpha} + \frac{\partial \bar{h}}{\partial t} \tag{2}
\]

The Eq. (2) stated in non dimensionised system by Sharma et al. [13]; where, the subsequent nondimensional factors are incorporated

\[\beta = \frac{r \sin \gamma}{R_j}; \quad \bar{p} = \frac{p}{p_s}; \quad \bar{h} = \frac{h}{C_t}; \quad \bar{t} = \frac{t}{\mu R_j^2 / C_t^2 p_s}; \quad C_t = \text{radial clearance}\]

\[\Omega = \omega \left( \frac{\mu R_j^2}{C_t^2 p_s} \right) ; \quad \alpha = \phi; \quad \beta = \text{coordinate in axial direction}; \quad \bar{p} = \text{normalised pressure};\]

3. In this study the operating and geometrical parameters for this analysis are given in Table (1). Performance parameters for bearing were carried out and worked out the solution by the iterative technique followed by Sharma et al. [13]. The boundary conditions used for the analysis of lubricant flow field are described in Gangrade et al. [3].

**Table 1: Geometric and operating parameters for hydrodynamic conical journal bearing**

| **Bearing factors**          | **size** |
|------------------------------|----------|
| Aspect ratio (\(\lambda\))   | 1.0      |
| Journal radius (\(R_j\)), mm | 50       |
| Length of bearing (L), mm    | 100      |
| Clearance ratio (C/R)        | 0.001    |
| Semi cone angle (\(\gamma\)) | 5°, 10°, 20° |
| Eccentricity Ratio (\(\varepsilon\)) | 0.1 – 0.6 |
| Pressure (\(p_s\)), MPa     | 0.5      |
| Journal speed (v), m/sec     | 2.6, 5.2 |
| Lubricating fluid viscosity (\(\mu\)), Pa·Sec | 0.0277 |
| Lubricating fluid density (\(\rho\)), Kg/m³ | 860 |
3. Validation of mathematical model

The numerically simulated results for hydrodynamic conical journal bearing have been validated on customized hydrodynamic conical journal bearing test rig for aspect ratio \( \lambda = 1 \) and semi cone angle \( 10^\circ \) assembled at VJTI, Mumbai India [3]. The CHJB-test-rig created for this application is capable to measure the value of pressure distribution at predefined points in hydrodynamic conical journal bearing. In this test-rig; all physically applicable limits have been considered and results have been compared with the FEA simulation model for validation of hydrodynamic conical journal bearing of \( 10^\circ \) semi cone angle as shown in Fig.2.

![Fig. 2: Confirmation of FEA results by experiments on customized test-rig](image)

4. Results and discussion

Results have been discussed in this section for load capacity, stiffness constants, damping constants and rotor threshold speed. The influences of numerous parameters for bearing were numerically simulated by using the finite element model. Stability performance of bearing is evaluated and discuss by using the code developed in Fortran-77.

4.1 Axial and radial load carrying capacity \( (\bar{W}_r, \bar{W}_d) \)

In this section, axial and radial load carrying capacity has been presented as a function of eccentricity ratio for conical journal bearing. From results, in Fig.3 it is observed that bearing capability to resist the load in axial direction \( \bar{W}_d \) increases with increase of semi cone angles and found that for aspect ratio \( \lambda = 1 \), \( \bar{W}_d \) increases in the order of 2.25 and 6.24 times for semi cone angle \( 10^\circ \) and \( 20^\circ \) respectively with respect to base bearing of semi cone angle of \( 5^\circ \). Whereas radial load capacity \( \bar{W}_r \) in hydrodynamic conical journal bearing is increases with the increase of semi cone angle. Fig. 3 shows this effect with semi cone angles \( (\gamma = 5^\circ, 10^\circ, 20^\circ) \) on hydrodynamic conical journal bearing for aspect ratio \( \lambda = 1 \) and displays the percentage rise in the value of \( \bar{W}_r \) in the order 46.35% for bearing of semi cone angle \( 20^\circ \) as compared to the base bearing of semi cone angle \( 5^\circ \) for same operating conditions \( (\varepsilon = 0.5 \) and \( v = 5.2 \text{ m/sec} \) In application, when the load carrying capacity in axial direction \( \bar{W}_d \) is considered for primary importance, then designer have the choice to select suitable semi cone angle at design stage, for better performance of conical journal bearing. The variation in the results with upward and downward nature of curves for variation in eccentricity ratio may be due to numerical instability in calculating the values by the program (code).
Fig. 3: Variation in axial load ($\bar{W}_a$) and radial load ($\bar{W}_r$) w.r.t. eccentricity ratio ($\varepsilon$) and semi cone angles ($\gamma = 5^\circ, 10^\circ, 20^\circ$), aspect ratio ($\lambda = 1.0$) for speed ($v = 2.6, 5.2$ m/sec)

4.2 Direct stiffness coefficient ($\bar{S}_{11}, \bar{S}_{22}$)

Direct fluid film stiffness constants are anticipated to change with increase of bearing angle ($\gamma$) as the quantity of lubricant is increased in clearance space [17]. This is also due to change in direction of fluid film reaction with change in bearing angle and accordingly change in the value of axial and radial components of force in bearing. It is shown in Fig. 4 for a bearing of aspect ratio ($\lambda = 1$), the value of $\bar{S}_{11}$ for bearing angles $10^\circ, 20^\circ$ increases in the order of $11.85\%$ and $51.63\%$ respectively with respect to base bearing with semi cone angle $5^\circ$, for bearing operating at an eccentricity ratio ($\varepsilon = 0.5$) and relative journal velocity of $5.2$ m/sec. However, for the same operating conditions and bearing size ($\lambda = 1$), the value of $\bar{S}_{22}$ rises in the order of $12.16\%$ and $52.93\%$ for bearing angles $10^\circ, 20^\circ$ respectively as related to the base bearing having semi cone angle $5^\circ$.

Fig. 4: Variation in direct stiffness coefficient ($\bar{S}_{11}$) and ($\bar{S}_{22}$) w.r.t. eccentricity ratio ($\varepsilon$) for bearing angles ($\gamma = 5^\circ, 10^\circ, 20^\circ$), aspect ratio ($\lambda = 1.0$) for speed ($v = 2.6, 5.2$ m/sec)
4.3 Direct damping coefficient \((\bar{C}_{11}, \bar{C}_{22})\)

In the present work the variations of direct damping coefficient \((\bar{C}_{11}, \bar{C}_{22})\) has been discussed for various bearing angle \((\gamma = 5^\circ, 10^\circ, 20^\circ)\). As realised from the Fig. 5, the value of \(\bar{C}_{11}\) for bearing with aspect ratio \((\lambda = 1)\), increases almost 10.83% and 44.29% for bearing angles 10°, 20° respectively as related to base bearing with semi-cone angle 5°, when journal bearing operated at an eccentricity ratio \((\varepsilon = 0.5)\) and relative velocity of journal 5.2 m/sec. Whereas, in Fig. 5, also observed that \(\bar{C}_{22}\) increases in the order of 11.10% and 45.40% respectively for semi cone angles 10°, 20° with respect to base bearing of angle 5°.

![Graph showing variation in direct damping coefficient](image)

Fig. 5: Variation in direct damping coefficient \((\bar{C}_{11})\) and \((\bar{C}_{22})\) w.r.t. eccentricity ratio \((\varepsilon)\) for semi cone angles \((\gamma = 5^\circ, 10^\circ, 20^\circ)\), aspect ratio \((\lambda = 1.0)\) for speed \((v = 2.6, 5.2 \text{ m/sec})\)

4.4 Stability threshold speed margin \((\bar{\omega}_{th})\)

In the present paper, rotor stability performance has been carried out by using perturbation method for steady-state equilibrium position of journal in clearance space. The influence for aspect ratio \((\lambda = 1.0)\) and bearing angle \((\gamma = 5^\circ, 10^\circ, 20^\circ)\) on threshold speed \((\bar{\omega}_{th})\) of bearing for variation in eccentricity ratio \((\varepsilon)\) up to 0.6 is shown in Fig. 6. It is found that value of \(\bar{\omega}_{th}\) decreases in the order of 0.23% and 1.15% for semi cone angles 10°, 20° respectively with respect to fundamental bearing of angle 5° when bearing is expected to operate at an eccentricity ratio \((\varepsilon = 0.5)\) and velocity of journal 5.2 m/sec.

![Graph showing variation in threshold speed](image)

Fig. 6: Variation in threshold speed \((\bar{\omega}_{th})\) w.r.t. eccentricity ratio \((\varepsilon)\) for semi cone angles \((\gamma = 5^\circ, 10^\circ, 20^\circ)\), aspect ratio \((\lambda = 1.0)\) for speed \((v = 2.6, 5.2 \text{ m/sec})\)
5. Conclusions

Stability analysis of hydrodynamic conical journal bearings for bearing angles ($\gamma = 5^\circ, 10^\circ, 20^\circ$), aspect ratio ($\lambda = 1.0$) and journal operating speeds ($v = 2.6, 5.2$ $m/s$) was performed for variation in eccentricity ratio ($\varepsilon$) up to 0.6 by using numerical method. The results are summarized as follows.

- Axial load carrying capacity ($\bar{W}_a$) of bearing increases 6.24 times and radial load carrying capacity ($\bar{W}_r$) increases in the order of 46.34% for aspect ratio ($\lambda = 1$) when bearing angle increases from $5^\circ$ to $20^\circ$ for bearing operating at an eccentricity ratio ($\varepsilon = 0.5$) and journal speed 5.2 $m/sec$.

- The value of direct stiffness constants ($\bar{s}_{11}, \bar{s}_{22}$) increases by 51.63% and 52.93% with increase of value in bearing angle from $5^\circ$ to $20^\circ$ for aspect ratio ($\lambda = 1$) at an eccentricity ratio ($\varepsilon = 0.5$).

- Direct damping coefficients ($\bar{c}_{11}, \bar{c}_{22}$) improve the performance of bearing with increase in the value of bearing angle by damping out the oscillations. The value of $\bar{c}_{11}, \bar{c}_{22}$ increases significantly at higher eccentricity ratio ($\varepsilon = 0.6$).

- Threshold speed ($\bar{\omega}_{th}$) decreases with increase of semi cone angle and this drop in value of threshold speed could be compensated by reducing the aspect ratio or size of bearing for same operating conditions. So, judicious selection of bearing angle along with bearing size is essential for better performance of bearing with rotor threshold speed ($\bar{\omega}_{th}$).

The results from the present study of hydrodynamic conical journal bearing are useful for academic interest and provide an understanding for combined radial and axial load in application.

References

[1] Kim, K., Lee, M., Lee, S. and Jang, G. (2017), “Optimal design and experimental verification of fluid dynamic bearings with high load capacity applied to an integrated motor propulsor in unmanned underwater vehicles”, Tribology International, Vol. 114, pp. 221–233.

[2] Chen, W. J. (2012), “Rotordynamics and bearing design of turbochargers”, Mechanical Systems and Signal Processing, Vol. 29, pp. 77–89

[3] Gangrade, A. K., Phalle, V. M. and Mantha, S. S., (2018) "Performance analysis of a conical hydrodynamic journal bearing", Iranian Journal of Science and Technology, Transactions of Mechanical Engineering, 2018, ISSN 2228-6187.

[4] Gangrade, A. K., Phalle, V. M. and Mantha, S. S., (2017), "Effect of aspect ratio and semi cone angle on the stability behaviour of a conical hydrodynamic journal bearing", International conference on Advances in Thermal Systems, Materials and Design Engineering (ATSMDE2017), VJTI, Mumbai, Dec. 21-22, 2017.

[5] Gangrade, A. K., Phalle, V. M. and Mantha, S. S., (2018), “Parametric investigations of short length hydro-dynamically lubricated conical journal bearing”, Jurnal Tribologi 19, pp.57-78.

[6] Korneev, A. Y. (2014), “Rigid-rotor dynamics of conical hydrodynamic bearings”, Russian Engineering Research, Vol. 34, pp. 131–135.

[7] Yousif, A. E. and Nancy, S. M., (1994), “The Lubrication of Conical Journal Bearings with Bi-Phase (Liquid-Solid) Lubricants”, Wear, Vol. 172, pp. 23-28.

[8] Gamal, M. A. R. and Al-Hanaya, A. M. (2014), “MHD Flow of a Non-Newtonian Power Law through a Conical Bearing in a Porous Medium”, Journal of Modern Physics, Vol.5, pp. 61-67.
[9] Hong, G., Xinmin, L. and Shaoqi, C. (2009), “Theoretical and Experimental Study on Dynamic Coefficients and Stability for a Hydrostatic/ Hydrodynamic Conical Bearing”, Journal of Tribology, Vol. 131, pp. 041701-1-7.

[10] Korneev, A. Y. and Yaroslavtsev, M. M. (2010), “Dynamic Characteristics of Conical Multiple-Pad Hydrodynamic Liquid-Friction Bearings”, Russian Engng. Research, Vol.30, pp. 365-369.

[11] Kim, H., Jang, G. and Ha, H. (2012), “A Generalized Reynolds Equation and its Perturbation Equations for Fluid Dynamic Bearings with Curved Surfaces”, Tribology International, Vol. 50, pp. 6-15.

[12] Sharma, S. and Awasthi, R. K. (2016), “Effect of Aspect Ratio on the Performance and stability of Hydrodynamic Journal Bearing”, International Journal of Advance research and Innovation, Vol. 4, pp. 96-105.

[13] Sharma, S. C., Phalle, V. M. and Jain, S.C. (2011), “Performance Analysis of a Multirecess Capillary Compensated Conical Hydrostatic Journal Bearing”, Tribology International, Vol. 44(5), pp. 617-626.

[14] Luis, S. A. (1991), “Effect of Eccentricity on the Force Response of a Hybrid Bearing”, STLE Tribology Transactions, Vol. 34, pp. 537 – 544.

[15] Lund, J. W. (1974), “Stability and Damped Critical Speeds of a Flexible Rotor in Fluid-Film Bearings”, ASME Journal of Engineering for Industry, Vol. 96(2), pp. 509 – 517.

[16] Rahmani, F., Dutt, J. K. and Pandey R. K. (2016), “Performance behaviour of elliptical-bore journal bearings lubricated with solid granular particulates”, Particuology, Vol. 27, pp. 51 – 60.

[17] Khakse, P. G., Phalle, V. M. and Mantha, S. S. (2016), “Performance Analysis of a Nonrecessed Hybrid Conical Journal Bearing Compensated With Capillary Restrictors”, Journal of Tribology, Vol. 138, pp. 011703-1-9.

[18] Gangrade, A. K., Phalle, V. M. and Mantha, S. S. (2018) “CFD simulation of water lubricated conical hydrodynamic journal bearing”, Research Journal of Engineering and Technology, Vol. 9 (1), pp. 105 – 119.

[19] Phalle, V. M., Gangrade, A. K. and Mantha, S. S. (2015), —Influence of Semi Cone Angle on the Performance of a Conical Hydrodynamic Journal Bearing, STLE Annual Meeting & Exhibition, Texas, USA, May 17-21, 2015.