Study on static characteristics of water-lubricated textured herringbone grooved journal bearings based on laminar cavitating flow lubrication model

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Abstract. This paper aims to investigate static characteristics of water-lubricated textured herringbone groove journal bearing under laminar cavitating flow. A theoretical model for the bearing was established based on two-phase flow and population balance equation. Field distribution and static characteristics of the bearing are analysed. The result shows the friction torque of the bearing is reduced due to the texture effect; And the frictional torque is reduced with the increasing of texture area ratio and height. The load carrying capacity of the bearing is increased, while the friction torque are slightly affected by the cavitation effect. The existence of texture increases the bubble number density in the bearing-lubrication process.

1. Introduction
Water-lubricated hydrodynamic herringbone journal bearing is a potential support way for the high-speed rotary machine. However, friction power loss of the bearing is increased when the bearing runs at a high speed. It has previously been observed that texture fabricated on surface can improve static performances of hydrodynamic lubrication bearings [1, 2], including reducing friction power loss and so on. Thus, it is significant to propose a water-lubricated textured herringbone groove journal bearing to reduce the friction power loss under high speed. When the bearing is under high speed, initial cavitation number will increase [3], so the cavitation effect should be considered when modelling. However, a single-phase mixing flow model was used in the literature in regard to the water-lubricated bearing [3, 4]. This model cannot effectively describe the cavitation-flow lubrication state.

In this paper, a complete hydrodynamic lubrication model for the water-lubricated textured herringbone groove journal bearings under the cavitating flow is established using the two-phase flow and the transport theory. Based on the two-phase flow theory, the generalized Reynolds is derived considering the momentum transfer effect at the gas-liquid interface. Based on the population equilibrium equation, the evolution of bubble size distribution under the action of breakup and coalescence is described. The static characteristics of the water-lubricated textured herringbone groove bearing in the cavitation state is analysed using the proposed model, and the influence of texture parameters on the static characteristics of the bearing is analysed.
2. Theoretical model

2.1 Generalized Reynolds equation for cavitating flow

The texture herringbone grooved journal bearing coordinate system is shown in Fig. 1. The velocity of the journal is the X axis direction. The bearing width is the Y axis direction. The lubricant film thickness $h$ is the Z axis direction. The texture is rectangular and the aspect ratio is constant, the texture depth ratio is defined as $h_t$, the texture area ratio is defined as $S_t$. Textures are equally spaced along the ridge.

![Figure 1. Schematic diagram of textured herringbone grooved journal bearing.](image)

It is obvious that momentum transfer effect exist at the gas-liquid interface of the cavitation flow. However, the classic Reynolds equation is no longer applicable to the lubrication state of cavitation flow, and the classical Reynolds equation needs to be modified using a two-phase flow theory that considers the gas-liquid interface effect. Based on the two-phase flow theory, and the generalized Reynolds equation with the interface effect can be written as \[5\]:

$$\frac{\partial}{\partial y} \left( \frac{h^3}{12\mu} \frac{\partial (C_w p)}{\partial y} \right) + \frac{\partial}{\partial x} \left( \frac{h^3}{12\mu} \frac{\partial (C_w p)}{\partial x} \right) = \frac{\partial}{\partial x} \left( \frac{C_w u_w h}{2} + \frac{h^3}{12\mu} M(x) \right)$$

The film thickness of a textured journal bearing can be written as:

$$h(\varphi, \psi) = h_0(\varphi) + h_g(\varphi, \psi) + h_t(\varphi, \psi)$$

Where, $\varphi = x/2\pi R$, the film thickness $h_0(\varphi)$ of the journal bearing with smooth surface is $h_0(\varphi) = c(1 + \varepsilon \cos \varphi)$, The depth of the herringbone groove is $h_g$. Dimensionless texture depth $H_t = h_t/c$.

Coordinate transformation is used to transform the physical plane to the computational plane. The coordinate system $(x, y)$ are transformed to the coordinate system $(\eta, \lambda)$ by the following formula

$$\eta = x - \frac{y}{\tan \beta}; \quad \lambda = y / \sin \beta$$

The boundary conditions are:

$$p|_{\eta=0} = 0; \quad p|_{\eta=\eta_{out}} = \frac{\partial p}{\partial \eta}|_{\eta=\eta_{out}} = 0; \quad p|_{\lambda=l/2\sin \beta} = p|_{\lambda=-l/2\sin \beta} = 0$$

The interface momentum transfer item $M(\eta)$ is expressed as [5]

$$M(\eta) = -\int_0^\varphi \left\{ \int_A \rho_w u_n (u - u_b) dA \right\} f_{eq}(\eta, \varsigma) d\varsigma + \int_0^\varphi \left\{ \int_A C_{Dw} \rho_w (u - u_b)^2 dA \right\} f_{eq}(\eta, \varsigma) d\varsigma + \int_0^\varphi \left\{ \int_A \left( \frac{\sigma}{(3/4\pi)^{1/3} \varsigma^{1/3}} \right) n dA \right\}$$

The $f_{eq}(\eta, \varsigma) d\varsigma$ is defined as the bubble number density in equilibrium status around $\eta$ with the volume between $\varsigma$ and $\varsigma + d\varsigma$, $C_{w}$ is the expressed volume fraction of water[6]. The circumferential velocity equation of the water film is written as:

$$u = \frac{1}{2C_{w}} \left( \frac{\partial}{\partial \eta} (C_w p) - M(\eta) \right) (x^2 - h_z) + \frac{u_z}{n}$$
The velocity of the bubble is written by equation \[6\]

\[u_b = \frac{2c}{\rho \pi c_d R_b^2} \frac{1}{x^2} \]

(7)

2.2 The population balance equation of bubble volume

The interface effect in cavitation flow is related to the interface area, and the interface area is closely related to the volume distribution of bubbles. The breakup and coalescence of bubbles may occur due to collision between bubbles and fluid eddy and collisions between bubbles. The bubble volume is randomly changed due to the mechanism of breakup and coalescence, and the random distribution of bubble volume can be described using a probability density distribution function \(f(\eta, \zeta, t)\). The \(f(\eta, \zeta, t)\) denote the number of bubbles per unit volume around the point \(\eta\) with the volume between \(\zeta\) and \(\zeta + d\zeta\). The evolution of function \(f(\eta, \zeta, t)\) in cavitation flow is governed by the population balance equation, and the population balance equation in the coordinate system \((\eta, \lambda)\) is written as

\[
\frac{\partial f}{\partial t} + \frac{\partial }{\partial \eta} (u_f f) = -b(\zeta)f(\varphi, \zeta) + \int^{\infty}_\zeta h_b(\xi, \zeta)b(\xi)f(\varphi, \xi) d\xi - f(\varphi, \zeta) \int^{\infty}_\zeta c(\zeta, \xi)f(\eta, \xi) d\xi + c_p \chi(\zeta) \sqrt{(p_v - p)}
\]

(8)

\(h_b(\xi, \zeta)\) is the daughter bubble volume redistribution function; \(b(\zeta)\) is the breakage frequency; The \(c(\zeta, \xi)\) is coalescence closure; The \(\chi(\zeta)\) is the source term of the gas nucleus growth. Where, the \(\beta(\zeta, \zeta)\) is the redistribution function of bubble volume[6].

3. Results and discussions

The parameters used in the numerical calculation are listed in Table 1.

| Item                          | Value  |
|-------------------------------|--------|
| Bearing width \(L (mm)\)      | 30     |
| Collar diameter \(R (mm)\)    | 16     |
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| Radius clearance \(e (mm)\)   | 0.02   |
| Groove number \(N\)           | 12     |
| Groove to ridge ratio         | 1      |
| Groove angle \(\beta (deg)\)  | 20     |
| Groove depth \(h_g (\mu m)\)  | 40     |
| Viscosity of water \(\mu_w (Pa.s)\) | 0.001 |
| Pressure of supply water \(p_{in} (MPa)\) | 0.1 |
| Density of water \(\rho_w (kg/m^3)\) | 1000 |
| Bearing rotating speed \(n (rpm/min)\) | 20000 |
| Bubble surface tension \(\sigma (N/m)\) | 0.3 |

3.1 Influence of texture and cavitation on the field distribution of bearings

Fig.2 shows the distribution of bubble number density under different models. It can be seen that cavitation bubbles are mainly distributed in the divergent zone of the bearing, which shows the negative pressure in the divergent zone is conducive to the growth of the gas nucleus into bubbles. It also can be seen that the bubble volume is a skewed distribution. In addition, the number density of cavitation bubbles of herringbone grooved bearing with the texture is slightly increased compared to bearing with smooth surface. It means that the cavitation effect is enhanced for the herringbone grooved journal bearings with the texture.
Fig. 2. Distribution of bubble number density ($\varepsilon = 0.8; H_t = 0.5; S_t = 0.1$)

Fig. 3 shows the pressure distribution of the herringbone grooved journal bearings. It can be seen that the load capacity of the herringbone grooved journal bearings with texture is slightly reduced compared to herringbone grooved journal bearings with non-texture. It can be seen that the hydrodynamic pressure is weakly enhanced due to cavitation effect for herringbone grooved journal bearings with texture. Since the volume fraction of cavitation bubbles is small, and the influence of cavitation effect on the hydrodynamic pressure distribution is weak.

Fig. 3. Comparison of pressure distribution ($\varepsilon = 0.8; H_t = 0.5; S_t = 0.1$)

Fig. 4 shows the variation of static characteristics of cavitation texture herringbone grooved journal bearings with eccentricity ratio for different circumferential texture ratios $S_t$ and texture depth $H_t$. The results show that the load capacity and friction torque of textured herringbone grooved journal bearings is less than that of non-textured herringbone grooved journal bearings under the state of cavitation. And the friction torque gradually decrease with the increase of texture rate $S_t$ and texture depth $H_t$ under a specified eccentricity ratio. This result may be explained by the fact that with the increase of area ratio, the equivalent oil film thickness increases.
4. Conclusion
A theoretical model of cavitating flow lubrication for the water-lubricated textured spiral groove thrust bearing has been established based on the two-phase flow theory and the population balance equation. The influence of texture parameters and cavitation effect on the static characteristics of the bearing has been analysed. Based on the result and discussion, the main conclusion can be drawn as follows:

- A skewed pressure distribution appears with regard to bubble volume in equilibrium state for both textured and non-textured bearings.
- The bubble number density of textured bearing is larger than that of non-textured bearing under the same working condition.
- The frictional torque of bearing is reduced with the increasing of texture area ratio and texture height.
- The load carrying capacity of the bearing is increased by the cavitation effect.

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