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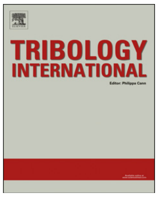

Study on the bubbly lubrication of journal bearings at various shear rates and temperatures

Hua-rui Yang, Xiao-Li Wang*, Yu-yan Zhang, Jin-fang Du

School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

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ABSTRACT

The rheological properties of bubbly oil are measured under relatively low to high shear rates using a rheometer. A constitutive equation including shear rate and temperature is constructed and used to develop the bubbly lubrication model of journal bearings, in which cavitation algorithm is applied. The effects of air volume fraction and shear rate on bearing performance are analyzed. The results show that as volume fraction increases, maximum pressure, load capacity, friction force and leak flow increase slightly at lower shear rates, decline obviously at higher shear rates, but increase to a peak and then decrease at intermediate shear rates.

1. Introduction

Nowadays, journal bearings are usually operated at higher shear rates. However, the previous constitutive equations and lubrication models of bubbly oil have been limited to extremely low shear rates. Hayward [1] proposed an empirical viscosity relationship for bubbly oil through the capillary viscosity test. Nikolajsen [2] presented analytical models for the viscosity and the density of bubbly oil considering both the reduction of viscosity due to the addition of air and the increase in viscosity due to the increase in shear force against surface tension by the deformation of bubbles. The results exhibited an increase in load capacity of journal bearings with increasing aeration level due to the increase of the viscosity. Ng et al. [3] found that the relationship between the viscosity and the aeration level was dependent on shear rate in the experiment by a sealed rheometer, and the shear rate range was from 50 to 250 s^{-1} in the tests. The experimental results obtained by Abivin et al. [4] showed that the bubbles increased the viscosity of the oil, but the shear rate was limited to 25 s^{-1}. Alshmakhy et al. [5] measured the viscosity of bubbly oil at various aeration levels using different types of viscometer and the results showed that the type of measuring device had a significant effect. As for the lubrication performance of bubbly oil, the conclusions about the effect of aeration level on the bearing performance have always been inconsistent. Chamniprasart et al. [6] derived an extended Reynolds equation based on the continuum theory to account for the fact that bubbly oil is non-Newtonian. They concluded that the amount of air entrained in the lubricant affected the bearing pressure in a significant way, while the bubble size had only a small effect. Chun [7] used the viscosity and density model presented by Nikolajsen [2] in THD analysis of high speed journal bearings considering turbulence and found that there existed an increase in the load capacity as the aeration level increased. Choi et al. [8] analyzed the effect of air bubbles on the load capacity of journal bearings and obtained a critical volume fraction. Goodwind et al. [9] performed the similar investigations through theoretical and experimental work but the conclusion was so different, that is, lubricant aeration had a negligible effect on the steady load capacity for most practical conditions. In addition, the research conclusions on the bubbly lubrication of squeeze film dampers were also different from those of journal bearings. Most studies reported that the increase in aeration level reduced the damper performance [10–12]. For instance, Younan et al. [13] showed that the damper film force and damping decreased as the aeration level increased.

It is evident that the conclusions about the effects of oil aeration on the bearing performance have been inconsistent due to various constitutive models, lubrication equations and operation conditions. The objective of this paper is to investigate the bubbly lubrication of journal bearings at various shear rates and temperatures. The rheological properties of bubbly oil are measured at relatively low to high shear rates by using the rheological test rig. A modified lubrication model of journal bearings lubricated with bubbly mixtures is developed through the constitutive equation of bubbly oil including shear rate and temperature. The effects of air volume fraction and shear rates on the bearing performance are analyzed numerically.

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* Corresponding author. Tel.: +86 13718955298.
E-mail address: xiaoli_wang@bit.edu.cn (X.-L. Wang).

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Nomenclature

c	radial clearance (m)
F	cavitation index
F_f	friction force (N)
h	film thickness (m)
$\overline{h}$	non-dimensional film thickness, $\overline{h}=h/c$
L/D	length–diameter ratio
p	film pressure (Pa)
$\overline{p}$	non-dimensional pressure, $\overline{p}=p/p_{\text{ref}}$
p_0	ambient pressure (Pa)
p_a	pressure inside a bubble (Pa)
$\overline{p}_a$	non-dimensional pressure inside a bubble $\overline{p}_a=p_a/p_{\text{ref}}$
p_c	cavitation pressure (Pa)
p_{in}	inlet pressure (Pa)
$\overline{p}_{\text{in}}$	non-dimensional inlet pressure, $\overline{p}_{\text{in}}=p_{\text{in}}/p_{\text{ref}}$
p_{ref}	reference pressure, $p_{\text{ref}}=\eta_0 UR/c^2$ (Pa)
Q_y	leak flow (m^3/s)
r	bubble radius in the bearing (m)
$\overline{r}$	non-dimensional bubble radius, $\overline{r}=r/r_{\text{in}}$
r_{in}	initial bubble radius (m)
R	shaft radius (m)
T	temperature (°C)
u, v	velocity in x, y direction (m/s)
U	shaft surface velocity (m/s)
W	load capacity (N)
W_ζ	load capacity in ζ-direction (N)
W_ξ	load capacity in ξ-direction (N)
x,y,z	coordinates of circumferential, axial and radial directions, respectively (m)
α	void fraction
$\overline{\alpha},\overline{\beta},\omega_\tau$	relaxation coefficients
α_{in}	initial void fraction
β	air volume fraction
β_{in}	initial volume fraction
$\dot{\gamma}$	shear rate (1/s)
ε	eccentricity ratio
η	viscosity of bubbly oil (mPa s)
η_0	reference viscosity, $\eta_0=m_0(U/c)^{n-1}$ (Pa s)
η_l	viscosity of pure oil (mPa s)
η_x^*,η_y^*	defined effective viscosity in x-direction and y-direction, respectively (Pa s)
λ	downhill factor
ρ	density of bubbly oil (kg/m^3)
$\overline{\rho}$	non-dimensional density, $\overline{\rho}=\rho/\rho_l$
ρ_a	density of air (kg/m^3)
$\rho_{a_{\text{in}}}$	inlet density of air (kg/m^3)
$\overline{\rho}_{a_{\text{in}}}$	non-dimensional inlet density of air, $\overline{\rho}_{a_{\text{in}}}=\rho_{a_{\text{in}}}/\rho_l$
ρ_l	density of oil (kg/m^3)
ρ_c	unified density considering cavitation (kg/m^3)
ρ_l	density of pure oil (kg/m^3)
σ	surface tension (N/m)
$\overline{\sigma}$	non-dimensional surface tension, $\overline{\sigma}=\sigma/p_{\text{ref}}r_{\text{in}}$
τ	shear stress (mPa)
$\overline{\tau}$	non-dimensional shear stress, $\overline{\tau}=\tau c/\eta_0 U$
τ_x,τ_y	shear stress in x-direction and y-direction, respectively (Pa)
τ_{xs},τ_{ys}	shear stress acting on the journal surface in x-direction and y-direction, respectively (Pa)
$\varphi,\overline{y},\overline{z}$	non-dimensional coordinates of circumferential, axial and radial directions, respectively, $\varphi=x/R$, $\overline{y}=y/R$, $\overline{z}=z/h$
ϕ	single variable
ω	shaft angular velocity (rad/s)

Subscripts

a	air
c	cavitation
in	state at inlet of the bearing
l	oil

No subscripts

bubbly	oil

2. Experimental study on the constitutive equation of bubbly oil

2.1. Rheological experimental system of bubbly oil

Fig. 1 shows the rheological experimental system of bubbly oil. Oil and air are fed from oil tank and air tank respectively into the mix pump through flow meter and control valve. The air and oil are mixed completely in the mix pump, and the homogeneous bubbly oil is then extracted from the sampling valve. The bubbly oil with various aeration levels is obtained by leaving the sample for various period of time, during which the coalescing or even disappearing of some bubbles would happen gradually, thus making the aeration level decreases. Every 2 min, some oil of the sample is taken for the measurement of aeration level and viscosity. The bubbly oil sample at atmospheric pressure is photographed by a microscope so that the void fraction α representing the oil aeration level can be estimated using Image-Pro Plus software. Meanwhile, the viscosity and shear stress of bubbly oil with the same void fraction are measured through Physica MCR 101 rotary viscometer. The temperature range is only set as 20–90 °C, for bubbles will rupture and disappear at higher temperature. The shear rate range is set as 45–45,000 s^{-1}. The bubble size is almost the same, and therefore the effect of bubble size does not have to be considered in the present test. CD15W/40 is selected as the experimental oil.

2.2. Rheological properties of bubbly oil at various shear rates and temperatures

The measured viscosities of bubbly oil versus void fraction at 20 °C under shear rates of 45 s^{-1}, 142 s^{-1} and 969 s^{-1} are shown in Fig. 2. It can be seen that at extremely low shear rate (i.e. $\dot{\gamma}=45\ s^{-1}$), the viscosity of bubbly oil increases as the void fraction increases and the following relation can be obtained by fitting the experimental data.

$$\eta=\eta_l(1+0.33\beta) \tag{1}$$

where η and η_l are the viscosity of bubbly oil and pure oil respectively at $\dot{\gamma}=45\ s^{-1}$, and β is the air volume fraction, which obeys the Armand correlation [14] and has the relationship with the measured void fraction α as follow:

$$\beta=0.833\alpha \quad (\beta\le 0.91) \tag{2}$$