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Static characteristics of a fluid film bearing with TiO_2 based nanolubricant using the modified Krieger–Dougherty viscosity model and couple stress model

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ABSTRACT

Static characteristics of a journal bearing operating on TiO_2 based nanolubricant is obtained by a variable viscosity approach. The predicted shear viscosities of TiO_2 based nanolubricant at different volume fractions and aggregate particle sizes are obtained using modified Krieger–Dougherty model and are found to be in good agreement with experimental shear viscosities. The modified Reynolds equation considers the Krieger–Dougherty viscosities and couple stress effects of TiO_2 nanoparticle additives at different volume fractions and particle sizes. Results reveal a significant improvement in load carrying capacity of journal bearing operating on TiO_2 based nanolubricant as compared to plain oil without TiO_2 nanoparticles.

1. Introduction

Increasing severity of load and speed conditions in modern day machines has constantly challenged tribologists to develop improved solutions to enhance the performance of support bearings. In addition to new designs in bearing configurations, a lot of importance is given towards improving the properties of the oil used. It has been shown that the presence of small micro structured particles suspended in oil enhances its lubrication properties. The couple stress model of microcontinuum theory [1–3] was applied to these fluids and the analysis revealed an increase in load carrying capacity and stability of journal bearings [4–8]. Since the advent of nanotechnology, nanoparticle additives have been used to improve the properties of many carrier fluids such as coolants and lubricating oils. Nanoparticles owing to their small size are capable of accessing areas within extremely small surface asperities and therefore hold great potential in improving the tribological properties of lubricants and contact surfaces. Over the last two decades, numerous studies have been carried out with regard to usage of nanoparticles as lubricant additives [9–16]. The nanoparticles used were generally, metals such as: Cu, Ni, Ag, Pd, and Mo; metal oxides such as: TiO_2, CuO, ZnO, ZrO_2, and SiO_2; sulphides such as: WS_2, MoS_2, and PbS; carbon-based compounds such as: fullerenes, CNT's, MWCNT's, and nano-diamonds; and few other compounds such as: LaF_3, PTFE, and $CaCO_3$. However, all these studies on nanoparticle lubricant additives were focused on their influence on lubricating properties in the boundary lubrication regime. Very few studies have been carried out to study the influence of nanoparticle additives in the hydrodynamic lubrication regime. Nair et al., [17] and Shenoy et al., [18] have studied the influence of nanoparticle based lubricants on performance of circular journal bearings and externally adjustable fluid film bearing, respectively. The studies revealed an improvement in the static characteristics of fluid film bearings. However, the limitation with the above mentioned studies [17,18] was that both the analyses employed viscosity values provided for a single nanoparticle concentration by Wu et al., [19] for CuO, TiO_2, and nanodiamond based nanolubricants for calculating the bearing characteristics. Variation in viscosity with nanoparticle concentration was not considered. There is also no reported study on the couple stress effects of nanoparticle additives on fluid film lubrication.

In this study, a novel method for studying the influence of lubricant viscosity variation, due to increasing concentrations of nanoparticle additives and their couple stress effects, on the static characteristics of a journal bearing operating on TiO_2 based nanolubricant is presented. Various viscosity models have been employed to predict the relative viscosities of nanolubricants for varying nanoparticle concentrations. Stable TiO_2 nanolubricant

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Nomenclature

a	radii of primary nanoparticles (nm)
a_a	radii of aggregate nanoparticles (nm)
C	radial clearance (m)
D	fractal index
d	couple stress parameter (m) $d=\sqrt{\eta/\mu}$
$\overline{d}$	non-dimensional couple stress parameter $\overline{d}=d/C$
e	eccentricity (m)
F_f	friction force (N)
$\overline{F}_f$	non-dimensional friction force $\overline{F}_f=F_fC/\mu_{bf}\omega R^2L$
h	film thickness (m) $C\overline{h}=C+e\cos\theta$
$\overline{h}$	non-dimensional film thickness $\overline{h}=(h/C)=1+\varepsilon\cos\theta$
L	length of the bearing (m)
p	lubricant film pressure (N/m^2)
$\overline{p}$	non-dimensional film pressure $\overline{p}=pC^2/\mu_{bf}UR$
Q_Z	side leakage (m^3/s)
$\overline{Q}_z$	non-dimensional side leakage $\overline{Q}_z=Q_zL/CR^3\omega$
R	radius of the journal (m)
t	time (s)
U	tangential velocity of the journal (m/s) $U=\omega R$
$W_r,\overline{W}_r$	radial component of load carrying capacity (N) $\overline{W}_r=W_rC^2/\mu_{bf}\omega R^3L$
$W_t,\overline{W}_t$	tangential component of load carrying capacity (N) $\overline{W}_t=W_tC^2/\mu_{bf}\omega R^3L$
$W,\overline{W}$	load carrying capacity (N) $\overline{W}=WC^2/\mu_{bf}\omega R^3L$
x	bearing coordinates in the circumferential direction (m) $x=R\theta$
z	bearing coordinates in the axial direction (m) $z=\overline{z}L$
μ_{bf}	viscosity of plain engine oil (Pa-s)
μ_{nf}	viscosity of the nanolubricant (Pa-s)
$\overline{\mu}$	non-dimensional relative viscosity $\overline{\mu}=\mu_{nf}/\mu_{bf}$
ϕ	nanoparticle volume fraction
ϕ_a	effective volume fraction
ϕ_m	maximum particle packing fraction
ϕ^*	viscosity percolation threshold (critical volume fraction at which viscosity approaches infinity)
ε	eccentricity ratio $\varepsilon=e/C$
θ	angular coordinate (rad)
θ_m	starting of the cavitation zone (rad)
ω	angular velocity of the journal (rad/s)
ψ	attitude angle (rad)
$[\eta]$	intrinsic viscosity
η	material constant responsible for couple stress property

samples were formulated using the two-step approach. Viscosity of the nanolubricants is also experimentally measured using a Rheometer. Nanoparticle aggregation within the dispersion is measured using DLS particle size analyser. The study identifies the theoretical viscosity model which is capable of predicting viscosity values that are in close agreement to experimental results. The selected viscosity model is then used for computing the static characteristics of journal bearings. Influence of couple stress effects of nanoparticle additives on the bearing characteristics is also studied.

2. Experimental

Experimental studies involve formulation of stable TiO_2 based nanolubricant samples at different concentrations. Shear viscosities of the nanolubricant samples are then studied using a rheometer. Particle size distributions of the samples are also obtained using DLS particle size analyzer.

2.1. Materials

TiO_2 nanoparticles (size <100 nm (BET), purity—99.5% trace metal basis) and SAE 30 engine oil are used in the formulation of nanolubricant samples. Oleic acid is used as the surfactant. GR grade hydrochloric acid and deionised water (Millipore Elix-3) was used in the pre-processing of nanoparticles.

2.2. Nanolubricant preparation

The purchased nanoparticles are subjected to an acid treatment process reported in Li et al. [20] to improve the surfactant adsorption on to the nanoparticle surfaces. The morphology and chemical composition of the nanoparticles are characterized by scanning electron microscopy and Fourier transform infrared spectroscopy, respectively. SEM images are obtained using LEO 435 VP apparatus. FT-IR spectrum of the nanoparticles is obtained using Shimadzu FTIR 8400S apparatus. The acid treated nanoparticles are dispersed in SAE 30 engine oil using ultrasonication. An appropriate amount of oleic acid is used as a surfactant to improve the dispersion stability. A combination of direct and indirect sonication coupled with mechanical agitation was found to offer the best dispersion stability. Direct sonication was carried out using a probe sonicator of frequency 20 kHz at 40% amplitude. The indirect sonication was carried out on a bath sonicator at 33 kHz frequency. The resultant nanolubricant samples exhibited good dispersion stability for 75 days.

2.3. Shear viscosity analysis

TiO_2 based nanolubricant samples at concentrations ranging from 0.05 to 2.5 wt% are prepared using the procedure mentioned in Section 2.2. The shear viscosities of the nanolubricant samples are studied using a Bohlin Gemini rotational rheometer. The tests were carried out on strain controlled mode using a cone (4° and 40 mm diameter) and plate geometry. The rheometer has an integrated peltier plate temperature control unit with a range of -30 °C to $+200$ °C. The analysis is carried out on a continuous shear rate ramp up to a maximum shear of 40 s^{-1}. The shear viscosities are measured at plate temperatures ranging from 10 to 80 °C ($\pm$0.1 °C) in steps of 10 °C. The ambient room temperature is maintained at 25 °C.

2.4. Particle size analysis

The dynamic light scattering method of particle size analysis is used to measure the size of the TiO_2 nanoparticle aggregates dispersed in the engine oil. The measurements are carried out using Malvern Zetasizer Nano ZS instrument. Particle size distributions for nanolubricant samples at concentrations ranging from 0.05 to 2.5 wt% are obtained. Three trials are carried out for each sample and the average values are considered for analysis. All the readings were taken at an ambient temperature of 25 °C.

3. Theoretical

The relative viscosities of TiO_2 based nanolubricant samples, as a function of nanoparticle volume fractions and nanoparticle