Effect of Load Orientation on the Performance of a Four-Lobe Bearing

G. Bhushan
National Institute of Technology,
Kurukshetra-136119 (Harayana)

S.S. Rattan
National Institute of Technology,
Kurukshetra-136119 (Harayana)

R. Kumar
HCTM
Kaithal, (Harayana)

Abstract: *It is observed that among multi-lobe bearings, a four-lobe bearing possesses good stability characteristics. Sometimes the line of action of the load does not pass through the axis of a bearing and is shifted on either side by a few degrees. Load orientation affects the performance of a bearing. The effect of load orientation on the stability of a four-lobe bearing has been analyzed in this paper. The stability of the bearing is observed to improved for the negative values of load orientation i.e. when the load line is shifted in the direction of rotation.*

Keywords: *Four-lobe bearing, finite-element method, load orientation.*

1. INTRODUCTION

The present trend in the industry is to run the turbomachines at high speeds. The ordinary circular bearings, which are the most common type of the bearings, are found to be unable at high speeds. It is found that the stability of these bearings can be increased by the use of multi-lobes. The analysis of multi-lobe bearings was first published by Pinkus [1]. It was followed by Lund and Thomson [2] and Malik [3] et.al., who gave some design data which included both static and dynamic characteristics for laminar, as well as turbulent flow regimes. The experimental stability analysis of such types of ~~bearing [4] [5] showed~~ that the analytical stability analysis reflects the general trends in experimental data. The various types of multilobe bearings reported in the literature are two-lobe (offset halves, elliptical, orthogonally-displaced), three lobe and four-lobe bearings [6]-[8]. Among various multilobe bearings a four-lobe bearing also possesses good stability characteristics. The performance of a four-lobe bearing has been investigated for various parameters like L/D ratio, ellipticity ratio and turbulence [9]. The load orientation also affects the performance of a bearing[10]. The present study is undertaken to investigate the effect of load orientation on the performance of a four-lobe dam bearings supporting rigid and flexible rotors.

2. NOMENCLATURE

C	: radial clearance
c_m	: minimum film thickness for a centered shaft
$C_{xx}, C_{xy}, C_{yx}, C_{yy}$	: oil-film damping coefficients
$C_{xx}, C_{xy}, C_{yx}, C_{yy}$	: dimensionless oil-film damping coefficients, $C_{xx}=C_{xx}$ ($\omega c/W$)
C_0, C_1, C_2, C_3, C_4	: coefficients of the characteristic equation
D	: diameter
e	: eccentricity
F	: dimensionless shaft flexibility, W/ck
h	: oil-film thickness, c ($1+\varepsilon\cos\theta$)
~~h~~	: himensionless oil-film thickness, h/2c
2k	: shaft stiffness
$K_{xx}, K_{xy}, K_{yx}, K_{yy}$	: oil-film stiffness coefficients
$K_{xx}, K_{xy}, K_{yx}, K_{yy}$	: dimensionless oil-film stiffness coefficients, $K_{xx} = K_{xx}$ (c/W)
L	: bearing length
N	: journal rotational speed
O_i	: lobe center of lobe i (i=1,2,3,4)
p	: oil-film pressure
R	: journal radius
S	: Sommerfeld no., $\left(\frac{\mu NLD}{W}\left(\frac{R}{C}\right)^2\right)$
V	: pheripheral speed of journal
W	: bearing external load
x, z	: coordinates for bearing surface (x-peripheral, z-along shaft axis)

1

ϕ	:	attitude angle
α	:	whirl rate ratio, $\alpha = \dot{\phi}/\omega$
β	:	squeeze rate ratio, $\beta = \dot{\varepsilon}/\omega$
ε	:	eccentricity ratio, e/c
δ	:	ellipticity ratio, $(1-c_m/c)$
θ	:	angle measured from the line of centers in the direction of rotation
θ_g	:	oil-groove angle
ρ	:	fluid density
μ	:	average fluid viscosity
ω	:	rotational speed
γ	:	load orienation angle
v	:	dimensionless threshold speed, $\omega(c/g)^{1/2}$
g	:	gravitational acceleration const.

3. BEARING GEOMETRY

The geometry of a four-lobe bearing is shown in Figure 1. A four-lobe pressure dam bearing comprises four lobes whose centers of curvatures are not in the geometrical center of the bearing. Thus, though the individual lobes are circular, the geometrical configuration as a whole is not. For concentric position of the rotor, there are two reference clearances of the bearing: a major clearance c given by a circle circumscribed by the lobe radius and a minor clearance c_m given by an inscribed circle. Thus the center of each lobe is shifted by a distance $c_p = (c-c_m)$ known as ellipticity of the bearing. The various eccentricity and ellipticity are non-dimensionalized by dividing the major clearance c.

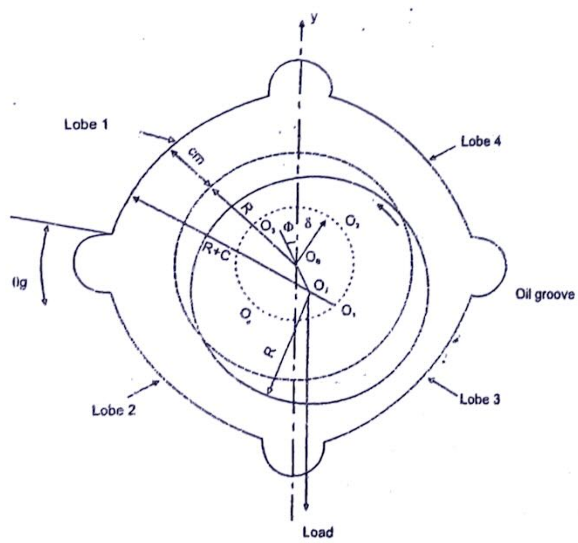


Fig. 1. A four-lobe bearing (Sectional side view)

Ellipticity ratio $(\delta) = (c-c_m)/c = 1-c_m/c$

Eccentricity ratio $(\varepsilon) = e/c$

$\varepsilon_1 = e_1/c, \varepsilon_2 = e_2/c, \varepsilon_3 = e_3/c, \varepsilon_4 = \varepsilon_4/c$

The various eccentricity ratios and attitude angles of the lobes of a four-lobe bearing are given by:

$$\varepsilon_1^2 = \varepsilon^2 + \delta^2 - 2\varepsilon\delta \cos(\pi/4-\phi)$$

$$\varepsilon_2^2 = \varepsilon^2 + \delta^2 + 2\varepsilon\delta \sin(\pi/4-\phi)$$

$$\varepsilon_3^2 = \varepsilon^2 + \delta^2 + 2\varepsilon\delta \sin(\pi/4+\phi)$$

$$\varepsilon_4^2 = \varepsilon^2 + \delta^2 - 2\varepsilon\delta \cos(\pi/4+\phi)$$

$$\phi_1 = 5\pi/4+\gamma + \sin^{-1}(\varepsilon(\sin \pi/4-\phi)/\varepsilon_1)$$

$$\phi_2 = 7\pi/4+\gamma + \sin^{-1}(\varepsilon(\cos \pi/4-\phi)/\varepsilon_2)$$

$$\phi_3 = \pi/4+\gamma - \sin^{-1}(\varepsilon(\cos \pi/4+\phi)/\varepsilon_3)$$

$$\phi_4 = 3\pi/4+\gamma - \sin^{-1}(\varepsilon(\sin \pi/4+\phi)/\varepsilon_4)$$

4. ANALYSIS

The non-dimensionalized Reynolds Equation for the laminar flow is:

$$\frac{\delta}{\delta x}\left(\frac{\bar{h}^3}{12}\frac{\delta \bar{p}}{\delta x}\right) + \left(\frac{D}{L}\right)^2 \frac{\delta}{\delta z}\left(\frac{\bar{h}^3}{12}\frac{\delta \bar{p}}{\delta z}\right) = \frac{\pi}{2}\frac{\delta \bar{h}}{\delta x} + \pi\varepsilon\,\alpha \sin 2x + \pi\beta\cos 2x \quad \text{...(1)}$$

The solution of the equation (1) for pressure distribution in the finite element technique is obtained by minimizing the following variational integral [11] over the individual elements:

$$J_e(p_e) = \int_{A_e}\int \left[\frac{1}{2}\frac{h^3}{12}\left\{\left(\frac{\delta p_e}{\delta x}\right) + \left(\frac{D}{L}\right)^2\left(\frac{\delta p_e}{\delta z}\right)^2\right\} + \frac{\pi}{2} h \frac{\delta p_e}{\delta x} - \frac{\pi}{2}\varepsilon\cos 2x \frac{\delta p_e}{\delta x} + \frac{\pi}{2}\beta\sin 2x \frac{\delta p_e}{\delta x}\right] dA_e \quad \text{... (2)}$$

where Pe = dimensionless film pressure in the eth element.

Each lobe of the bearing is analysed separately. Since the pressure profile has to be symmetrical about the center line of the bearing, only half of the lobe is taken for analysis. Each half is divided into 21 × 5 elements. The mesh size is reduced near the trailing edge where heavy pressures are produced. The resulting matrix is each case is stored in the banded form and is then solved by the Gauss-elimination method. Stiffness and damping coefficients are calcualted separately for each lobe and then added. The values of these stiffness and damping coefficients, shaft flexibility, and dimensionless speed are then used to evaluate the coefficients of the characteristic equation, which is a polynomial of the 6th order for flexible rotors. This characteristic equation has been taken from Hahn [12] and is obtained from the general case of an eccentrically mounted rotor on a flexible shaft.

The characteristic equation is:

$$s^6 F^2 v^4 C_0 + s^5 v^4 (F^2 C_1 + FC_2) +$$
$$s^4 v^2 (v^2 F^2 C_3 + 2FC_0 + v^2 + v^2 FC_4) +$$
$$s^3 V^2 (2FC_1 + C_2) + s^2 (2FV^3 C_3 + v^2 C_4 + C_0) +$$
$$sC_1 + C_3 = 0 \qquad \text{... (3)}$$

For a rigid rotor, the value of F is taken as zero. The system is considered as stable if the real part of all roots is negative. For a particualr bearing geometry and eccentricity ratio, the values of dimensionless speed are increased until the system becomes unstable. The maximum value of speed for which the bearing is stable is then adopted as the dimensionless threshold speed. The stability threshold curve divides any figure into major zones. The zone above this curve is unstable whereas the zone below this curve is stable. The minimum value of this curve is termed the minimum threshold speed. Mostly the curve has a vertical line, towards the left of which the bearing is stable at all speeds. This portion is called the zone of infinite stability. With an increase in minimum threshold speed the stability curve shifts upwards thus increasing the stable zone. Similarly with an increase in zone of infinite stability the stability threshold curve shifts towards right increasing the stable zone. Thus with increase in minimum threshold speed or zone of infinite stability or both the stability increases. The present analysis has been done for the bearing with the following parameters:

$$L/D = 1,\ \delta = 0.5,\ \theta_g = 20°$$

Sometimes the line of action of the load does not pass thrugh the axis of a bearing and is shifted on either side by a few degrees. To study the effect of load orientation angle (γ) on the performance of the bearing, the value of γ is varied from -15° to +15°. The stability curves are then drawn for different values of γ and the performance of bearing is predicted. The load orientation is taken to be positive if it is oriented in the opposite direction to that of shaft rotation and negative if it is oriented in the same direction. To consider the effect of liner flexibility of rotor, the value of dimensionless flexibility (F) is varied between 0.5 to 4.0 as most of the practical rotors have the value of F between this range.

5. RESULTS AND DISCUSSION

The effect of load orientation on the stability of a four-lobe bearing is shown in Figs. 2 to 6. Figure 2 shows the effect of load orientation on the stability of a four-lobe bearing supporting a rigid rotor (F=0). It is observed from the figure that postive values (0° to +15°) of load orientation angle adversely affect the stability of the bearing. The plot shows that zone of infinite stability decreases (from 0.096 at $\gamma = 0°$ to 0.085 at $\gamma = +15°$) with the increase in positive value of load orientation angle, while there is no change in the value of minimum threshold speed (remains constant at 5.05). The negative values of the load orientation have positive effects on

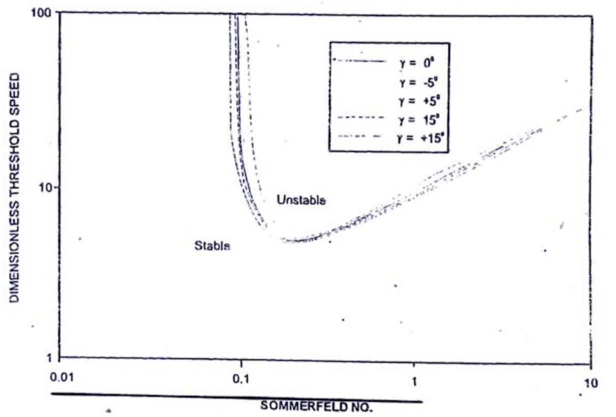
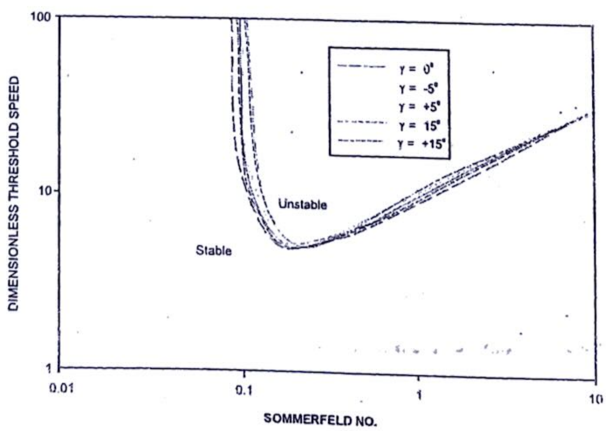


Fig. 2. Effect of load orientation on the stability of a four-lobe bearing supporting a rigid rotor (F=0).



SOMMERFELD NO.

Fig. 3. Effect of load orientation on the stability of a four-lobe bearing supporting a flexible rotor (F=0.5).

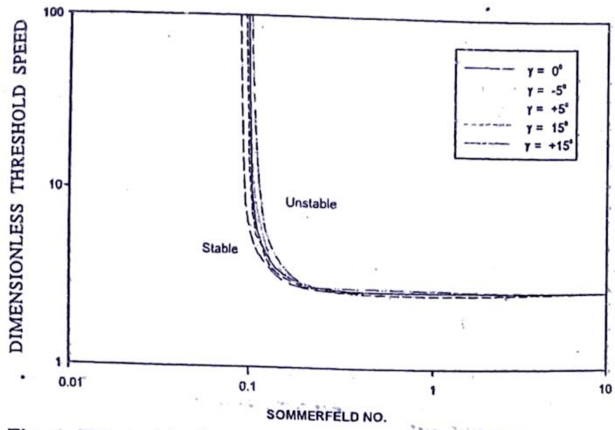


Fig. 4. Effect of load orientation on the stability of a four-lobe bearing supporting a flexible rotor (F=1.0).

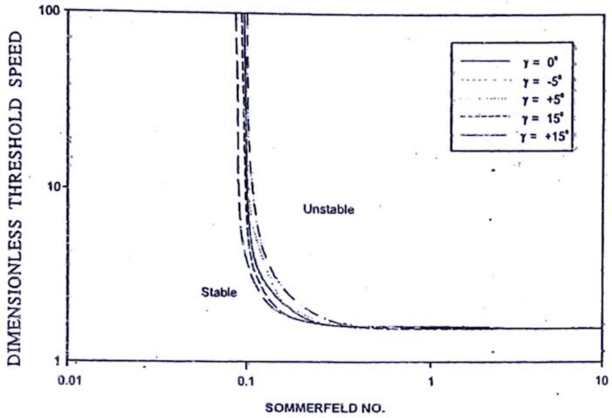


Fig.5. Effect of load orientation on the stability of a four-lobe bearing supporting a flexible rotor (F=2.0).

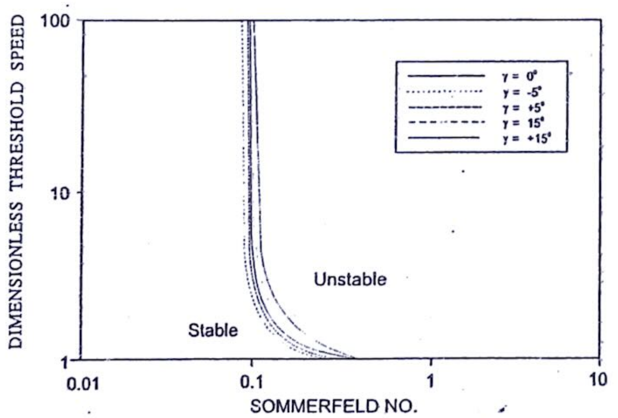


Fig. 6. Effect of load orientation on the stability of a four-lobe bearing supporting a flexible rotor (F=4.0).

the stability of the bearing. The plot shows that zone of infinite stability increases (from 0.096 at $\gamma = 0°$ to 0.105 at $\gamma = -15°$) with the increase in load orientation angle from 0° to -15°, again there is no change in the value of minimum threshold speed which remains constant at 0.05. These results in tabular forms are shown in Table 1.

Table 1. Values of minimum threshold speed and zone of infinite stability at various load orientations for a rigid rotor

Angle of load orientation	Minimum threshold speed	Zone of infinite stability (Up to S)
0°	5.05	0.096
+5°	5.05	0.092
+15°	5.05	0.085
-5°	5.05	0.099
-15°	5.05	0.105

The effect of load orientaion on the stability of an orindary four-lobe bearing supporting a flexible rotor is shown in Figs. 3 to 6. It is seen that the minimum threshold speed is not much affected by load orientation angle for a particualr value of F. However, the zone of infinite stability decreases with the increase in positive values of load orientation angle and increases with the increase in negative values of load orientation angle. The negative values of the load orientation have positive effect on the stability of the bearing in the same manner as for a rigid rotor.

The increase in the flexibility of rotor does not affect the zone of infinite stability as observed from Fig. 3 to 6 but the minimum threshold speed decreases from 2.80 to 0.51 as the flexibility of rotor is increased from F=0.5 to F=4.0.

6. CONCLUSIONS

1. In case of a four-lobe bearing supporting a rigid rotor the zone of infinite stability increases with increase in negative value of load orientation angle and is adversely affected with increase in positive value of load orientation angle. However the value of minimum threshold speed is almost unaffected with change is load orientation angle.

2. The stability of a four-lobe bearing supporting a flexible rotor is affected in the same manner as that of a rigid rotor. Thus the stability of a four-lobe bearing with rigid as well as flexible rotor increases with increase in negative value of load orientation and decreases with increase in positive value of load orientation.

3. The flexibility of the rotor also affects the stability. The minimum threshold speed reduces with the

increase in flexibility of the rotor while the zone of infinite stability remains constant. Thus the stability of a rotor decreases with increase in flexibility of the rotor.

REFERENCES

1. O. Pinkus, "Analysis and Characteristics of Three-Lobe Bearings", *ASME Journal of Basic Engineering*, vol. 81, pp. 19, 1959.

2. J.W. Lund, and K.K. Thomson, "A Calculation Method and Data for the Dynamic Coefficients of Oil Lubricated Journal Bearings", *Proceedings of the ASME Design and Engineering Conference, Minneapolis*, pp. 1, 1978.

3. M. Malik, Mahesh Chandra and R. Sinhasan, "Design Data for Offset-Halves Journal Bearings in Laminar and Turbulent Flow Regimes", *ASLE Trans.*, pp. 133-140, 1982.

4. J.C. Nicholas, L.E. Barrett, and M.E. Leader, "Experimental –Theoretical Comparison of Instability Onset Speeds for a Three Mass Rotor Supported by Step Journal Bearing", *Trans. ASME, Journal of Mechanical Design*, pp. 344-351, 1980.

5. R.D. Flack, M.E. Leader, and E.J. Gunter, "An Experimental Investigation on the Response of a Flexible Rotor Mounted in Pressure Dam Bearings", *Trans. ASME, Journal of Mechanical Design*, pp. 842-850, 1980.

6. D.F. Li, K.C. Choy and P.E. allaire, "Stability and Transient Characteristics of Four Multilobe Journal Bearing Configurations", *Journal of Lubrication Technology*, vol. 102, p. 291, 1980.

7. A Singh "Stability of Finite Two-lobe Journal Bearings Bearings for Rigid and Flexible Rotors", *PhD. Dissertation, Allahabad University*, 1978.

8. N.P. Mehta, "Investigations of Hydrodynamic Bearing performance by Finite Element Method", *PhD. Dissertation, Allahabad University*, 1981.

9. G. Bhushan, S.S. Rattan, and N.P. Mehta, "Effect of Turbulence, Ellipticity Ratio and L/D Ratio on the Performance of a of Four-Lobe Bearings with Rigid and Flexible Rotors", *The Journal of Institution of Engineers (India)*, vol. 83, pp. 57-61, 2002.

10. N.P. Mehta, S.S. Rattan and A. Verma, "Combined Effect of Turbulence, Load Orientation and Rotor Flexibility on the Performance of Three-lobe Bearings", *Tribology Transactions*, vol. 35, p. 530, 1992.

11. G.F. Booker, and K.H. Heubner. "Application of Finite Elements of Lubrication: An engineering Approach", *Trans. ASME, Journal of Lubrication Technology*, pp. 313-323, Oct. 1972.

12. E.J. Hahn, "The Excitability of Flexibility Rotors in Short Sleeve Bearings", *Trans. ASME, Journal of Lubrication Technology*, pp. 105, 1975. ❐