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Static Characteristics of Journal Bearings Operating on TiO_2 Nanolubricants at Low Shear Condition

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Abstract The use of TiO_2 nanoparticles as lubricant additives is reported to improve the static performance characteristics of journal bearings. A variable viscosity analysis using Krieger-Dougherty viscosity model and couple stress model reported an increase in load carrying capacity of fluid film bearings operating on TiO_2 nanolubricants at high shear condition. The shear condition was modelled using the maximum particle packing fraction of TiO_2 nanoparticle aggregates. The current study simulates the static characteristics of journal bearings for low shear conditions and compares it with the published results for high shear. Results reveal an increase in load carrying capacity for journal bearings operating at low shear conditions in comparison to high shear for nanolubricants. Results point to an increase in operational region of the journal bearing at low speed conditions due to the presence of TiO_2 nanoparticle additives.

Keywords Hydrodynamic journal bearings, TiO_2 nanoparticle, High shear and Low shear conditions

1. Introduction

The use of nanoparticles as additives in carrier fluids for enhanced physiochemical properties has gained significant research interest over the past two decades. The resulting dispersion of nanoparticles in base fluids is termed as nanofluids. Owing to the increase in thermal conductivity of nanofluids in comparison to base fluids, nanofluids have found increased use in heat transfer applications [1, 2]. Coolants [3-5], refrigerants [6-8], cutting fluids [9-11], and lubrication [12-15] are few other applications using nanoparticle additives. Addition of nanoparticles is reported to improve the tribological properties of base oils under conditions of boundary lubrication [16, 17]. Wu et al. [18] has compared the performance of CuO, TiO_2, and nano-diamond nanoparticles as additives in base oils. The paper also reports an increase in viscosity of base oil due to the addition of nanoparticle additives. TiO_2 nanoparticles were reported to provide comparatively higher viscosity increase and also displayed enhanced tribological behaviour. The viscosity values of nanolubricants provided by Wu et al. [18] were used subsequently by Nair et al. [19] and Shenoy et al. [20] to perform a variable viscosity analysis of journal bearings operating on nanolubricants. These studies reported an increase in load carrying capacity of journal bearings operating on nanolubricants. A more generalized study was performed by Binu et al. [21, 24] by obtaining a viscosity model for TiO_2 nanolubricants and performing a variable viscosity analysis in conjunction with couple stress model to obtain journal bearing performance characteristics under the influence of particle concentration and particle size. The current paper extends the results published in Binu et al. [24] by considering the viscosity variations of TiO_2 nanolubricants at low shear conditions. The results of this paper compares the static journal bearing characteristics published by Binu et al. [24] at high shear with the results obtained for low shear. The maximum particle packing fraction ϕ_m is used as the control variable.

2. Viscosity Model

A modified Krieger-Dougherty model is reported to simulate viscosities of TiO_2 nanoparticle dispersions in engine oil for increasing TiO_2 nanoparticle concentrations that are in good agreement with experimental results [21, 24]. The modified Krieger-Dougherty (K-D) model is expressed as equations 1 and 2 shown below.

$$\mu_{nf} = \mu_{bf}\left(1-\frac{\phi_a}{\phi_m}\right)^{-2.5\phi_m} \quad (1)$$

Where,

$$\phi_a = \phi\left(\frac{a_a}{a}\right)^{3-D} \quad (2)$$

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The above general equation for nanofluids was customised for TiO_2 nanolubricants by Binu et al. [24] by measuring the aggregate to primary particle size ratio (a_a / a) for TiO_2 nanolubricants using DLS particle size analysis. For primary particle size of 100 nm, the obtained ratio was 7.77.

2.1. Maximum Particle Packing Fraction

In the modified Krieger-Dougherty model presented in equation 1, ϕ_m is the maximum particle packing fraction in the suspension, which is dependent on the extent of shear. For high-shear applications, 0.605 is the prescribed value and for low shear applications ϕ_m is taken as 0.5 [22]. The fractal index *D* is generally taken as 1.8 for nanofluids [22]. The modified Krieger-Dougherty model therefore reduces to equation 3, presented below.

$$\bar{\mu} = \frac{\mu_{nf}}{\mu_{bf}} = \left(1 - \frac{\phi}{0.605}\left(\frac{a_a}{a}\right)^{1.2}\right)^{-1.51} \quad (3)$$

3. Theoretical

The governing equation for this analysis is the modified Reynolds equation; integrated with the modified Krieger-Dougherty viscosity model to simulate the influence of TiO_2 nanoparticle concentration and the couple stress model to simulate the influence of TiO_2 nanoparticle size on the journal bearing performance characteristics. The governing equation is presented in equation 4. Further details on the numerical formulation and validation of the theoretical framework is presented in Binu et al. [21, 24].

$$\frac{\partial}{\partial\theta}\left[\bar{f}\left(\bar{h},\bar{d}\right)\frac{\partial\bar{p}}{\partial\theta}\right] + \left(\frac{R^2}{L^2}\right)\frac{\partial}{\partial\bar{z}}\left[\bar{f}\left(\bar{h},\bar{d}\right)\frac{\partial\bar{p}}{\partial\bar{z}}\right] = 6\bar{\mu}\bar{u}\frac{\partial\bar{h}}{\partial\theta} \quad (4)$$

Where, $\bar{f}\left(\bar{h},\bar{d}\right) = \bar{h}^3 - 12\bar{d}^2\left[\bar{h} - 2\bar{d}\tanh\left(\frac{\bar{h}}{2\bar{d}}\right)\right]$.

In solving the Reynolds equation, the effective viscosity term, $\bar{\mu} = \frac{\mu_{nf}}{\mu_{nf}}$ in the RHS, is simulated for varying TiO_2 nanoparticle concentration, using the modified Krieger-Dougherty viscosity model, expressed as equation 1.

The modified Reynolds equation is thus equipped to include the effective viscosity of nanolubricants and particle size of TiO_2 aggregates in modeling the hydrodynamic pressure distribution. Equation 4 is solved numerically using finite difference scheme to obtain the pressure distributions at both high shear and low shear conditions. The pressure distributions are then used to compute the load carrying capacity and friction force at low shear and high shear conditions.

3.1. Load Carrying Capacity

Load carrying capacity of the bearing is obtained by integrating nodal hydrodynamic pressures across the bearing surface. The two components of generated oil film force, along the line of center and perpendicular to the line of center, are computed using the pressure integration equations given below.

$$\bar{W}_r = \frac{W_r C^2}{\mu_{bf}\omega R^3 L} = -\int_0^{\theta_m}\int_0^1 \bar{p}\cos\theta d\theta d\bar{z} \quad (5)$$

$$\bar{W}_t = \frac{W_t C^2}{\mu_{bf}\omega R^3 L} = \int_0^{\theta_m}\int_0^1 \bar{p}\sin\theta d\theta d\bar{z} \quad (6)$$

3.2. Friction Force

The friction force generated within the oil film thickness, due to its continuous shearing by the surface motion of journal, is computed by integrating the shear stresses induced around the journal surface. The effective viscosity of TiO_2 nanolubricants with considerations to both volume fraction and aggregate particle size influences the friction force. The shear stress developed at the journal surface is given by the equation stated below [24].

$$\tau = \mu\left.\frac{\partial u}{\partial y}\right|_{y=h} - \eta\left.\frac{\partial^3 u}{\partial y^3}\right|_{y=h} \quad (7)$$

Substituting for *u* using equation 7, the shear stress is obtained as:

$$\tau = \mu\left(\frac{U}{h} + \frac{h}{2\mu}\frac{\partial p}{\partial x}\right) \quad (8)$$

The non-dimensional friction is then obtained by the integration of shear stress equation as:

$$\bar{F}_f = \frac{F_f C}{R^2 L\mu_{bf}\omega} = \int_0^1\int_0^{2\pi}\left[\frac{\bar{\mu}}{\bar{h}} + \frac{\bar{h}}{2}\frac{\partial\bar{p}}{\partial\theta} - \bar{d}\frac{\partial\bar{p}}{\partial\theta}\tanh\left(\frac{\bar{h}}{2\bar{d}}\right)\right]d\theta d\bar{z} \quad (9)$$

The standard friction parameter is then computed as:

$$f\left(\frac{R}{C}\right) = \frac{\bar{F}_f}{\bar{W}_R} \quad (10)$$

4. Results and Discussions

The comparison of static characteristics for low shear and high shear is performed at a volume fraction of ϕ = 0.02. Comparisons are made of maximum non-dimensional pressures for plain engine oil and nanolubricants at high and low shear conditions. A comparison of static characteristics of journal bearings is also provided between values obtained between the aforementioned modified Krieger-Dougherty model and the Bicerano model [25]. The Bicerano model provides effective viscosities of suspensions and is expressed as:

$$\mu_{nf} = \mu_{bf}\left\{\left(1 - \frac{\phi}{\phi^*}\right)^{-2}\left[1 - 0.4\left(\frac{\phi}{\phi^*}\right) + 0.34\left(\frac{\phi}{\phi^*}\right)^2\right]\right\} \quad (11)$$

Figs. 1, 2, and 3 illustrates the variation in maximum pressure, load carrying capacity, and friction force for the mentioned conditions respectively. It is observed in Fig. 1 that, the Bicerano model [25] severely under predict the maximum pressure in comparison to modified Krieger-Dougherty model. It is also observed from Fig. 1 that, at low shear applications, the generated maximum hydrodynamic pressure is higher than induced pressure at high shear rate. This could be attributed to the shear thinning behaviour of TiO_2 nanolubricants at high shear rates. A similar trend is also observed for load carrying capacity of journal bearings illustrated in Fig. 2.

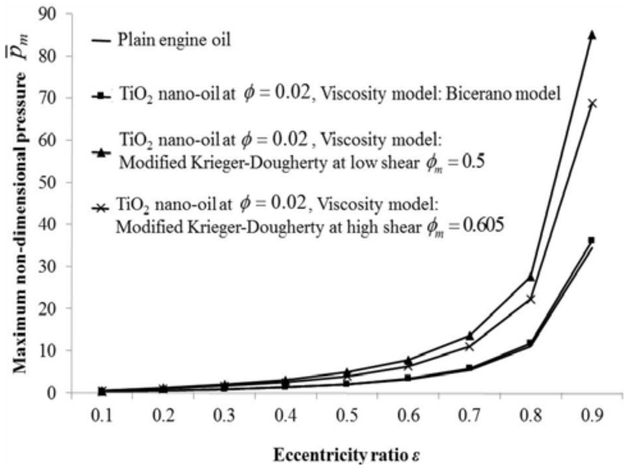

Figure 1. Maximum non-dimensional pressures for plain engine oil compared with maximum pressures for TiO_2 nanolubricant at 0.02 volume fraction simulated using Bicerano model, and modified Krieger – Dougherty (at low and high shears)

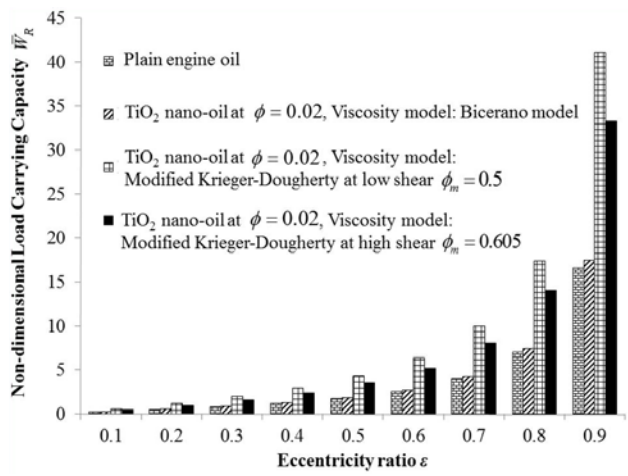

Figure 2. Load carrying capacity for plain engine oil compared with load capacity for TiO_2 nanolubricant at 0.02 volume fraction simulated using Bicerano model, and modified Krieger – Dougherty (at low and high shears)

Fig. 2 reveals that, especially at higher eccentricity ratios, an apparently higher load carrying capacity is observed for journal bearings operating at low shear rates in comparison to high shear rates. This observation would mean that, usage of TiO_2 nanolubricant could extend the operation range of journal bearings at lower speeds, characterized by smaller film thickness, in comparison to optimum speeds. Fig. 3 depicts a proportionate increase in friction force for low shear rates in comparison to high shear rates. A quantitative comparison of maximum pressure, load capacity, and friction force is provided in Table 1. The characteristics are computed at an eccentricity ratio of 0.6. Percentage variations of considered steady state characteristics in comparison to plain engine oil is also provided below.

It can be observed from the above results that TiO_2 nanolubricants offer higher load carrying capacity at low volume fractions in comparison to plain engine oil. It is also observed that fluid film bearings at low shear applications will experience higher hydrodynamic pressures and load carrying capacity, in comparison to plain engine oil.

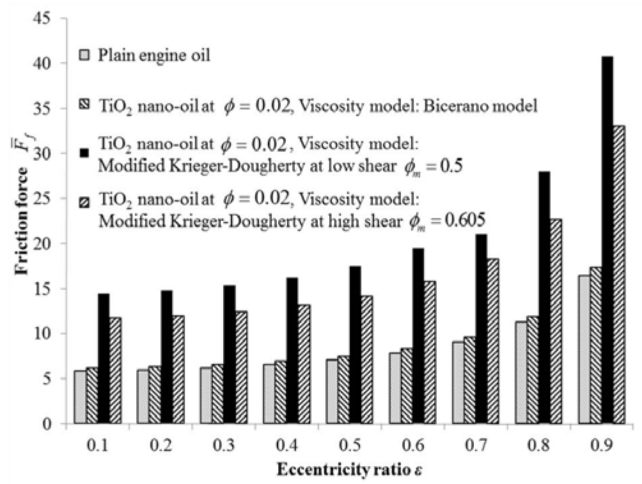

Figure 3. Friction force for plain engine oil compared with load capacity for TiO_2 nanolubricant at 0.02 volume fraction simulated using Bicerano model, and modified Krieger – Dougherty (at low and high shears)

Table 1. Influence of shear rate on steady state characteristics

Bearing Static Characteristics	Plain Engine Oil ($\phi = 0$)	TiO_2 Nano Lubricant ($\phi = 0.02$)		
		Bicerano Model	Modified Krieger-Dougherty model for low shear	Modified Krieger-Dougherty model for high shear
Maximum non-dimensional pressure	3.1480	3.3136	7.7981	6.3071
Non-dimensional load carrying capacity	2.58	2.7157	6.391	5.169
Non-dimensional friction force	7.8686	8.2824	19.492	15.765

Percentage variations of steady state characteristics in comparison to plain engine oil is listed below.

Load carrying capacity:

- Bicerano model = 5.23%
- Modified Krieger-Dougherty model (low shear) = 147%
- Modified Krieger-Dougherty model (high shear) = 100.3%

Friction force:

- Bicerano model = 5.25%
- Modified Krieger-Dougherty model (low shear) = 147.7%
- Modified Krieger-Dougherty model (high shear) = 100.3%

5. Conclusions

The study simulates the journal bearing performance characteristics, viz. maximum pressures, load carrying capacity and friction force for TiO_2 nanolubricants under low shear conditions. The obtained characteristics are then compared with the published results for high shear conditions [24]. Results reveal increased pressures and corresponding load carrying capacity of journal bearing operating with TiO_2 nanolubricants at low shear condition in comparison to high shear. This result reveals the potential of using nanoparticle additives to improve hydrodynamic performance at low shear conditions characterised by low speed of journal rotation.

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