Effect of Bearing Parameters of the Regular and Reversible Rotation Type Herringbone Grooved Journal Bearing

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The effect of bearing parameters of a new type of herringbone grooved journal bearing, which produces an oil film bearing pressure with a shaft or bearing rotation in either direction, 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, may new applications will be possible.

A new type of reversible rotation herringbone grooved journal bearing, which produces an oil film bearing pressure with a shaft or bearing rotation in either direction, is proposed, and the effect of bearing parameters of this bearing in the case of either grooved member or smooth member rotation are determined by a numerical analysis using the narrow groove theory [4] and Gümbel condition in this paper.

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

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direction with rotational speed ω.

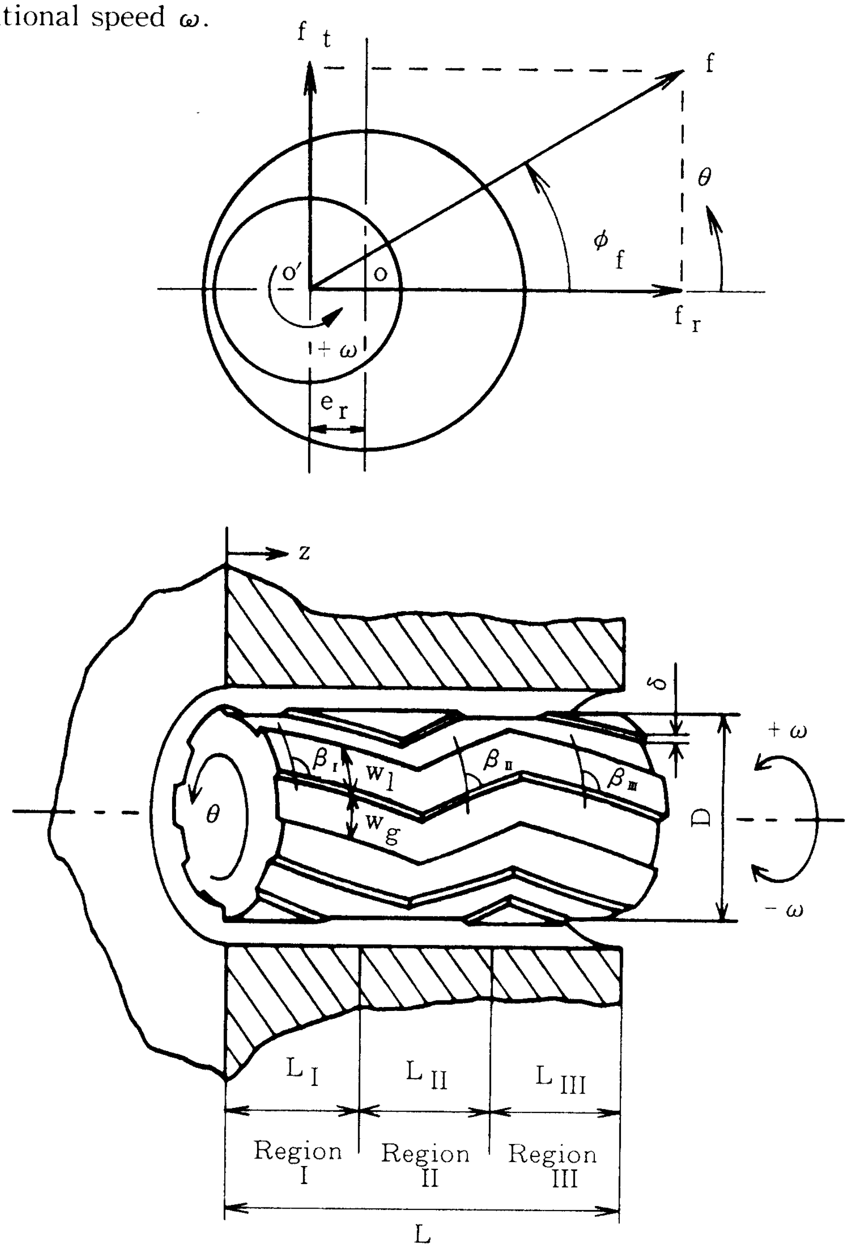


Fig. 1 The reversible rotation type herringbone grooved journal bearing.

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 :

$$q^z = \rho\left(k_1\frac{\partial p}{\partial z} + k_2\frac{\partial p}{r\partial\theta} + k_4\cos\beta\right)$$
$$q^\theta = \rho\left(k_2\frac{\partial p}{\partial z} + k_3\frac{\partial p}{r\partial\theta} - k_4\sin\beta + rh_m\bar{\omega}\right) \tag{1}$$

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

$$
\begin{aligned}
k_0 &= (1-\alpha)h_g^3 + \alpha h_l^3 \\
k_1 &= (-1/12\mu)\{h_g^3 h_l^3 + \alpha(1-\alpha)(h_g^3 - h_l^3)\sin^2\beta\}/k_0 \\
k_2 &= (-1/12\mu)\{\alpha(1-\alpha)(h_g^3 - h_l^3)\sin\beta\cos\beta\}/k_0 \\
k_3 &= (-1/12\mu)\{h_g^3 h_l^3 + \alpha(1-\alpha)(h_g^3 - h_l^3)\cos^2\beta\}/k_0 \\
k_4 &= \{-r\delta(\omega_g - \omega_s)/2\}\alpha(1-\alpha)(h_g^3 - h_l^3)\sin\beta/k_0 \\
h_m &= \alpha h_g + (1-\alpha)h_l \\
\bar{\omega} &= (\omega_s + \omega_g)/2 - \Omega
\end{aligned}
\tag{2}
$$

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 $\xi =$ const. line and the interval between $\xi = \xi_1$ and $\xi = \xi_2$ on the $\eta =$ const. line are derived, as follows :

$$
\begin{aligned}
Q^z &= \int_{\eta_1}^{\eta_2} \rho(A\partial p/\partial\xi + B\partial p/\partial\eta + C)\,d\eta \\
Q^\theta &= \int_{\xi_1}^{\xi_2} \rho(D\partial p/\partial\xi + E\partial p/\partial\eta + F)\,d\xi
\end{aligned}
\tag{3}
$$

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

$$
\begin{aligned}
A &= k_1(r\partial\theta/\partial\eta)/(\partial z/\partial\xi) \\
B &= k_2\partial\theta/\partial\eta \\
C &= k_4 r\cos\beta(\partial\theta/\partial\eta) \\
D &= k_2 \\
E &= k_3(\partial z/\partial\xi)/(r\partial\theta/\partial\eta) \\
F &= (rh_m\bar{\omega} - k_4\sin\beta)(\partial z/\partial\xi)
\end{aligned}
\tag{4}
$$

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 (ξ = i$-$1/2, η = j$-$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 $\eta =$ const. line are solved by the LU-decomposition before the iterative calculation. Convergence is checked by the following equation:

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

where $\Delta P_{i,j}$ is the correcting pressure and ε is the convergence judgment number. Integral of the pressure 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 circmference direction (θ) is divided into N_θ divisions. $N_Z = 40$, $N_\theta = 36$ and $\varepsilon = 10^{-6}$ and used in the numerical calculation in this study.

4. The Effect of Bearing Parameters

It is important to investigate the effect of bearing parameters for the design of regular and reversible rotation type herringbone grooved journal bearing. The effect of bearing parameters α, Δ, β_I, β_{II}, and L_{II}/L on both the load carrying capacity in the radial direction (F_r) giving an indication of the stability for whirl and attitute angle (ϕ_r) with grooved member rotation (GMR) and smooth member roration (SMR) for the case of $L/D = 2$ are shown in

Figs. 2−6. The values in Figs. 2−6 excepting the values on the horizontal axis were calculated numerically using the optimum bearing parameters maximizing F_r at the radial eccentricity $\varepsilon_r = 0.1$ and the ratio of bearing length and bearing diameter $L/D = 2$ in Table 1.

The effect of α on F_r and ϕ_f with negative value ($-\phi_f$) is shown in Fig. 2. It can be seen that α has little effect on F_r. $-\phi_f$ is the same for both GMR and SMR at $\alpha = 0.3$, but with increasing α, $-\phi_f$ decreases linearly, and the rate of decrease of $-\phi_f$ is greater for GMR.

The effect of Δ on F_r and $-\phi_f$ is shown in Fig. 3. F_r takes a maximum value at $\Delta \fallingdotseq 1$ for the case of $\varepsilon_r < 0.3$ (the greatest value for the case of $\varepsilon_r = 0.1$). The maximum point of F_r vanishes with a decrease of Δ. For $\varepsilon_r = 0.3$, F_r increases continuously with a decrease of Δ and reaches a maximum value at $\Delta = 0$ which corresponds to no grooves. The influence of ε_r and Δ on $-\phi_f$ at $\Delta > 1$ are small for the case of GMR. $-\phi_f$ varies inversely with Δ for $\varepsilon_r = 0.1$ and $\varepsilon_r = 0.3$.

The effect of β_{I} on F_r and $-\phi_f$ is shown in Fig. 4. β_{Ig} is equivalent to β_{I} for the case of GMR, and β_{IS} is equivalent to $180^\circ - \beta_{\mathrm{I}}$ for the case of SMR. Fig. 4 shows that F_r and $-\phi_f$ do not vary much with β_{I}. The $-\phi_f$ for the case of SMR is slightly larger than $-\phi_f$ for the case of GMR.

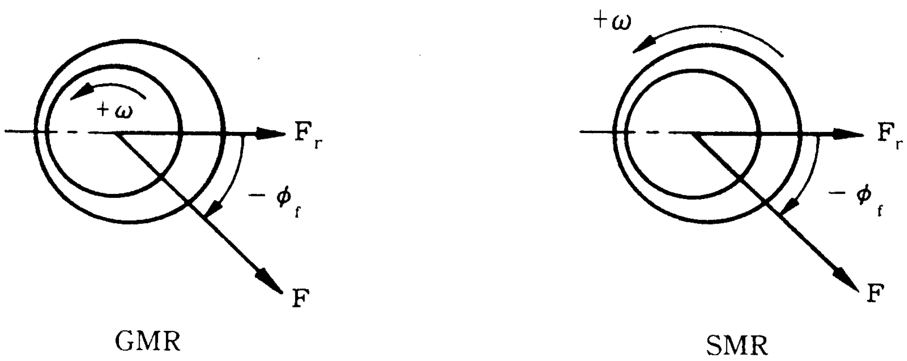
The effect of β_{II} on F_r and $-\phi_f$ is shown in Fig. 5. β_{IIg} is equivalent to β_{II} for the case of GMR, and β_{IIS} is equivalent to $180^\circ - \beta_{\mathrm{II}}$ for the case of SMR. Fig. 5 shows that there is little difference in F_r between GMR and SMR, and that for each ε_r, F_r varies with β_{IIg} and β_{IIS} giving the optimum value of β_{IIg} and β_{IIS}. It is also shown in Fig. 5 that $-\phi_f$ is a minimum near those values of β_{IIg} and β_{IIS} giving a maximum value of F_r.

The effect of L_{II}/L on F_r and $-\phi_f$ is shown in Fig. 6. The maximum value of F_r occurs near $L_{\mathrm{II}}/L = 0.5$. F_r is only slightly affected by the ratio L_{II}/L. $-\phi_f$ remains nearly constant for $\varepsilon_r = 0.3$, and the absolute value of $-\phi_f$ increases continuously with increase of L_{II}/L in the case of $\varepsilon_r = 0.1$.

The following are shown from these results for the regular and reversible rotation type herringbone grooved journal bearings. It is confirmed that Δ and β_{II} have a considerable influence on F_r and ϕ_f for this bearing. F_r and ϕ_f are not influenced very much by bearing parameters α, β_{I} ($= \beta_{\mathrm{III}}$), and L_{II}/L near the optimum value for this bearing. There is no significant difference in the characteristics of F_r for the case of GMR and SMR.

Table 1. Optimum bearing parameters maximizing F_r ($L/D=2$, $\varepsilon_r=0.1$)

	$(\alpha)_{opt}$	$(\Delta)_{opt}$	$(\beta_{I})_{opt}$	$(\beta_{II})_{opt}$	$(L_{II}/L)_{opt}$
GMR	0.500	1.034	147.82°	43.09°	0.467
SMR	0.501	1.068	31.25°	135.31°	0.480



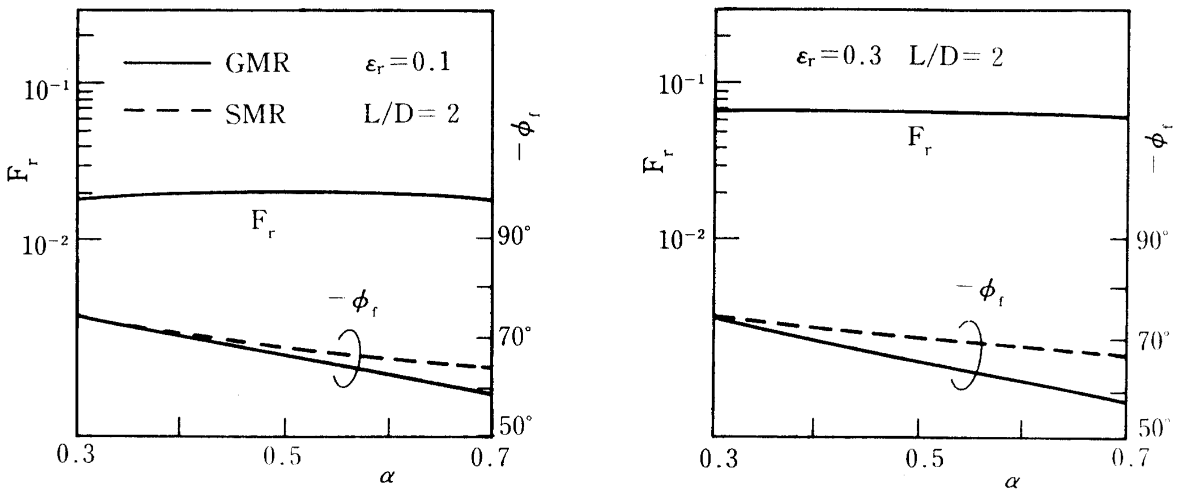


Fig. 2 The effect of α on F_r and $-\phi_f$

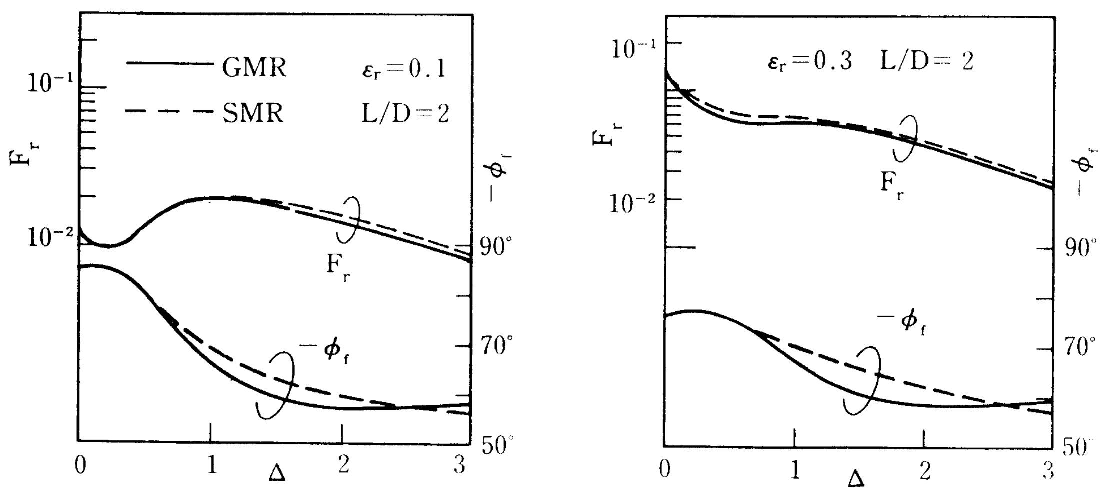


Fig. 3 The effect of Δ on F_r and $-\phi_f$

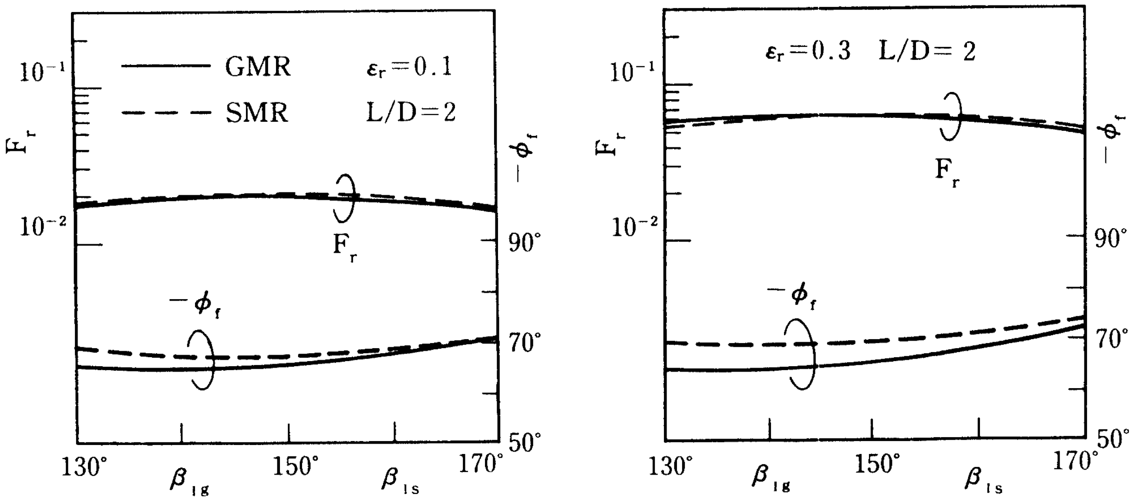


Fig. 4 The effect of β_I on F_r and $-\phi_f$

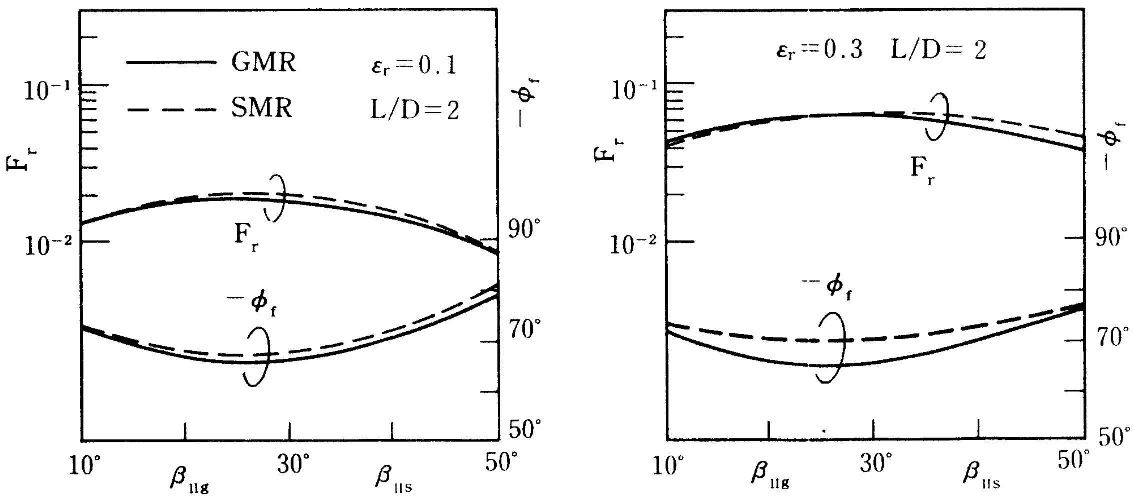


Fig. 5 The effect of β_{II} on F_r and $-\phi_f$

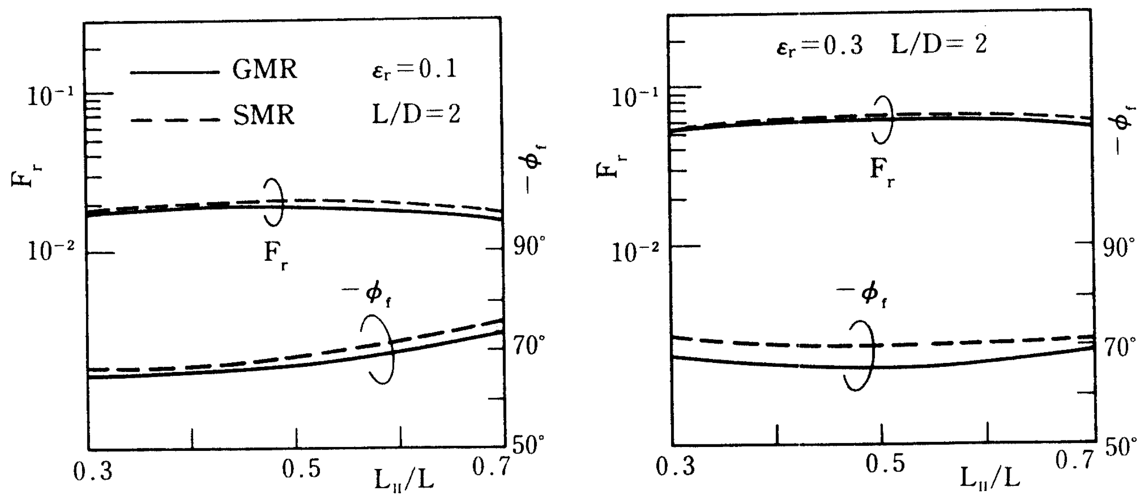


Fig. 6 The effect of L_{II}/L on F_r and $-\phi_f$

5. Conclusions

The effect of bearing parameters 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) The bearing parameters Δ and β_{II} have a considerable influence on the radial load component (F_r) related to stability and the attitute angle (ϕ_r) of this bearing, but F_r and ϕ_r are not influenced very much by bearing parameters α, β_I ($=\beta_{III}$), and L_{II}/L near the optimum value for this bearing.

(2) There is no significant difference in the bearing characteristics of F_r and ϕ_r, which are effected bearing parameters α, Δ, β_I, β_{II}, and L_{II}/L, for the case of grooved member and smooth member rotation.

References

1. Hamrock, B.J., and Fleming, D.P., "Optimization of Self-acting Herringbone Grooved Journal Bearing for Maximum Radial Load Capacity," 5th Gas Bear. Symp., Vol. 1, Paper 13 (1971).
2. Fleming, D.P., and Hamrock. B.J., "Optimization of Self-Acting Herringbone Journal Bearings for Maximum Stability," 6th Gas Bear. Symp., Paper C1 (1974).
3. Murata, S., Miyake,Y., and Kawabata, N., "Two-Dimensional Analysis of Herringbone Groove Journal Bearings," Bulletin of the JSME, Vol. 23, No. 181, July 1980, pp. 1220-1227.
4. Hsing, F.C., "Formulation of a Generalized Narrow Groove Theory for Spiral Grooved Viscous Pumps," ASME Journal of Lubrication Technology, Vol. 94, No. 1, January 1972, pp. 81-85.
5. Kawabata, N., "A Study on the Numerical Analysis of Fluid Film Lubrication by the Boundary Fitted Coordinates System," JSME International Journal, Series III, Vol. 31, No. 1, 1988, pp. 107-113.
6. Wilcock, D.F., "Design of Gas Bearing," MTI, (1972), 4. 2. 2.

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