Study of TiO_2 Nanoparticles as Lubricant Additive in Two-Axial Groove Journal Bearing

K. Yathish, K. G. Binu, B. S. Shenoy, D. S. Rao, R. Pai

Abstract**—**Load carrying capacity of an oil lubricated two-axial groove journal bearing is simulated by taking into account the viscosity variations in lubricant due to the addition of TiO_2 nanoparticles as lubricant additive. Shear viscosities of TiO_2 nanoparticle dispersions in oil are measured for various nanoparticle additive concentrations. The viscosity model derived from the experimental viscosities is employed in a modified Reynolds equation to obtain the pressure profiles and load carrying capacity of two-axial groove journal bearing. Results reveal an increase in load carrying capacity of bearings operating on nanoparticle dispersions as compared to plain oil.

Keywords**—**Journal bearing, TiO_2 nanoparticles, viscosity model, Reynolds equation, load carrying capacity.

I. Introduction

LUBRICANT additives play a major role in improving the tribological properties of modern day lubricants. Considering present day energy scenario and the ever increasing severity in operating conditions of machineries, it is imperative that we develop better tribological practices leading to reduced losses due to friction and wear. Journal bearings, being the more popular support mechanism in high speed applications, have been the focus of research for many tribologists. In addition to research on geometrical aspects of the sleeve, such as, externally adjustable pad bearings [1]–[3], thrust is also on promoting load capacity of journal bearings using improved lubricants.

The use of nanoparticles as lubricant additive has been a major subject of research in the past decade. Various metals and metal oxide nanoparticles have been studied as lubricant additives in thin film lubrication [4]–[11]. These studies have reported reduced friction and wear in tribo-surfaces with the use of nanoparticle lubricant additives. However, the application of nanoparticles in hydrodynamic lubrication is not clearly understood and represents a major gap in research. Nair et al. [12] and Shenoy et al. [13] obtained performance characteristics of fluid film bearings based on the viscosity results provided by Wu et al. [14] and reported an increase in load carrying capacity. The above listed studies had considered only single nanoparticle concentration for obtaining the performance characteristics. The effect of viscosity variations with increasing nanoparticle concentrations needs to be studied. Viscosity of colloidal dispersions has been studied and modeled over the past many decades. The first viscosity model for dilute concentrations (ϕ =0.01) of spherical particles was provided by Einstein [15] in 1956 and is expressed as:

$$\overline{\mu} = \frac{\mu_{ps}}{\mu_{bf}} = 1 + 2.5\phi \tag{1}$$

The applicability of Einstein's equation was extended by Brinkman [16] to cover moderate particle concentrations as:

$$\overline{\mu} = \frac{\mu_{ps}}{\mu_{bf}} = \frac{1}{(1-\phi)^{2.5}} \tag{2}$$

A more general viscosity model was later developed by Batchelor [17] by considering the particle interactions as:

$$\overline{\mu} = \frac{\mu_{ps}}{\mu_{bf}} = 1 + 2.5\phi + 6.5\phi^2 \tag{3}$$

These classical viscosity models were developed primarily for micrometer sized particle dispersions in base fluids. Their applicability to nanoparticle dispersions was studied by Kole et al. [18], who reported that for CuO nanoparticles in gear oil, these classical viscosity models severely underpredict viscosity variations with increasing particle volume fractions.

In this study, TiO_2 nanoparticle suspensions were formulated with low volume fractions in engine oil using two-step method. Their dynamic viscosities were experimentally measured using rheometer. From the measured viscosities, a mathematical model is derived based on assumed linearity of shear viscosity with volume fraction. The obtained viscosity model is then employed to predict shear viscosities at various volume fractions. The predicted viscosities are then used in the computations of load carrying capacity of two-axial groove journal bearing. The classical Reynolds equation for fluid film lubrication is modified to incorporate relative viscosities of nanoparticle dispersions. The modified equation is solved numerically using finite difference scheme to obtain the pressure profiles for various volume fractions of TiO_2

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nanoparticle dispersions. The load carrying capacity is then computed and compared with results for plain oil.

II. Experimental Analysis

A. Materials

TiO_2 nanoparticles used in this study were purchased from Sigma-Aldrich. The purchased TiO_2 nanoparticles were a mixture of rutile and anatase phase with primary particle size of < 100 nm (BET). The reasons for selecting TiO_2 nanoparticles are: a) TiO_2 nanoparticles are chemically stable and hence will not react with base fluid and tribo-surfaces at lubricating temperatures. b) TiO_2 nanoparticles are easily available, and c) TiO_2 nanoparticles are safe for human handling. The base fluid used in the formulation of nano-oil is engine oil (SAE 30) of viscosity 0.1078 Pa-s at 40 °C. Oleic acid was used as surfactant in the formulation of stable nanolubricants. The selection of Oleic acid as surfactant was on the basis of a separate dispersion stability analysis carried out by the authors.

B. Characterization of TiO_2 Nanoparticles

The morphology and chemical composition of purchased TiO_2 nanoparticles were characterized by TEM analysis with EDX. FT-IR spectrum of TiO_2 nanoparticles is also presented.

C. Formulation of TiO2 Based Nanolubricant

The nanolubricant was formulated using the two-step approach. The purchased TiO_2 nanoparticles were subjected to an acid treatment process to remove the silica coating for better dispersion stability [19]. The processed TiO_2 nanoparticles were dispersed in engine oil using ultrasonication along with specified concentration of surfactant to prevent aggregation. A combination of direct (25 kHz frequency) and indirect sonication (33 kHz frequency) was used at 39% amplitude with a pulse interval of 10:2 for an optimized duration. Oleic acid was used as surfactant at an optimum concentration subject to TiO_2 nanoparticle concentration and base fluid considered.

D. Shear Viscosity Analysis

Stable dispersions of TiO_2 nanoparticles in engine oil was obtained at low concentrations ranging from 0.05 wt. % to 2.5 wt. % using the formulation approach mentioned in Section II *C.* The prepared samples were then subjected to shear viscosity measurements using a rotational rheometer. Shear viscosity variations due to varying concentrations as well as varying temperatures were studied. Temperatures were varied from 20°C to 80°C in steps of 10°C. The shear rate was kept constant at 40 per second.

III. Theoretical Analysis

A. Governing Equations for Journal Bearing

The classical two-dimensional Reynolds equation for hydrodynamic lubrication is expressed as:

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(h^3\frac{\partial p}{\partial z}\right)=6\mu u\frac{dh}{dx} \qquad (5)$$

Equation (5) is numerically solved to obtain the pressure distribution within the oil film developed in the clearance between bearing and journal. Integrating the pressures over the bearing area leads to load carrying capacity of the bearing.

Physical configuration of the two-axial groove journal bearing along with the coordinates is shown in Fig. 1.

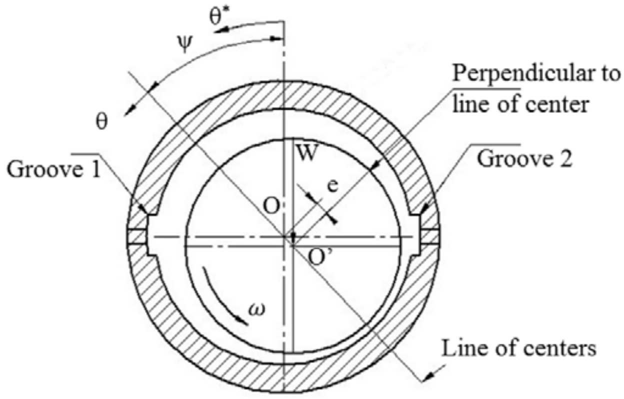

Fig. 1 Axial grooved Journal bearing configuration

In a plain journal bearing, the coordinate θ in the circumferential direction is taken from the position of maximum film thickness. In case of a grooved bearing shown in Fig. 1, this position needs to be found beforehand. This is done by assuming an arbitrary value of attitude angle ψ and the coordinate θ is measured from the vertical position. Using this arbitrary angle ψ, the lubricant film thickness in journal bearing is given by:

$$h = C\left(1+\varepsilon\cos\left(\theta^{*}-\psi\right)\right) \qquad (6)$$

The following dimensionless parameters are used to obtain the non-dimensional forms of (5) and (6):

Angular coordinate $\theta = \frac{x}{R}$; Axial coordinate $\bar{z} = \frac{z}{L}$;

Bearing length to width ratio $\lambda = \frac{L}{D}$;

Dimensionless film thickness $\bar{h} = \frac{h}{C}$;

Dimensionless pressure $\bar{p} = \frac{pC^2}{\mu uR}$;

Eccentricity ratio $\varepsilon = \frac{e}{C}$; and

Non-dimensional relative viscosity $\bar{\mu} = \dfrac{\mu_{ps}}{\mu_{bf}}$

where, μ_{ps} is the viscosity of nanoparticle suspension in oil and μ_{bf} is the viscosity of base fluid.

The non-dimensional Reynolds equation thus obtained is of the form,

$$\frac{\partial}{\partial\theta}\left[\bar{h}^3\frac{\partial\bar{p}}{\partial\theta}\right]+\left(\frac{R^2}{L^2}\right)\frac{\partial}{\partial\bar{z}}\left[\bar{h}^3\frac{\partial\bar{p}}{\partial\bar{z}}\right]=6\bar{\mu}\frac{\partial\bar{h}}{\partial\theta} \tag{7}$$

where, the non-dimensional film thickness is expressed as

$$\bar{h}=\frac{h}{C}=1+\varepsilon\cos\left(\theta^{*}-\psi\right) \tag{8}$$

B. Solution Scheme

The non-dimensional Reynolds equation, presented as (7), is solved numerically using finite difference method. The standard Reynolds boundary conditions are used in the solution scheme in which the negative pressures arising due to cavitation are neglected. The pressures at the ends of the bearing are also equated to zero, except for groove nodes. The pre-set non-dimensional groove pressure for a finite bearing is provided by Stachowiak [20] as $\bar{p}=0.2$. The boundary conditions could then be expressed as,

$\bar{p}=0.2$ at $\bar{z}=0$ and $\bar{z}=1$ at the grooves [20]

$\bar{p}=0$ at $\bar{z}=0$ and $\bar{z}=1$, for all nodes other than nodes in the grooves.

The boundary conditions as applied to the journal bearing are illustrated in Fig. 2.

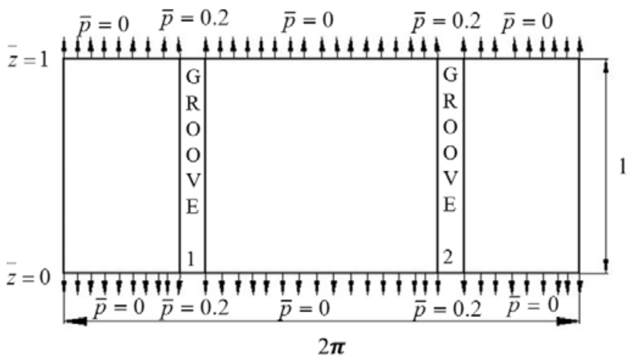

Fig. 2 Illustration of Reynolds boundary condition applied to grooved journal bearing

Central difference scheme is employed in discretizing the equation and Gauss-Siedel with SOR method is employed for numerical solution. MATLAB codes were developed for the computations. A rectangular grid is employed in the central difference scheme. The generated mesh of the bearing area with 130 (circumferential) × 22 (axial) nodes used in the computations is shown in Fig. 3. Fig. 3 also shows the node numbers for both the axial grooves.

C. Nanofluid Viscosity Model

Stable TiO_2 dispersions in engine oil were prepared using procedure explained in section II C at TiO_2 volume fractions ranging from 0.0001 to 0.005 (0.05 wt. 5 to 2.5 wt. %). Fig. 4 shows the variation in experimental shear viscosity of TiO_2 dispersions in engine oil with increasing TiO_2 concentrations expressed in volume fraction ϕ.

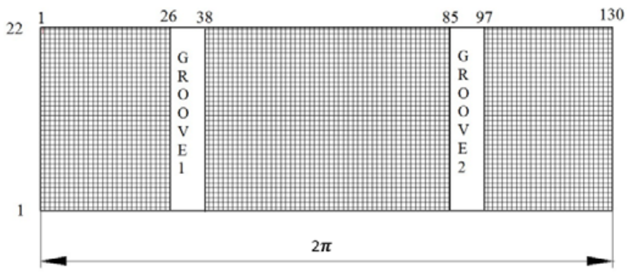

Fig. 3 Mesh size and groove nodes

Fig. 4 shows the variation in experimental shear viscosity of TiO_2 dispersions in engine oil with increasing TiO_2 concentrations expressed in volume fraction ϕ. The linear trend line equation for the viscosity variation is obtained as:

$$\mu_{ps}=8.4851\phi+0.2189 \tag{9}$$

The above equation in employed in the numerical solution of modified Reynolds equation to simulate the relative viscosity $\bar{\mu}$ at different TiO_2 concentrations.

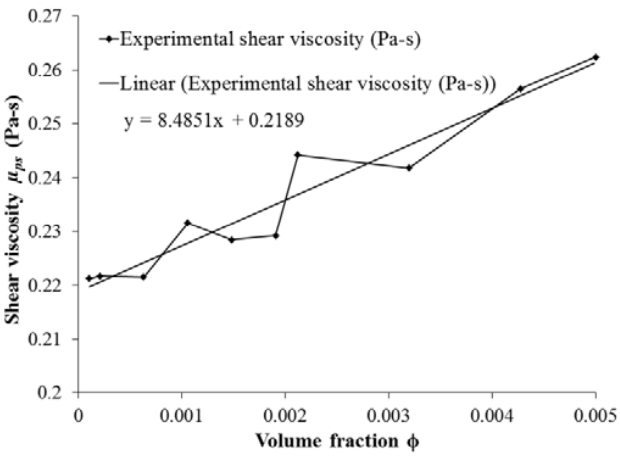

Fig. 4 Shear viscosity of TiO2 nanolubricant as a function of TiO_2 volume fraction

D. Load Carrying Capacity

The load carrying capacity of the journal bearing is obtained by integrating the pressures across the bearing area. The integration is performed numerically using Simpson's 1/3 rule.

The non-dimensional load components along the line of centers and its perpendicular directions are obtained as:

$$\overline{W}_o = \frac{W_o C^2}{\mu U L R^2} = -R\int_0^1 \int_0^{2\pi} \overline{p} \cos\left(\theta^* - \psi\right) d\theta d\overline{Z} \quad (10)$$

$$\overline{W}_{\frac{\pi}{2}} = \frac{W_{\pi/2} C^2}{\mu U L R^2} = -R\int_0^1 \int_0^{2\pi} \overline{p} \cos\left(\theta^* - \psi\right) d\theta d\overline{Z} \quad (11)$$

The non-dimensional load capacity is then obtained as

$$\overline{W} = \sqrt{\overline{W_o}^2 + \overline{W_{\pi/2}}^2} \quad (12)$$

The attitude angle is calculated as $\phi = \tan^{-1}\left(\frac{\overline{W_o}}{W_{\pi/2}}\right)$

The load capacities are evaluated for different volume fractions of TiO_2 nanoparticles and compared with non-dimensional load for plain engine oil.

IV. Results and Discussions

A. Validation of Computational Code

The computational code developed in MATLAB to solve the non-dimensional Reynolds equation for a two-axial groove journal bearing is validated by comparing the attitude angle and Sommerfeld number obtained from the code with the published results of Pinkus [21]. Table I presents a comparison of computed results with published results of Pinkus [21].

TABLE I
Validation of Computational Code

Eccentricity ratio	Attitude angle		Sommerfeld number	
	Code	Pinkus [21]	Code	Pinkus [21]
0.2	64	63.968	0.714	0.6837
0.4	53	51.649	0.275	0.2843
0.4	45	42.588	0.125	0.1302
0.6	28	29.648	0.041	0.0462
0.8	22	22.887	0.019	0.0188
0.9	64	63.968	0.714	0.6837

From Table I, it can be observed that the computed results from the MATLAB code are in good agreement with the published results of Pinkus [21].

The validated code is used in calculating the hydrodynamic pressures for two-axial groove journal bearings operating on TiO_2 based nanolubricant samples. A sample relative pressure distribution across the bearing area is presented in Fig. 5 for TiO_2 nanoparticle concentration $\phi = 0.03$ and eccentricity ratio $\varepsilon = 0.7$.

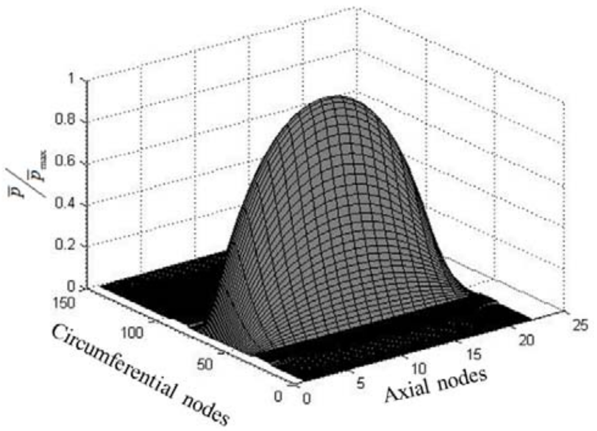

Fig. 5 Pressure distribution for $\phi = 0.03$ and $\varepsilon = 0.7$

B. Characterization of Nanoparticles

The morphology and chemical characterization of purchased nanoparticles are carried out using TEM and related EDX analysis. Fig. 6 shows the TEM micrograph and the acquired EDX spectrum.

As seen from Fig. 6, the purchased nanoparticles have formed aggregates of size ~ 250 nm. The aggregates are nearly spherical in shape. The EDX spectrum confirms the chemical composition of TiO_2. The EDX also reveals the presence of silica coating on the nanoparticles.

C. Viscosity Analysis

Experimental viscosity analysis of the prepared nanolubricant samples reveals an increasing trend in viscosity of engine oil due to the addition of TiO_2 nanoparticle additives. Fig. 7 presents the viscosity variations at different TiO_2 concentrations and temperatures obtained using rotational rheometer as explained in section II D. It is observed from Fig. 7 that, the increase in viscosity with additive concentration is more significant at low temperatures and less influential at higher temperatures.

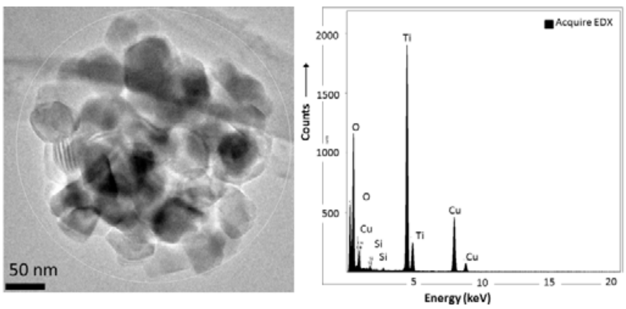

Fig. 6 TEM image of purchased TiO_2 nanoparticles along with EDX spectrum

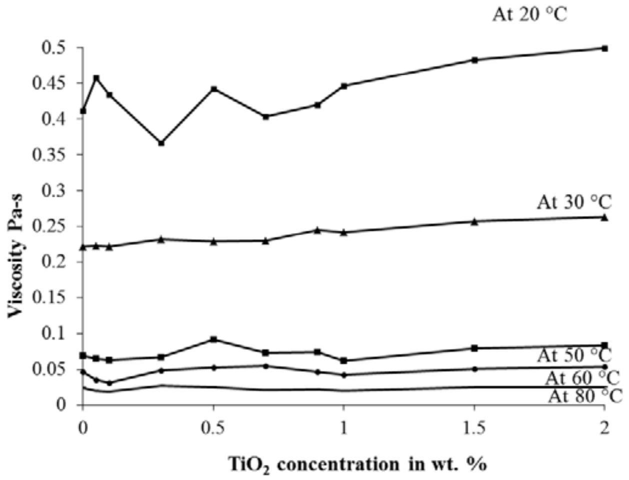

Fig. 7 Experimental shear viscosities at different TiO_2 concentrations and temperatures

The viscosity variation with additive concentration has been linearly modeled for various TiO_2 concentrations at 30 °C and the linear trend line is presented in Fig. 4. Even though the experimental viscosities exhibit scatter, linear trend line is in fairly good agreement with the measured viscosities.

The experimentally obtained viscosities are compared with simulated viscosities using the classical models described in Section I (1 to 3). The comparison is presented in Fig. 8.

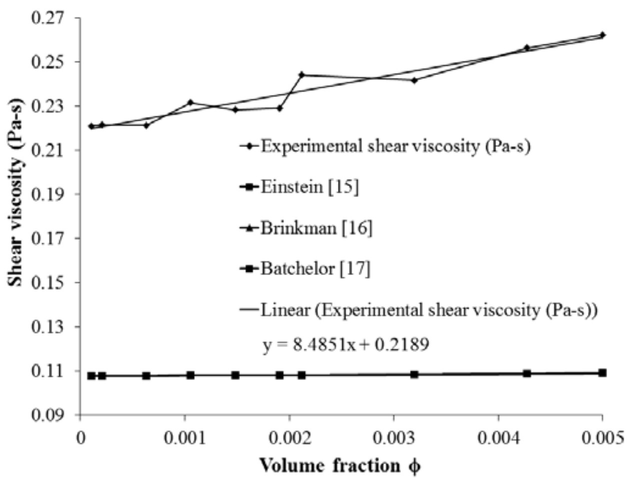

Fig. 8 Comparison of viscosity models with experimental viscosities

As seen in Fig. 8, classical viscosity models (1 to 3) are found to severely underpredict the viscosities for nanoparticle dispersions. At the low volume fractions of additives considered, the classical models show negligible variation in viscosity. Hence, this study uses the linear trend line (9) obtained for experimental viscosities to simulate viscosities of TiO_2 nanolubricant samples for hydrodynamic bearing analysis.

D.Hydrodynamic Pressure Profiles

Fig. 9 compares relative non-dimensional pressures at the bearing mid-plane for different additive concentrations. The ratio of non-dimensional pressure to maximum pressure was obtained for an eccentricity ratio of $\varepsilon = 0.7$ and additive concentrations ranging from 0.001 to 0.05.

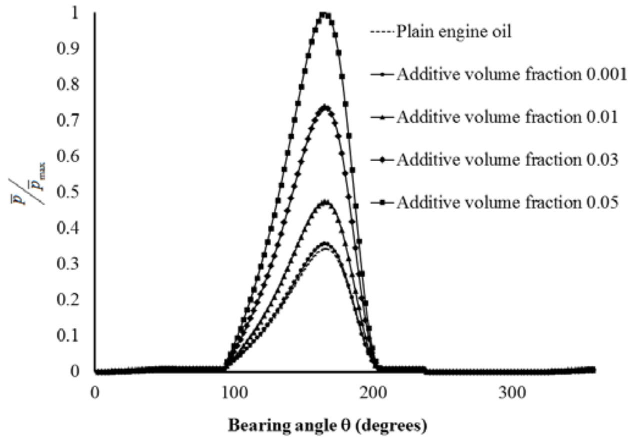

Fig. 9 Comparison of non-dimensional pressures for different TiO_2 nanoparticle concentrations at an eccentricity ratio of $\varepsilon = 0.7$

As seen in Fig. 9, the non-dimensional pressures increase with increasing TiO_2 nanoparticle concentrations. This increase in hydrodynamic pressures could be attributed to increase in viscosities of corresponding TiO_2 nanolubricant samples. Fig. 10 provides a comparison of resultant load carrying capacities for increasing TiO_2 nanoparticle concentrations.

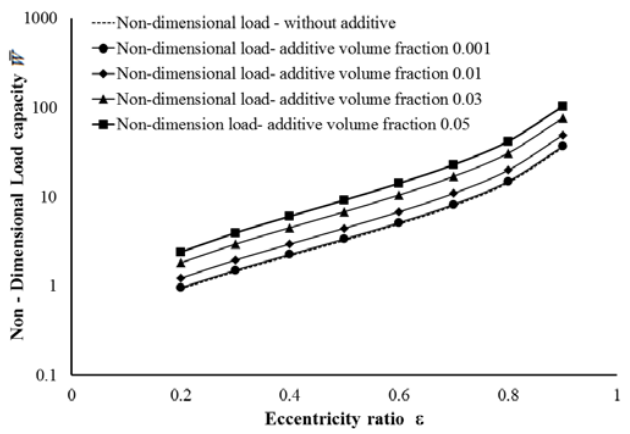

Fig. 10 Comparison of load carrying capacities at different TiO_2 nanoparticle concentrations at

As seen in Fig. 10, load carrying capacities increases with increasing TiO_2 nanoparticle concentrations. It is observed that for a very low additive volume fraction of 0.001, the load carrying capacity is found to increase by only 4%. However, at increasing additive volume fraction of 0.01, the load carrying capacity increases by 38% in comparison to plain engine oil.

The increase in hydrodynamic pressures and corresponding increase in load carrying capacity observed in Figs. 9 and 10 should however, be viewed in relation to viscosity variations with both, volume fractions and temperatures. As seen in Fig. 7, at high temperatures (> 80°C), the influence of nanoparticles on viscosity of base lubricant is negligible. This could mean that, at higher temperatures usually observed in journal bearings subject to continuous operation at high loads, the viscosity variations due to nanoparticle additive might not result in significant improvement in load carrying capacity. However, the presence of nanoparticles will definitely aid in improving load carrying capacity at lower temperatures, especially during start-up, where journal bearings usually experience surface contact and wear. The influence of particle size on viscosities and bearing performance also, needs to be studied.

V. Conclusion

A novel approach of studying the influence of nanoparticle lubricant additives on load carrying capacity of journal bearings is presented. The presence of 0.01 volume fraction of TiO_2 nanoparticles in engine oil was found to increase the load carrying capacity by 38%. However, this increase in load capacity should be experimentally validated. The effect of additive particle size on the bearing performance also needs to be investigated.

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Dr. Pai has published more than 100 research papers in Journals, International and National conferences. He has supervised 04 Ph.D. students in the area of Tribology Water Lubricated Bearings, Externally adjustable bearings and Tri-taper bearings and Tribology of machining metal matrix composites. He was a principal investigator for research projects by Philips, Bharat Heavy Electricals and GE JFWTC Global Research Centre, Bangalore. He has conducted more than 10 short courses in the field of Tribology. Currently he is heading Director-Research (Technical), Manipal University, Manipal.