Static Characteristics of the Optimal Finite-Width Journal Bearing Lubricated with Soybean-Based Oils

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Abstract

Environmentally friendly vegetable-based oils are showing some potential performance merits for industrial lubricants. This paper presented the static characteristics of the optimal thermohydrodynamic finite-width full circular journal bearing lubricated with soybean-based oils using Broyden-Fletcher-Goldfarb-Shanno (BFGS) method. Modified Reynolds equation and adiabatic energy equation are formulated. The non-Newtonian power-law model are obtained experimentally. Oil film pressure distribution and oil film temperature distribution are calculated numerically using finite difference method. The objective function is to minimize the flow rate and temperature difference. The design variables are clearance-to-radius ratio, c/r and length-to-diameter ratio, l/d and subject to its constraints as $0.001 \leq c/r \leq 0.004$ and $0.5 \leq l/d \leq 4.0$.

In this study, BFGS method can reach optimum clearance-to-radius ratio and length-to-diameter ratio where the static characteristics of the journal bearing are investigated.

Keyword: Modified Reynolds equation, Energy equation, non-Newtonian power law model, Soybean-based oils, Thermohydrodynamic journal bearing, Broyden-Fletcher-Goldfarb-Shanno, Optimum design, Finite-width journal bearing.

INTRODUCTION

Many research works investigated the lubrication characteristic of bearings with non-Newtonian lubricant for over three decade. Horowitz and his colleague obtained the analytical pressure distribution for a finite width full circular journal bearing by approximating the shear rate with a cubic equation of shear stress. Hashimoto and Wada examined theoretically the combined effects of nonlinear characteristics and fluid film inertia and the dynamic behavior of circular type squeeze film bearing. Hsu has introduced the cubic shear stress law for the non-Newtonian lubricants and has studied the static performance characteristics for infinitely long bearings.

In this paper, the static characteristic of finite journal bearing with Pseudo plastic lubricants is examined theoretically and experimentally included thermal effect.

THEORY

In this paper, and Broyden-Fletcher-Goldfarb-Shanno (BFGS) method has been applied to obtain the optimum finite-width journal bearing as.

Step 1. At i=1, initial values x1,x2 are maked and Hessian Matrix $[B_{i=1}]$ equals to Unit Matrix $[I]$ at first iteration.

Step 2. Compute the gradient of the function at point X_i and set $S = -[B] . \nabla f_i$

Step 3. Find Optimal Step Length α in the direction S_i and set $X_{i+1} = X_i + \alpha . S_i$

Step 4. Test the point X_{i+1}, for $|\nabla f| \leq \varepsilon_s$ stoping error, where ε_s is small quantity, take $X^* \cong X_{i+1}$ and stop the process. Otherwise, go to next step.

Step 5. Update the Hessian Matrix as

$$[B_{i+1}] = [B_i] + \left(1 + \frac{g_i^T [B_i] g_i}{d_i^T g_i}\right) \frac{d_i d_i^T}{d_i^T g_i} - \left(\frac{d_i g_i^T [B_i]}{d_i^T g_i}\right) - \left(\frac{[B_i] g_i d_i^T}{d_i^T g_i}\right)$$

where $d_i = X_{i+1} - X_i$

$g_i = \nabla f_{i+1} - \nabla f_i$

Step 6. Set the new iteration number as i = i+1 and go to Step 2.

In this study, the refined soybean oil was mixed with 3% diester, 4% polyisobutylene and 0.02% silicone oil by weight. The soybean-based oil has non-Newtonian behavior as dilatant fluids. The power law model derived by Jiin-Yuh Jang and Chong-Ching Chang [7] can be approximated as

$$\tau = m\left(\frac{\partial u}{\partial y}\right)^{n=1}\frac{\partial u}{\partial y} \qquad (1)$$

$$m = m_o \exp\left[-\beta\left(T - T_o\right)\right] \qquad (2)$$

Where m is the consistency parameter at temperature of the oil T; m_o is the parameter at inlet oil temperature To; n is viscometric constant and β is the viscosity temperature index.

Density, ρ = 905.7 kg/m^3	
Specific heat, C_P = 1914 J/kg^{o}C	
Viscosity consistency at T_o, m_o = 0.02857 Pa.s	
Viscometric constant, n = 1.088	
Viscosity temperatrue index, β = 0.0395 ^{o} C^{-1}	
Inlet oil temperature, T_o = 38 ^{o}C	
Ambient pressure, P_o = 1 atm	

Table 1. Soybean-based oil properties

The non-dimensional modified Reynolds' equation can be derived as

$$\frac{\partial}{\partial\theta}\left\{\frac{h^{n+2}}{nm}\frac{\partial P}{\partial\theta}+\frac{\partial P}{\partial\theta}\right\} + \left(\frac{D}{L}\right)^2\frac{\partial}{\partial\xi}\left\{\frac{h^{n+2}}{m}\frac{\partial P}{\partial\xi}\right\} = 6\left(\frac{u}{c}\right)^{n-1}\frac{\partial h}{\partial\theta} \qquad (3)$$

The dimensionless film thickness h of circular journal bearings can be written as:

$$h = 1+\varepsilon\cos\theta \qquad (4)$$

The Reynolds boundary conditions at inlet and outlet along the axial direction can be expressed as:

$$P(0,\xi) = P\,(\theta,\xi) = P(\theta,-\xi) = 0 \qquad (5)$$

$$P(\theta,\xi) \geq 0 \qquad (6)$$

The adiabatic energy equation is formulated with the assumptions that the heat generated within the film is completely carried away by the lubricant and the temperature variation across the oil film is neglected:

$$\rho c_P\left(u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial z}\right) = \mu\left[\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right] \qquad (7)$$

The energy equation can be written in dimensionless form as:

$$A\left(\frac{\partial T}{\partial\theta}\right)+B\frac{D}{L}\left(\frac{\partial T}{\partial z}\right) = \alpha\frac{m}{h^{n+1}}\left(E+F\right) \qquad (8)$$

where $T = \beta(\overline{T}-T_0)$ (9)

$$A = \frac{1}{2}-\frac{1}{12}\left[\frac{h^{n+1}c^{n-1}}{nmu^{n-1}}\left(\frac{\partial P}{\partial\theta}\right)\right] \qquad (10)$$

$$B = -\frac{1}{12}\left(\frac{D}{L}\right)^2\left[\frac{h^{n+1}c^{n-1}}{nmu^{n-1}}\left(\frac{\partial P}{\partial z}\right)\right] \qquad (11)$$

$$E = \int_0^1\left[1-\frac{1}{2}\frac{h^{n+1}c^{n-1}}{mnu^{n-1}}\frac{\partial P}{\partial\theta}\left(1-2\eta\right)\right]^{n-1}d\eta \qquad (12)$$

$$F = \int_0^1\left[1-\frac{1}{2}\frac{h^{n+1}c^{n-1}}{mnu^{n-1}}\frac{\partial P}{\partial\theta}\left(1-2\eta\right)\right]^{n-1}\left[-\frac{1}{2}\left(\frac{D}{L}\right)\left(\frac{h^{n+1}c^{n-1}}{mu^{n-1}}\right)\frac{\partial P}{\partial z}(1-2\eta)\right]^2 d\eta \qquad (13)$$

Dissipation number $\alpha = \dfrac{(2\pi N)^n m_o\beta}{\rho C_P}\left(\dfrac{r}{c}\right)^{n+1}$ (14)

The boundary conditions can be written as:

$$T(0,\xi) = 0 \qquad (15)$$

$$T(\theta,\xi) = T(\theta,-\xi) \qquad (16)$$

All dimensionless terms were derived by Jiin-Yuh Jang and Chong-Ching Chang [7].

The dimensionless oil film force components in radial and tangential direction F_ε and F_ϕ are obtained by integrating the dimensionless film pressure as:

$$W_\varepsilon = -\int_0^1\int_0^{3\pi} P\cos\theta\, d\theta . d\xi \qquad (17)$$

$$W_\varphi = \int_0^1\int_0^{3\pi} P\sin\theta\, d\theta . d\xi \qquad (18)$$

The dimensionless load W and attitude angle

$$W = \sqrt{W_{\varphi}^{2} + W_{\varphi}^{2}} \quad , \phi = \tan^{-1}\left(\frac{W_{\varphi}}{W_{\varepsilon}}\right) \qquad (19)$$

Integration of the shear stress along the journal circumference gives directly the frictional drag from the following:

$$F = \sigma \int_{0}^{1} \int_{0}^{2\pi} \frac{\overline{m}}{h^{n}} \left(1 + \frac{h^{n+1}}{2mn\sigma} \frac{\partial P}{\partial \theta}\right)^{n} d\theta . d\xi \qquad (20)$$

Friction Coefficient: F / W

Flowrate along with θ axis,

$$Q_{\theta} = -\frac{1}{12} \frac{h^{n+2}}{nm} \frac{\partial P}{\partial \theta} \left(\frac{c}{r}\right)^{n} + \left(\frac{2\pi N}{60}\right)^{n-1} \left(\frac{c}{r}\right) \left(\frac{h}{2}\right) \qquad (21)$$

Flow rate along with ξ axis,

$$Q_{\xi} = -\frac{1}{12} \frac{h^{n+2}}{m} \frac{\partial P}{\partial \xi} \left(\frac{c}{r}\right)^{n} \left(\frac{L}{D}\right)^{-2} \qquad (22)$$

and dimensionless temperature difference,

$$\Delta T = T_{\max} - T_{average} \qquad (23)$$

when $T_{\max}$, $T_{average}$ is dimensionless maximum temperature and dimensionless average temperature respectively.

Objective function is to minimize

$$f_{objective} = w1.Q + w2.\Delta T \qquad (24)$$

When Q and ΔT are in forms of design variables; c/r and l/d.

The constraints can be written as:

$$0.001 \leq c/r \leq 0.004$$
$$0.5 \leq l/d \leq 4.0 \qquad (25)$$

Static characteristics at the optimum point of the finite-width journal bearing lubricated with soybean-based oils were calculated numerically. In this simulation, the optimum journal bearing has length-to-diameter ratio, l/d= 2.0 and clearance-to-radius ratio, c/r = 0.0015 operated at $N = 1000$ rpm. Oil film pressure and temperature distributions along circumferential, θ and axial, ξ directions were shown in Figure1, 2, 3 and 4. respectively.

The dimensionless load carrying capacity and attitude angle were shown in Figure 5. and Figure 6. respectively. The dimensionless friction force and friction coefficient were presented in Figure 7 and Figure 8. To minimize the objective function by using BFGS method, the optimum design variables are c/r=0.0015 and l/d=2.0.

CONCLUSION

In this paper, the objective function can be written in forms of length-to-diameter ratio and clearance-to-radius ratio and is to minimized for optimum design. BFGS method can reach the optimum the static characteristic of a full circular bearing with non-Newtonian soybean-based oil has been investigated under adiabatic conditions. The apparent viscosity of soybean-based oils varies not only with the shear rate but also with temperature. The analysis is useful for predicting rising in temperature in the journal bearing lubricated with soybean-based oil. The thermal effect is more significant on the bearing characteristic.

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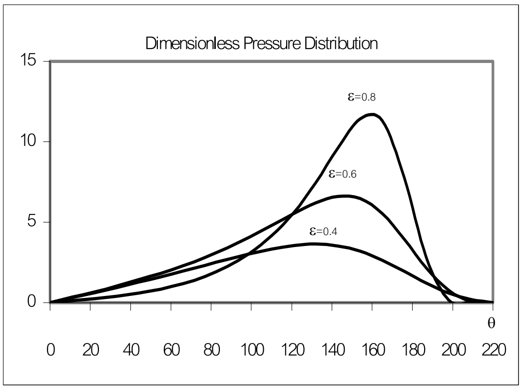

Figure 1. Dimensionless Pressure Distribution

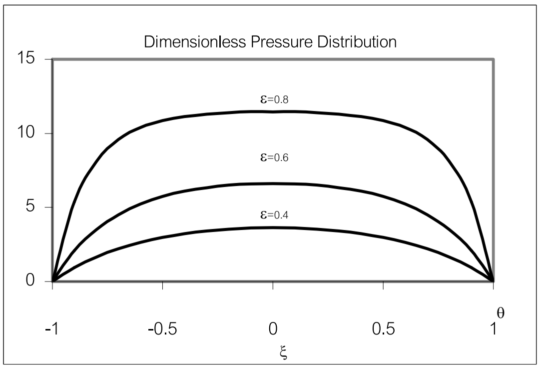

Figure 2 . Dimensionless Pressure Distribution

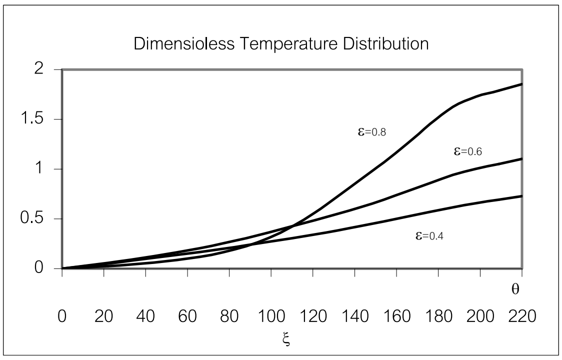

Figure 3. Dimensionless Temperature Distribution

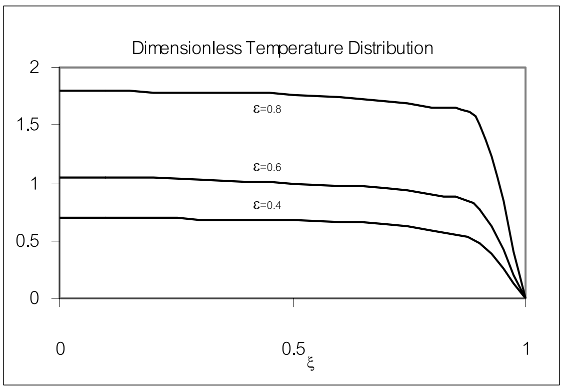

Figure 4. Dimensionless Temperature Distribution

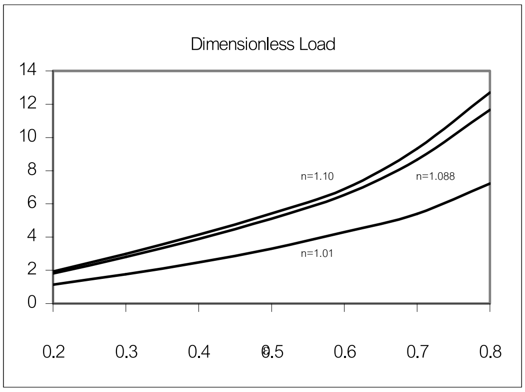

Figure 5 Dimensionless Load Carrying Capacity

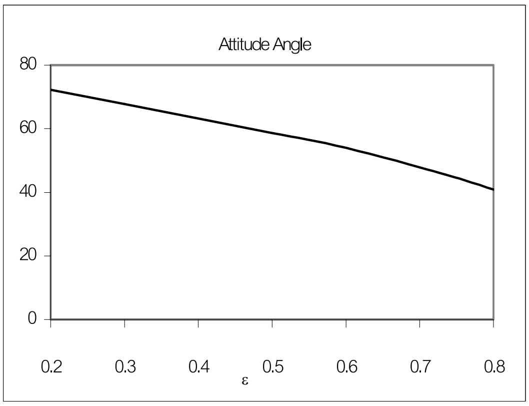

Figure 6. Attitude Angle

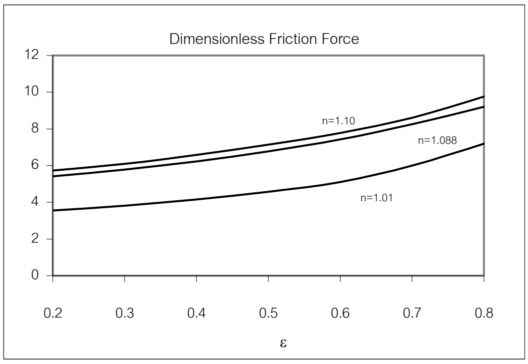

Figure 7. Dimensionless Friction Force

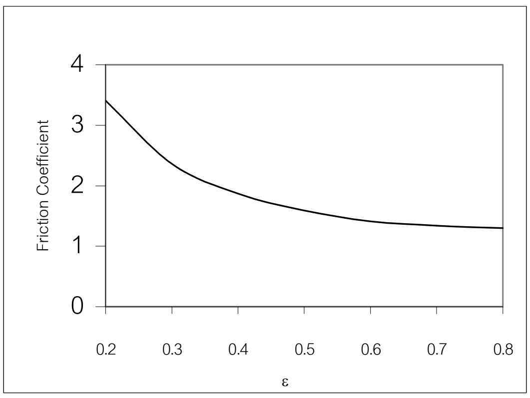

Figure 8. Dimensionless Temperature Distribution