Optimum Bearing Form of the Regular and Reversible Rotation Type Herringbone Grooved Journal Bearing

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The optimum bearing parameters, which maximize the load carrying capacity in the radial direction giving an indication of the stability for whirl, for the design of regular and reversible rotation type herringbone grooved journal bearing are determined by a numerical analysis using the narrow groove theory and Gümbel condition in this paper.

1. Introduction

A herringbone grooved journal bearing has the following characteristics : Construction is simple, maintenance is easy, reliability and stability are high, and bearing life is long.

The demand for this bearing is growing with the growth of miniaturization, and high speed requirements in the latest precision instruments. For example, this bearing is used for magnetic disks, video disks, and polygon mirror instruments.

Conventional studies on the standard type non-reversible herringbone grooved journal bearing have been done [1 − 3].

However studies on a herringbone grooved journal bearing, which can be rotated in either direction have not yet been done. If this type of bearing can be developed, many new applications will be possible.

A new type of reversible rotation herringbone grooved journal bearing is proposed in this paper, and a numerical analysis of the optimum bearing parameters of this bearing using the narrow groove theory [4] and Gümbel condition is made. The optimum bearing parameters, which maximize the load carrying capacity in the radial direction giving an indication of the stability for whirl, for the design of regular and reversible rotation type herringbone grooved journal bearing are determined numerically for the case of either grooved member or smooth member rotation.

2. Form of the Regular and Reversible Rotation Type Herringbone Grooved Journal Bearing

The reversible rotation type herringbone grooved journal bearing is shown in Fig. 1 . The grooved member is the shaft and the smooth member is the bearing. Grooves are cut from $z=0$ to $z=L$ equally around the circumference. The shaft or the bearing can rotate in either direction with rotational speed ω.

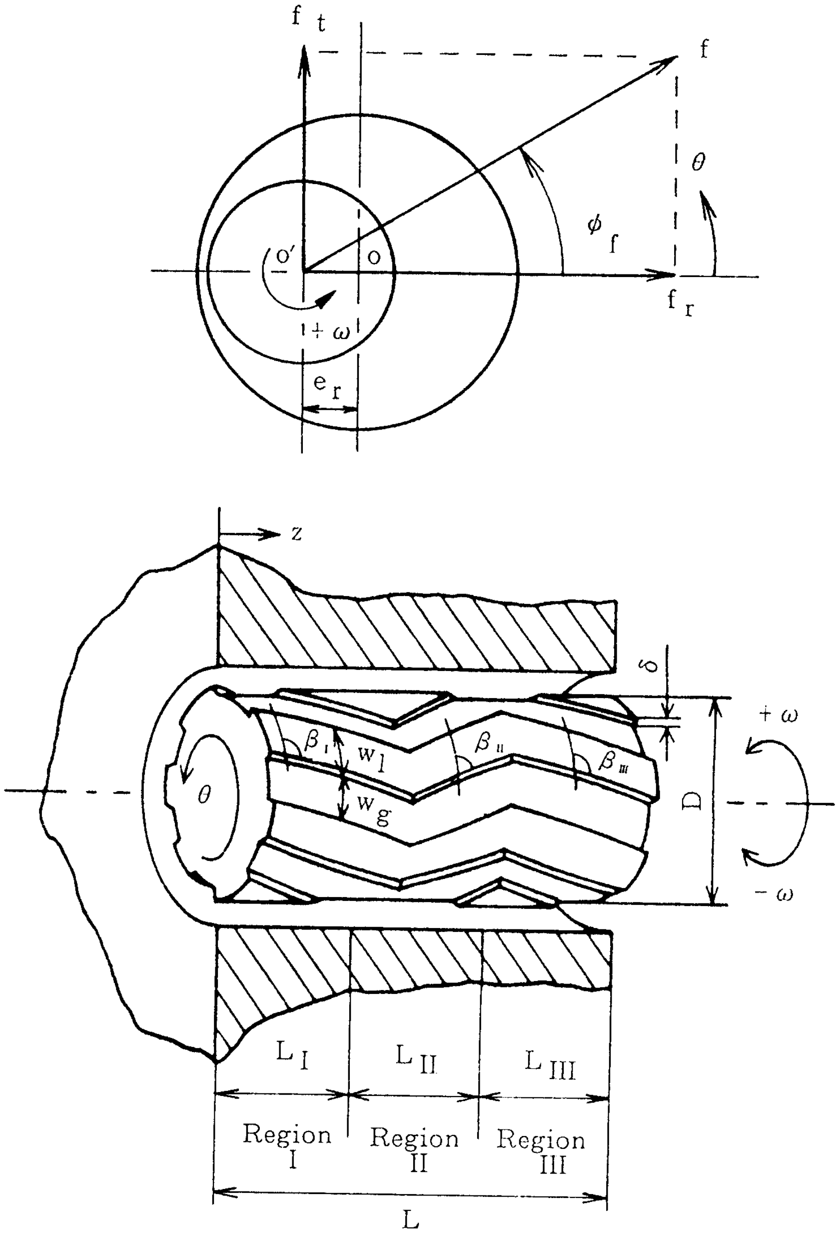

Fig. 1 The reversible rotation type herringbone grooved journal bearing.

3. Equations and Method of Numerical Calculation

The narrow groove theory, which assumes infinite grooves, is used in the numerical calculation of the reversible rotation type herringbone grooved journal bearing. The mass fluxes per unit length in the direction of z and θ (q^z and q^θ) are derived by the narrow groove theory, as follows :

$$q^z = \rho \left(k_1 \frac{\partial p}{\partial z} + k_2 \frac{\partial p}{r \partial \theta} + k_4 \cos\beta \right) \tag{1}$$

$$q^\theta = \rho \left(k_2 \frac{\partial p}{\partial z} + k_3 \frac{\partial p}{r \partial \theta} - k_4 \sin\beta + r\, h_m \tilde{\omega} \right)$$

where k_0, k_1, k_2, k_3, k_4, h_m, and $\tilde{\omega}$ are

$$k_0 = (1-\alpha)\, h_g^3 + \alpha\, h_1^3$$

$$k_1 = (-1/12\mu)\,\{h_g^3 h_1^3 + \alpha(1-\alpha)(h_g^3 - h_1^3)\sin^2\beta\}\,/k_0$$

$$k_2 = (-1/12\mu)\,\{\alpha(1-\alpha)(h_g^3 - h_1^3)\sin\beta\cos\beta\}\,/k_0$$

$$k_3 = (-1/12\mu)\,\{h_g^3 h_1^3 + \alpha(1-\alpha)(h_g^3 - h_1^3)\cos^2\beta\}\,/k_0 \tag{2}$$

$$k_4 = \{-r\,\delta\,(\omega_g - \omega_s)/2\}\,\alpha(1-\alpha)(h_g^3 - h_1^3)\sin\beta/k_0$$

$$h_m = \alpha\, h_g + (1-\alpha)\, h_1$$

$$\tilde{\omega} = (\omega_s + \omega_g)/2 - \Omega$$

The coordinates z and θ are transformed to the coordinates ξ and η in which intervals of grids are equal to 1, respectively. Mass fluxes which pass through the interval between $\eta = \eta_1$ and $\eta = \eta_2$ on the ξ =const. line and the interval between $\xi = \xi_1$ and $\xi = \xi_2$ on the η = const. line are derived, as follows :

$$Q^z = \int_{\eta_1}^{\eta_2} \rho\,(A\partial p/\partial \xi + B\partial p/\partial \eta + C)\, d\eta \tag{3}$$

$$Q^\theta = \int_{\xi_1}^{\xi_2} \rho\,(D\partial p/\partial \xi + E\partial p/\partial \eta + F)\, d\xi$$

where A, B, C, D, E, and F are

$$A = k_1\,(r\,\partial\theta/\partial\eta)\,/\,(\partial z/\partial\xi)$$

$$B = k_2\,\partial\theta/\partial\eta$$

$$C = k_4\, r\cos\beta\,(\partial\theta/\partial\eta) \tag{4}$$

$$D = k_2$$

$$E = k_3\,(\partial z/\partial\xi)\,/\,(r\,\partial\theta/\partial\eta)$$

$$F = (r\,h_m\tilde{\omega} - k_4\sin\beta)\,(\partial z/\partial\xi)$$

The pressure distribution on the grid cell, which means the regular square region made by the neighboring four nodes, is approximated by a linear distribution of four node pressures as in Reference [5], and substituting it into Eq. (3), so that the mass fluxes which flow in and out of the small square element on the (ξ, η) coordinates are obtained. It is difficult to determine analytical values of integrals of Eq. (3), so these must be determined by an approximate method. In the integrals of Eq. (3), A, B, C, D, E, and F are approximated to values at the center ($\xi = i - 1/2$, $\eta = j - 1/2$) of the grid cell. In the divergence formulation method [6], the balance of mass fluxes which flow in and out of the small square element on the (ξ, η) coordinates is considered. Using the divergence formulation method, the algebraic equations of node pressure are obtained as Eq. (5) by the law of conservation of mass.

$$\begin{aligned}&- a_7 p_{i-1,j+1} - a_4 p_{i,j+1} - a_8 p_{i+1,j+1}\\ &+ a_1 p_{i-1,j} + a_0 p_{i,j} + a_2 p_{i+1,j}\\ &- a_5 p_{i-1,j-1} - a_3 p_{i,j-1} - a_6 p_{i+1,j-1} = a_9\end{aligned} \tag{5}$$

where

$$\begin{aligned}
a_0 &= 3\ (A_1 + A_2 + A_3 + A_4 + E_1 + E_2 + E_3 + E_4)\\
&\quad + 2\ (B_1 - B_2 - B_3 + B_4 + D_1 - D_2 - D_3 + D_4)\\
a_1 &= -3\ (A_1 + A_3) + E_1 + E_3 + 2\ (B_1 - B_3 - D_1 + D_3)\\
a_2 &= -3\ (A_2 + A_4) + E_2 + E_4 - 2\ (B_2 - B_4 - D_2 + D_4)\\
a_3 &= -A_1 - A_2 + 3\ (E_1 + E_2) + 2\ (B_1 - B_2 - D_1 + D_2)\\
a_4 &= -A_3 - A_4 + 3\ (E_3 + E_4) + 2\ (B_3 - B_4 - D_3 + D_4)\\
a_5 &= A_1 + E_1 + 2\ (B_1 + D_1)\\
a_6 &= A_2 + E_2 - 2\ (B_2 + D_2)\\
a_7 &= A_3 + E_3 - 2\ (B_3 + D_3)\\
a_8 &= A_4 + E_4 + 2\ (B_4 + D_4)\\
a_9 &= 4\ (-C_1 + C_2 - C_3 + C_4 - F_1 - F_2 + F_3 + F_4)
\end{aligned} \tag{6}$$

Suffixes 1, 2, 3, and 4 for A, B, C, D, E, and F indicate values at points ($i - 1/2$, $j - 1/2$), ($i + 1/2$, $j - 1/2$), ($i - 1/2$, $j + 1/2$), and ($i + 1/2$, $j + 1/2$), respectively. In this study, the solution of Eq. (5) is obtained by the Gümbel condition, in which the negative pressure is replaced by zero in the iterative pressure calculation. This condition is used for the boundary condition with the assumption that lubricant supply is sufficient. Separated equations are calculated iteratively using the successive line over-relaxation method. Triagonal equations on the η = const.

line are solved by the LU-decomposition before the iterative calculation. Convergence is checked by the following equation :

$$\sqrt{\sum_{i=1}^{N_z} \sum_{j=1}^{N_\theta} \Delta P_{i,j}^2} < \varepsilon \qquad (7)$$

where $\Delta P_{i,j}$ is the correcting pressure and ε is the convergence judgment number. Integral of the pressur distribution is carried out numerically, and the load carrying capacity is obtained.

The axial direction (z) is divided into N_{I}, N_{II}, and N_{III} ($N_z = N_I + N_{II} + N_{III}$) divisions for regions I, II, and III, respectively, and the circumference direction (θ) is divided into N_θ divisions. $N_z = 40$, $N_\theta = 36$ and $\varepsilon = 10^{-6}$ are used in the numerical calculation in this study.

4. The Optimum Bearing Form

It is important to determine the optimum bearing form for the design of regular and reversible rotation type herringbone grooved journal bearing. The optimum bearing parameters $(\alpha)_{opt}$, $(\Delta)_{opt}$, $(\beta_I)_{opt}$, $(\beta_{II})_{opt}$, and $(L_{II}/L)_{opt}$ determining the optimum bearing form are obtained by means of the simplex method.

The optimum bearing parameters $(\alpha)_{opt}$, $(\Delta)_{opt}$, $(\beta_I)_{opt}$, $(\beta_{II})_{opt}$, and $(L_{II}/L)_{opt}$, which maximize the load carrying capacity in the radial direction F_r, giving an indication of the stability for whirl at the radial eccentricity $\varepsilon_r = 0.1$, depend on the ratio of bearing length and bearing diameter L/D. These are shown in Fig. 2 as (a) the case of grooved member rotation and (b) the case of smooth member rotation.

Where α, Δ, β_I, β_{II}, and L_{II}/L are equivalent to the groove ratio $\alpha = W_g/(W_g + W_l)$, the groove depth $\Delta = \delta / c$, the groove angle in region I, the groove angle in region II, and the ratio of the length of region II to the bearing length L in the Fig. 1, respectively. The suffix opt is equivalent to the optimum value of bearing parameter maximizing the load carrying capacity in the radial direction. The load carrying capacity F and the attitute angle ϕ_f are also shown in Fig. 2 .

From Fig. 2 it can be seen that $(\Delta)_{opt}$, $(\beta_I)_{opt}$, and $(L_{II}/L)_{opt}$ decrease and $(\beta_{II})_{opt}$ increases with increase in L/D with $(\alpha)_{opt}$ remaining constant in the case of grooved member rotation. In the case of smooth member rotation, $(\Delta)_{opt}$, $(\beta_{II})_{opt}$, and $(L_{II}/L)_{opt}$ decrease and $(\beta_I)_{opt}$ increases with increase in L/D with $(\alpha)_{opt}$ remaining constant.

The bearing length used was from L/D= 1 to L/D= 2, which is the usual bearing size of an oil film lubricated herringbone grooved journal bearing. From Fig. 2 values of the optimum bearing parameters for $1 < L/D < 2$ are, in the case of grooved member rotation, as follows : $(\alpha)_{opt} = 0.5$, $(\Delta)_{opt} = 1.05 \sim 1.3$, $(\beta_{I})_{opt} = 148 \sim 160$ deg, $(\beta_{II})_{opt} = 35 \sim 43$ deg, and $(L_{II}/L)_{opt} = 0.47 \sim 0.53$, and in the case of smooth member rotation, $(\alpha)_{opt} = 0.5$, $(\Delta)_{opt} = 1.05 \sim 1.25$, $(\beta_{I})_{opt} = 21 \sim 31$ deg, $(\beta_{II})_{opt} = 135 \sim 143$ deg, and $(L_{II}/L)_{opt} = 0.48 \sim 0.53$. These optimum bearing parameters will be able to use for the design of regular and reversible rotation type herringbone grooved journal bearing.

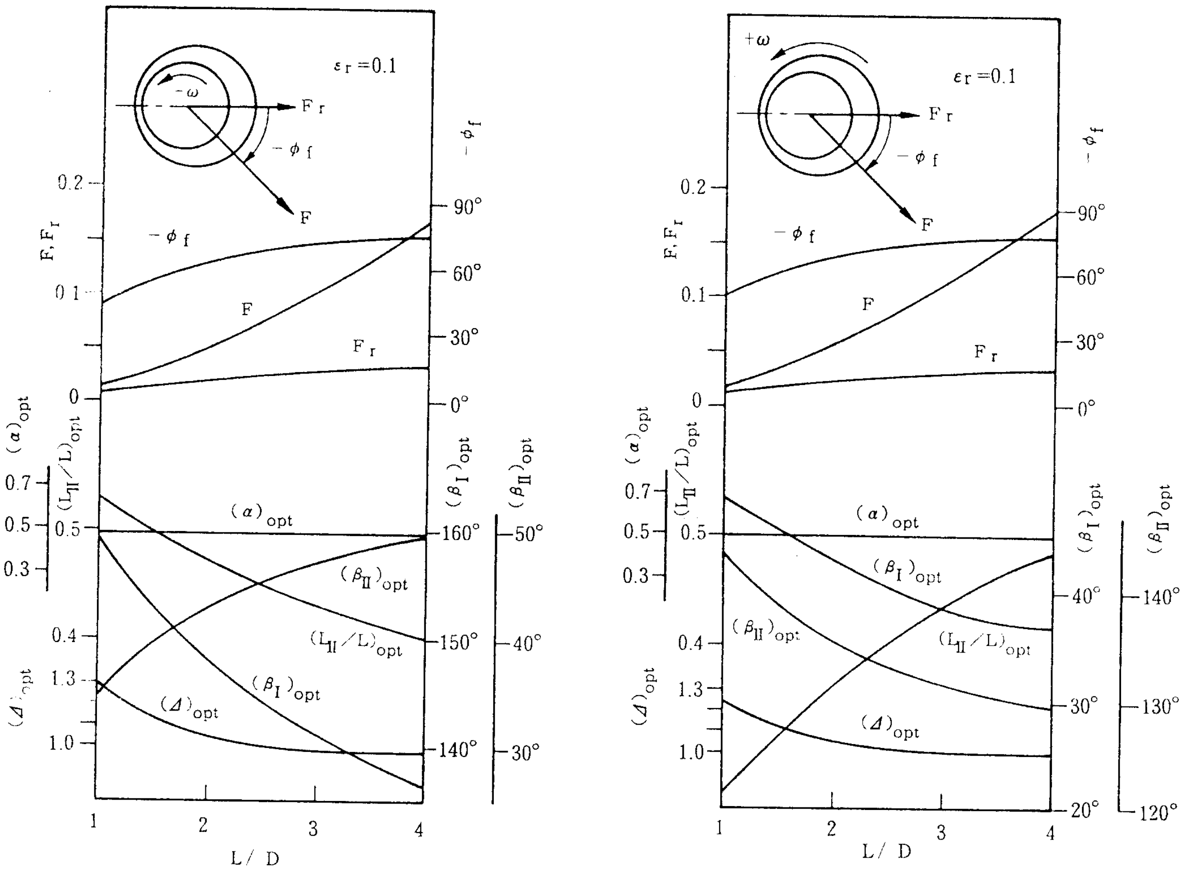

Fig. 2 (a) grooved member rotation Fig. 2 (b) smooth member rotation

Fig. 2 Optimum bearing parameters to maximize radial load component

5. Conclusions

The optimum bearing parameters, which maximize the load carrying capacity in the radial direction giving an indication of the stability for whirl, of a new type of herringbone grooved journal bearing in the case of either grooved member or smooth member rotation are determined by a numerical analysis using the narrow groove theory and Gümbel condition. The following can be concluded from the results.

(1) Values of the optimum bearing parameters determing the optimum bearing form of this bearing in the range of L/D from 1 to 2, which is the usual bearing size of

an oil film lubricated herringbone grooved journal bearing, are determined as follows :

For grooved member rotation :

$(\alpha)_{opt} = 0.5$

$(\Delta)_{opt} = 1.05 \sim 1.3$

$(\beta_{I})_{opt} = 148 \sim 160$ deg

$(\beta_{II})_{opt} = 35 \sim 43$ deg

$(L_{II}/L)_{opt} = 0.47 \sim 0.53$

For smooth member rotation :

$(\alpha)_{opt} = 0.5$

$(\Delta)_{opt} = 1.05 \sim 1.25$

$(\beta_{I})_{opt} = 21 \sim 31$ deg

$(\beta_{II})_{opt} = 135 \sim 143$ deg

$(L_{II}/L)_{opt} = 0.48 \sim 0.53$

Nomenclature

c = bearing clearance when co-centric

D, r = bearing diameter and radius, respectively

e_r, ε_r = radial eccentricity $\varepsilon_r = e_r / c$

f, F = load carrying capacity $F = f \cdot c^2 / \mu \omega D^4$

h_g, h_l = fluid film heights of groove and land, respectively

i, j = grid numbers

L = bearing length

N_z, N_θ = axial grid number, radial grid number

p = fluid film pressure

q, Q = mass fluxes per unit length, mass fluxes

w_g, w_l = groove width, land width (Fig. 1)

α = groove width ratio $\alpha = w_g / (w_g + w_l)$ (Fig. 1)

β = groove angle (Fig. 1)

δ, Δ = groove depth $\Delta = \delta / c$ (Fig. 1)

μ = viscosity of fluid

ρ = density

ϕ = attitute angle

ω = angular velocity of rotational element

ω_g, ω_s = angular velocities of grooved member and smooth member, respectively $\omega_g + \omega_s = \omega$

Suffix

f = load carrying capacity

g, s = grooved member, smooth member

i, j = grid numbers

r, t = components in radial and tangential direction

I, II, III = region I, region II, region III (Fig. 1)

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