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Dynamic Performance Characteristics of Finite Journal Bearings Operating on TiO_2 based Nanolubricants

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ABSTRACT

Dynamic stiffness and damping coefficients of a finite journal bearing operating on TiO_2 based nanolubricant are obtained using the linear perturbation approach. Time dependent version of governing Reynolds equation is modified to consider the couple stress effect of TiO_2 nanoparticle lubricant additives. The viscosity variation of lubricant with varying concentrations of nanoparticle additives is simulated using a modified Krieger-Dougherty model. The modified Reynolds equation is solved using linear perturbation approach to obtain the dynamic pressures and dynamic coefficients. Threshold stability maps are plotted depicting stable operating regions of journal bearing operating on TiO_2 nanolubricants. Results reveal an increase in stiffness and damping coefficients, and a corresponding improvement in whirl instability characteristics of journal bearings, with increase in TiO_2 nanoparticle concentration.

Keywords: Couple Stress Fluids, Dynamic Characteristics, Journal bearings, Nanofluids, TiO_2 nanoparticle additives, Viscosity model

INTRODUCTION

The severity of operating conditions on modern day support elements, such as, journal bearings, have promoted renewed interest in tribological research aimed at increasing the bearing's load carrying capacity. The inherent issue of whirl instability in fluid film bearings has also received great attention. Solution models generated over the years to address these issues could be generally categorized

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into two. Firstly, modifying the geometry of bearings and secondly, the use of lubricant additives to enhance the tribological properties of operating lubricants. The first approach has resulted in journal bearings with modified geometry, such as, externally adjustable pad bearings (Shenoy & Pai, 2009, 2010, 2011). The second approach has led to development of lubricants with chemical additives, which are activated at higher temperatures to generate sacrificial tribo-films to reduce friction and wear. However, stringent environment norms and the desire to develop additives, which are chemically stable and environment friendly, has led to researchers focusing on alternative additive technologies, such as, nanoparticles.

Chemically stable ceramic and metallic nanoparticles have found to function effectively as lubricant additives with significant increase in journal bearing load capacity (Li, Wang, Liu & Xue, 2006; Li, Zheng, Cao & Ma, 2011; Battez et al., 2007; Joly-Pottuz et al., 2008; Rico, Minondo & Cuervo, 2007; Peng et al., 2007; Peng, Kang, Hwang, Shyr & Chang, 2009; Mosleh, Atnafu, Belk & Nobles, 2009). Few theoretical studies have also shown an improvement in stability of journal bearings running on such nano-oils (Babu, Nair & Krishnan, 2012; Nair, Ahmed & Al-qahtani, 2009). However, a generalized theory to simulate the performance characteristics of journal bearings operating on nanoparticle additives is yet to be developed. Binu, Shenoy, Rao and Pai (2011) has presented an analytical model, which does consider additive concentrations, in modelling the static characteristics of journal bearings operating on engine oil dispersed with TiO_2 nanoparticles. This analytical model considers the couple stress effect of nanoparticle additives by using the nanoparticle size as the control parameter. The influence of nanoparticle additive concentration on viscosity of base fluid was integrated into the governing Reynolds equation using a modified Krieger-Dougherty viscosity model to simulate the viscosity variation.

Stability characteristics in journal bearings is important because the journal centre motion governs the oil film thickness and decides the operability of journal bearings for specific applications. Previous studies have reported improvement in journal bearing stability due to the presence of long chain polymer additives. These lubricants were characterized as couple stress fluids with the polymer molecule length of the additives being considered as couple stress factor. Binu et al. (2011) has reported an increase in the stability of journal bearings by conducting a non-linear transient analysis on journal bearings operating on couple stress fluids (Binu et al., 2011).

In this study, the analytical model developed by Binu et al. (2011) is used in studying the influence of TiO_2 nanoparticle additives on the dynamic characteristics of journal bearings. The governing Reynolds equation is modified to consider the variation in viscosities of nanolubricant samples due to varying nanoparticle concentration. The linear perturbation method is used to obtain the dynamic stiffness and damping characteristics. The influence of nanoparticle concentration on critical speeds and mass parameter of journal bearings are studied.

METHODS

Numerical Formulation

General governing equation. The governing equation for the analysis is the time-dependent form of Reynolds equation in two-dimensions for a couple stress fluid. The equation is expressed as shown below (Binu et al., 2011; Guha, 2004).

$$\frac{\partial}{\partial x}\left(f\left(h,d\right)\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(f\left(h,d\right)\frac{\partial p}{\partial z}\right)=6\mu U\frac{\partial h}{\partial x}+12\mu\frac{\partial h}{\partial t} \tag{1}$$

Where, $f(h,d)=h^3-12hd^2+24d^3\tanh\left(\frac{h}{2d}\right)$

The couple stress effect of nanoparticle additives on lubricant film thickness h is studied using standard couple stress parameter $d=\sqrt{\frac{\eta}{\mu_{bf}}}$. In the above equation, the size of nanoparticle additive is taken as the couple stress parameter with $[\eta]$ being the material property responsible for couple stresses and μ_{bf} being the viscosity of base lubricant.

The governing equation is obtained in dimensionless form using the following standard non-dimensional parameters (Binu et al., 2011; Guha, 2004).

$$\theta=\frac{x}{R};\ \overline{z}=\frac{z}{L};\ \overline{h}=\frac{h}{C};\ \overline{d}=\frac{d}{C};$$

$$\overline{t}=\omega t;\ \overline{p}=\frac{pC^2}{\mu\omega R^2};\ \overline{\mu}=\frac{\mu_{nf}}{\mu_{bf}};\ \lambda=\frac{L}{D}$$

The dimensionless form of equation-1 is written as:

$$\frac{\partial}{\partial\theta}\left(\overline{f}\left(\overline{h},\overline{d}\right)\frac{\partial\overline{p}}{\partial\theta}\right)+\frac{1}{4\lambda^2}\frac{\partial}{\partial\overline{z}}\left(\overline{f}\left(\overline{h},\overline{d}\right)\frac{\partial\overline{p}}{\partial\overline{z}}\right)=\ldots$$

$$\ldots 6\overline{\mu}\frac{\partial\overline{h}}{\partial\theta}+12\overline{\mu}\frac{\partial\overline{h}}{\partial\overline{t}} \tag{2}$$

Where, $\overline{f}(\overline{h},\overline{d})=\overline{h}^3-12\overline{d}^2\overline{h}+24\overline{d}^3\tanh\left(\frac{\overline{h}}{2\overline{d}}\right)$

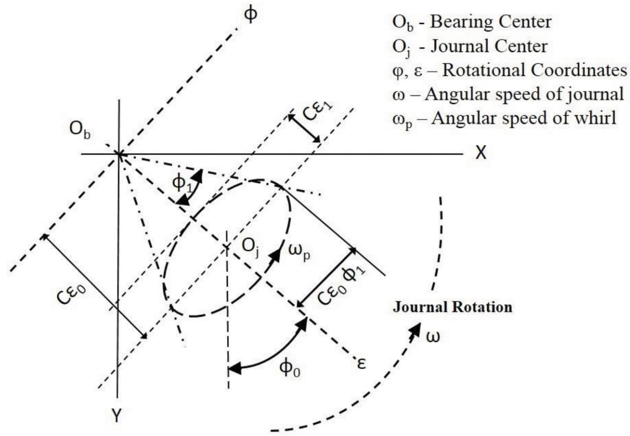

Figure 1. Rotational coordinate system

The rotational coordinate system for the journal centre is shown in Figure 1. Introducing the rotational coordinate system to equation (2), the governing non-dimensional form of Reynolds equation for dynamic analysis is presented below (Binu et al., 2011; Guha, 2004).

$$\frac{\partial}{\partial\theta}\left(\bar{f}\left(\bar{h},\bar{d}\right)\frac{\partial\bar{p}}{\partial\theta}\right)+\frac{1}{4\lambda^2}\frac{\partial}{\partial\bar{z}}\left(\bar{f}\left(\bar{h},\bar{d}\right)\frac{\partial\bar{p}}{\partial\bar{z}}\right)=\ldots$$

$$\ldots 6\bar{\mu}(1-2\dot{\phi})\frac{\partial\bar{h}}{\partial\theta}+12\bar{\mu}\frac{\partial\bar{h}}{\partial\bar{t}} \tag{3}$$

Where, $\bar{f}(\bar{h},\bar{d}) = \bar{h}^3 - 12\bar{d}^2\bar{h} + 24\bar{d}^3 \tanh\left(\frac{\bar{h}}{2\bar{d}}\right)$

Dynamic journal Bearing Characteristics. By considering small harmonic whirling of the journal centre within the bearing with whirl frequency ω_p, the instantaneous location of the journal centre is expressed using the equations provided below.

$$\varepsilon = \varepsilon_0 + \varepsilon_1 e^{i\Omega\bar{t}}$$
$$\phi = \phi_0 + \phi_1 e^{i\Omega\bar{t}} \tag{4}$$

For the first order perturbation, the corresponding film pressure and film thickness can be expressed in non-dimensional form as:

$$\bar{p} = \bar{p}_0 + \left(\varepsilon_1\bar{p}_\varepsilon + \varepsilon_0\phi_1\bar{p}_\phi\right)e^{i\Omega\bar{t}}$$
$$\bar{h} = \bar{h}_0 + \left(\varepsilon_1\cos\theta + \varepsilon_0\phi_1\sin\theta\right)e^{i\Omega\bar{t}} \tag{5}$$

In the above equation (4), $\overline{p}_0$ is the steady state pressure; $\overline{p}_\varepsilon$ and $\overline{p}_\phi$ are the perturbed pressures and $\Omega = \dfrac{\omega_p}{\omega}$ is the whirl frequency ratio.

Performing an order analysis as explained in Guha, (2004), Majumdar, Pai and Hargreaves (2004) and Lahmar (2005), the non-dimensional stiffness and damping coefficients are computed as shown below.

$$\begin{bmatrix} Z_{\varepsilon\varepsilon} & Z_{\varepsilon\phi} \\ Z_{\phi\varepsilon} & Z_{\phi\phi} \end{bmatrix}^T = -\int_0^{2\pi}\int_0^1 \begin{Bmatrix} \overline{p}_\varepsilon \\ \overline{p}_\phi \end{Bmatrix} \times (\cos\theta : \sin\theta)\, d\overline{z}\, d\theta \tag{6}$$

Where, $Z_{i,j} = A_{i,j} + i\,\Omega\, B_{i,j}$ and $(i, j) = (\varepsilon, \phi)$.

The non-dimensional stiffness and damping coefficients are presented below (Lahmar, 2005).

$$\overline{K}_{\varepsilon\varepsilon} = \mathrm{Real}\left(Z_{\varepsilon\varepsilon}\right) = -\mathrm{Re}\int_0^{2\pi}\int_0^1 \overline{p}_\varepsilon \cos\theta\, d\overline{z}\, d\theta;$$

$$\overline{K}_{\phi\varepsilon} = \mathrm{Real}\left(Z_{\phi\varepsilon}\right) = -\mathrm{Re}\int_0^{2\pi}\int_0^1 \overline{p}_\varepsilon \sin\theta\, d\overline{z}\, d\theta;$$

$$\overline{K}_{\varepsilon\phi} = \mathrm{Real}\left(Z_{\varepsilon\phi}\right) = -\mathrm{Re}\int_0^{2\pi}\int_0^1 \overline{p}_\phi \cos\theta\, d\overline{z}\, d\theta;$$

$$\overline{K}_{\phi\phi} = \mathrm{Real}\left(Z_{\phi\phi}\right) = -\mathrm{Re}\int_0^{2\pi}\int_0^1 \overline{p}_\phi \sin\theta\, d\overline{z}\, d\theta; \tag{7}$$

$$\overline{D}_{\varepsilon\varepsilon} = \mathrm{imag}\left(Z_{\varepsilon\varepsilon}\right) = -\mathrm{Im}\int_0^{2\pi}\int_0^1 \overline{p}_\varepsilon \cos\theta\, d\overline{z}\, d\theta;$$

$$\overline{D}_{\phi\varepsilon} = \mathrm{imag}\left(Z_{\phi\varepsilon}\right) = -\mathrm{Im}\int_0^{2\pi}\int_0^1 \overline{p}_\varepsilon \sin\theta\, d\overline{z}\, d\theta;$$

$$\overline{D}_{\varepsilon\phi} = \mathrm{imag}\left(Z_{\varepsilon\phi}\right) = -\mathrm{Im}\int_0^{2\pi}\int_0^1 \overline{p}_\phi \cos\theta\, d\overline{z}\, d\theta;$$

$$\overline{D}_{\phi\phi} = \mathrm{imag}\left(Z_{\phi\phi}\right) = -\mathrm{Im}\int_0^{2\pi}\int_0^1 \overline{p}_\phi \sin\theta\, d\overline{z}\, d\theta; \tag{8}$$

Stability parameters. The stability of journal bearings is then analysed using the stiffness and damping coefficients obtained in section B (Majumdar et al., 2004; Lahmar, 2005).

At the threshold of stability, the critical mass $\overline{M}_c$ and whirl ratio Ω_{cr} are expressed as (Lahmar, 2005):

$$\overline{M}_c = \frac{M_c \omega^2 C}{W_0} = \frac{A_{eq}}{\Omega^2_{cr}}$$

$$\Omega^2_{cr} = \left(\frac{\omega_p}{\omega}\right)^2 = \frac{\left(\overline{K}_{XX} - A_{eq}\right)\left(\overline{K}_{YY} - A_{eq}\right) - \overline{K}_{XY}\overline{K}_{YX}}{D_{XX}D_{YY} - D_{XY}D_{YX}} \tag{9}$$

Where, $A_{eq} = \dfrac{\overline{K}_{XX}\overline{D}_{YY} + \overline{K}_{YY}\overline{D}_{XX} - \overline{K}_{XY}\overline{D}_{YX} - \overline{K}_{YX}\overline{D}_{XY}}{\overline{D}_{XX} + \overline{D}_{YY}}$

The non-dimensional threshold speed of the rotor is then expressed as (Lahmar, 2005):

$$\overline{\omega}_{cr} = \omega_c \sqrt{\frac{M_c C}{W_0}} = \sqrt{\overline{M}_c} \tag{10}$$

Therefore, a journal bearing system is asymptotically stable when the journal mass c is less than $\overline{M}_c$. Likewise, a system is asymptotically stable when the operating speed of the rotor is less than $\overline{\omega}_{cr}$. A negative value of $\overline{M}_c$ means that the journal will always be stable for all values of journal mass $\overline{M}_c$. Similarly, a negative value of Ω_c^2 implies the absence of whirl (Lahmar, 2005).

Viscosity Model

Adding TiO_2 nanoparticles to engine oil is found to increase the viscosity of lubricant samples. The authors of this current paper have reported in a previously published study (Binu, Shenoy, Rao & Pai, 2014), the suitability of a modified Krieger-Dougherty viscosity model in simulating the dynamic viscosities of engine oil samples dispersed with TiO_2 nanoparticles. The study reports good agreement of experimental viscosities obtained using a rheometer with theoretical viscosities simulated using modified Krieger-Dougherty viscosity model. The modified Krieger-Dougherty viscosity model also considers the nanoparticle packing fraction, which is the ratio of aggregate particle size to the primary particle size. TiO_2 nanoparticle dispersions in engine oil showed an aggregate particle size distribution of 777 nm in the DLS particle size analysis that was performed and reported in the publication by Binu et al. (2014). The TiO_2 nanoparticles used in the study were of 100 nm primary particle size.

Therefore, the relative viscosities $\overline{\mu}$ of TiO_2 dispersions in engine oil simulated using modified Krieger-Dougherty equation is expressed as (Binu et al., 2014):

$$\overline{\mu} = \frac{\mu_{nf}}{\mu_{bf}} = \left(1 - \frac{\phi_a}{\phi_m}\right)^{-2.5\phi_m} \tag{11}$$

In which, the packing fraction is obtained as:

$$\phi_a = \phi\left(\frac{a_a}{a}\right)^{3-D} \tag{12}$$

a_a and a are the aggregate and primary particle size respectively. D is the fractal index having a typical value of 1.8 for nanofluids (Binu et al., 2014).

RESULTS AND DISCUSSIONS

The modified Reynolds equation (2), presented in section II of this paper, incorporates parameters which enable us to study the influence of TiO_2 nanoparticle concentration on dynamic bearing characteristics. The relative viscosity term $\overline{\mu}$, computed using the modified Krieger-Dougherty equation (11), integrates the effects of TiO_2 nanoparticle additive concentration on the dynamic characteristics of journal bearings.

The computational code developed for the analysis is validated by comparing the values of stiffness and damping coefficients with previously published results by Guha (2004). For Newtonian fluids $(\overline{d} = 0)$, the stiffness and damping coefficients obtained for increasing eccentricity ratio using the developed code is shown in Figure 2 and Figure 3. The dynamic coefficients are found to be in good agreement with the values presented in Guha (2004).

Upon validating the computational code, dynamic coefficients are computed for different values of nanoparticle concentrations. Table-1 provides the values of various operating parameters used in the analysis.

Table 1
Operating parameters

Bearing Details
L/D Ratio: 1.0 Bearing Angle: θ = 360° Full Bearing Bearing Type: Plain Compliant Bearing Bearing Clearance: 25 *microns*
Lubricant Details
Type: Couple stress fluid Additives: TiO_2 nanoparticles Couple stress parameter: $\overline{d} = \frac{d}{C} = 0.03108$ corresponding to aggregate nanoparticle size of 777 nm and bearing clearance of 25 microns. TiO_2 nanoparticle concentrations: ϕ = 0.001, 0.005, 0.01, 0.02

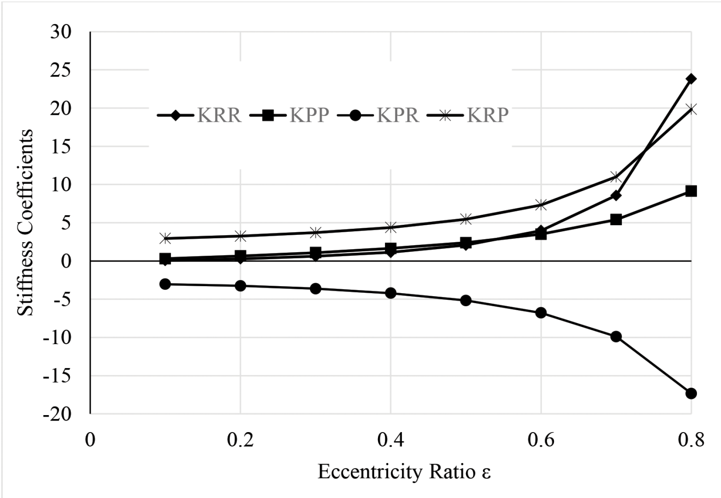

Figure 2. Stiffness Coefficients for Newtonian Lubricant $\overline{d} = 0$

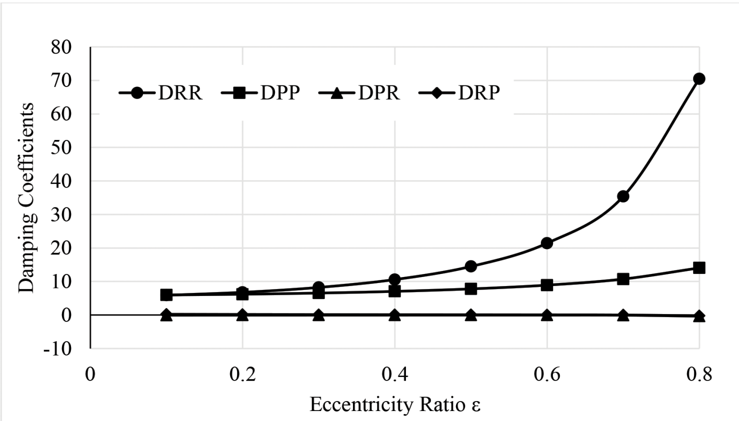

Figure 3. Damping Coefficients for Newtonian Lubricant $\overline{d} = 0$

The validated computational code was then used to obtain the dynamic characteristics of journal bearings operating on TiO_2 nanolubricants at different TiO_2 nanoparticle concentrations. Figure 4 and Figure 5 provides the variation in dynamic coefficients of TiO_2 nanoparticle dispersions of aggregate particle size 777 nm, which results in a couple stress parameter of 0.03108, with TiO_2 additive concentrations varying from 0.001 to 0.02. Results reveal an increase in dynamic coefficients with increasing nanoparticle additive concentrations.

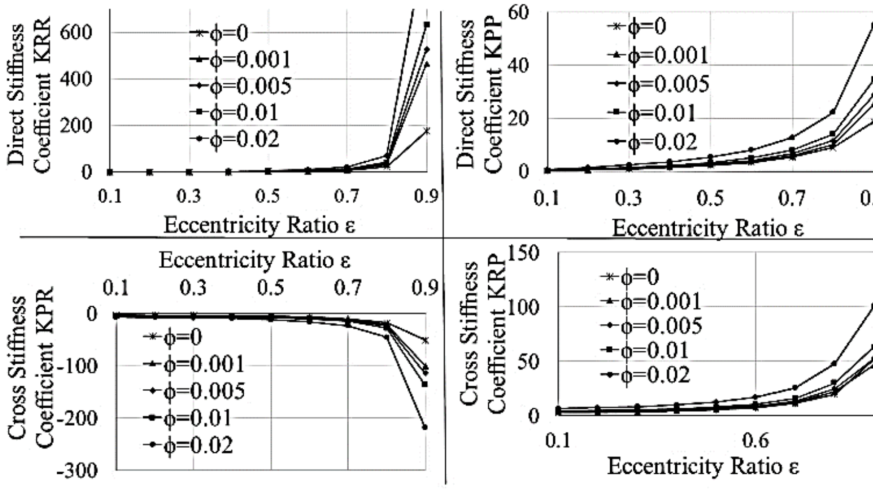

Figure 4. Stiffness coefficients at couple stress parameter $\overline{d} = 0.03108$ (aggregate TiO_2 particle size of 777 nm) for varying TiO_2 volume fractions

The increment in stiffness and damping coefficients with TiO_2 nanoparticle concentration is discussed below.

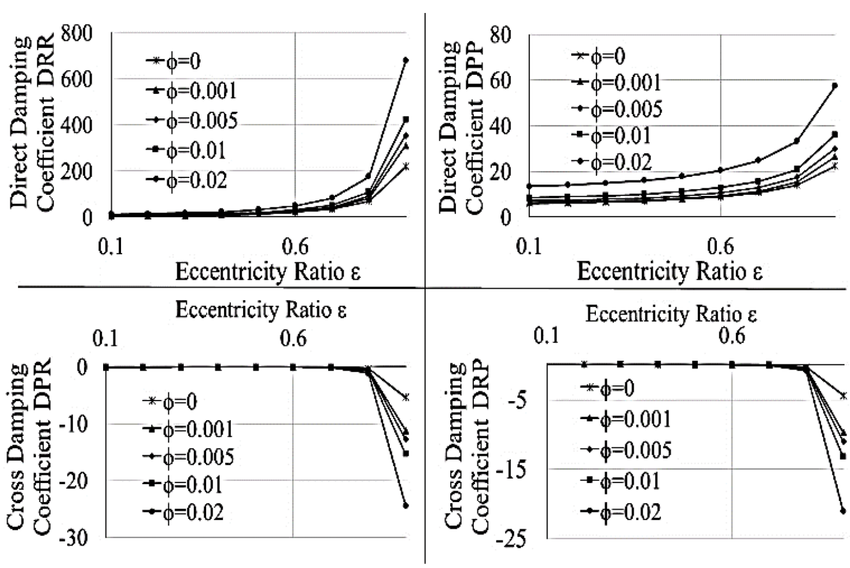

Figure 5. Damping coefficients at couple stress parameter $\overline{d} = 0.03108$ (aggregate TiO_2 particle size of 777 nm) for varying TiO_2 volume fractions

As observed in Figure 4 and Figure 5, the stiffness coefficients are considerably higher for nano lubricants in comparison to plain oil. This increase in stiffness coefficients being more prominent at higher eccentricities. A similar observation was also obtained for damping coefficients. When the TiO_2 nanoparticle size is kept constant at 777 nm and is added at a volume fraction of 0.001, the cross stiffness KRP is found to increase by 10% in comparison to plain oil.

The results also help us to understand the influence of volume fraction on the dynamic coefficients. Considering the cross-stiffness coefficient KRP at an eccentricity ratio of 0.8, it is observed that adding TiO_2 nanoparticle additives of aggregate size 777 nm (corresponding to $\overline{d} = 0.03108$), at a volume fraction ϕ=0.01, will increase the cross stiffness by 51% in comparison to plain oil. This increase in cross stiffness is more pronounced when TiO_2 nanoparticles are added at higher volume fractions.

Addition of 0.01 and 0.02 volume fractions increases the cross-stiffness parameter KRP by 51% and 140% respectively. However, it has to be mentioned that higher particle sizes and volume fractions will change the flow behavior and physical interactions of the particles leading to quicker sedimentation. Optimum values of TiO_2 nanoparticle sizes and volume fractions for acceptable dispersion stability has to be determined. Experimentation to determine optimum values are necessary. It also needs to be mentioned that, considering the changes in viscosity due to temperature variation will also provide a more accurate picture. The viscosity variations dealt with in this study does not account for the temperature variation prevalent in bearing area for high load and high speed applications. Hence a thermo hydrodynamic analysis of dynamic characteristics will offer more insights.

Influence of TiO_2 nanoparticle concentration on whirl instability of journal bearings is studied and presented below. The stability parameters comprising critical mass parameter, critical threshold speed (angular), and whirl ratio are computed and their variation with concentration of TiO_2 nanoparticle additives are studied.

Influence of TiO_2 nanoparticle concentration of a constant particle size of 777 nm on critical mass parameter $\overline{M}_{cr}$ is studied and the results are shown in Figure 6. As seen in Figure 6, stability of journal bearing systems is found to improve with addition of TiO_2 nanoparticles at increasing concentrations. The increase in stability is more prominent at eccentricity ratio more than 0.5.

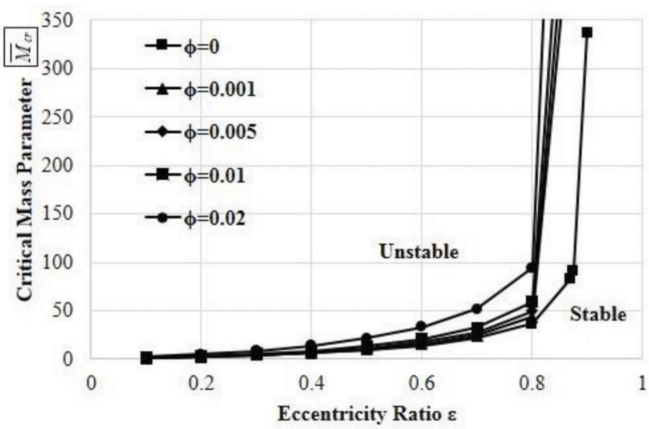

Figure 6. Variation in Critical Mass Parameter with nanoparticle volume fraction ϕ at constant couple stress parameter $\overline{d} = 0.03108$

Improvement in stability of journal bearing system as seen in Figure 6 is further analysed by plotting the threshold stability maps for varying nanoparticle concentrations.

The threshold stability map for varying TiO_2 nanoparticle concentrations at a constant particle size of 777 nm is shown in Figure 7.

The improvement in stability of journal bearing system due to the addition of TiO_2 nanoparticles at higher eccentricities is evident in threshold stability map Figure 7. This fact can also be seen in Figure 8, which shows the variation of critical whirl ratio for various TiO_2 nanoparticle concentrations.

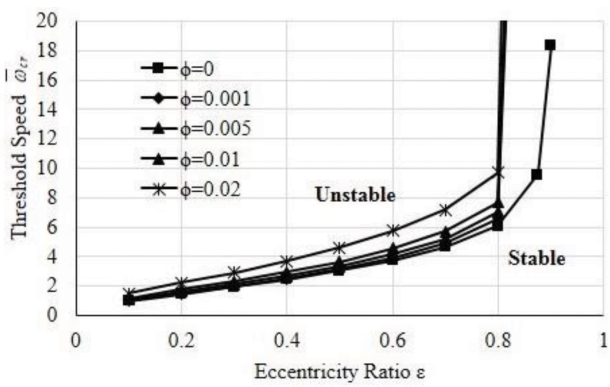

Figure 7. Threshold stability map for varying TiO_2 volume fractions at $\overline{d} = 0.03108$

Reason for pronounced influence of TiO_2 nanoparticle additives on stability characteristics of journal bearings at higher eccentricities can be attributed to comparable nanoparticle size and film thickness at higher eccentricities. Reduced film thickness associated with higher eccentricities could permit increased physical interactions between particles and between particles and surfaces, resulting in pronounced damping coefficients. However, its true influence will also be greatly influenced by dispersion stability and temperature reduction of oil film viscosity.

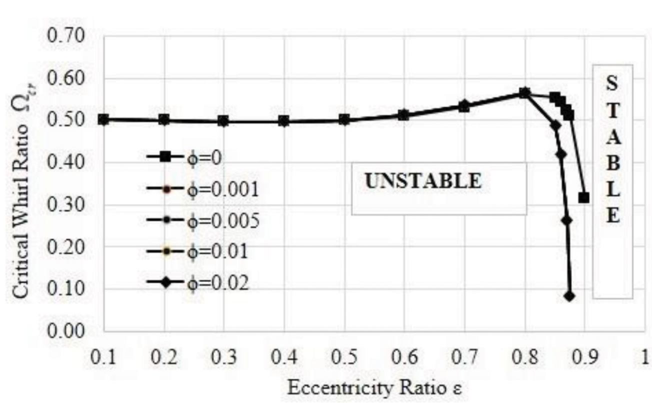

Figure 8. Critical whirl ratio for varying TiO_2 volume fractions at $\overline{d} = 0.03108$

As observed in Figure 8, there is negligible change in critical whirl ratio with increasing nanoparticle concentrations. However, Figure 7 shows that the threshold speed of journal bearing system is increasing with TiO_2 volume fractions. Therefore, even though the whirl ratio does not reveal significant variation with volume fraction, there is a significant reduction in unstable operating region at higher eccentricities due to the addition of nanoparticle additives.

Threshold stability maps and whirl ratio variation shown in Figure 7 and Figure 8 reveals that, the presence of TiO_2 nanoparticle additives clearly demonstrates an increase in stable operating region of journal bearing systems.

CONCLUSIONS

In this study, dynamic characteristics of journal bearing systems operating on TiO_2 nanoparticle dispersions in engine oil was obtained using linear perturbation approach. A modified Reynolds equation was developed integrating the influence of TiO_2 nanoparticle additive concentration on the dynamic characteristics of journal bearing systems. The results reveal a significant increase in stiffness and damping coefficients of journal bearing system due to the addition of nanoparticle additives. The threshold stability maps reveal an increase in stable operating region due to the volume fraction influence of TiO_2 nanoparticle additives. Results also reveal the influence of nanoparticle additives in stability is more relevant at higher eccentricities experienced during heavy-load and high-speed operations.

Further experimental studies focused on nanoparticle interaction within the oil film and the temperature influence on viscosity will generate more insights into the functioning of nanoparticle additives.

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NOMENCLATURE

a	Radii of primary TiO_2 nanoparticles (nm)
a_a	Radii of aggregate TiO_2 nanoparticles (nm)
C	Bearing clearance (mm)
D	Fractal Index
D_{xx}	Damping coefficients
d	Couple stress parameter
$\bar{d}$	Non-dimensional couple stress parameter
e	Eccentricity (m)
h	Film thickness (m)
$\bar{h}$	Non-dimensional film thickness
K_{xx}	Stiffness coefficients
L	Bearing length (m)
M	Mass parameter
M_c	Critical mass parameter
p	Hydrodynamic film pressure (N/m$^{2)}$)
$\bar{}$	Non-dimensional Hydrodynamic film pressure
t	Time (s)
$\bar{t}$	Non-dimensional time
U	Tangential velocity of journal (m/s)
W_0	Static load capacity
x	Circumferential bearing coordinates
z	Axial bearing coordinates
μ_{bf}	Viscosity of base fluid
μ_{nf}	Viscosity of nanofluids
$\bar{\mu}$	Relative viscosity
ϕ	Nanoparticle volume fraction
ϕ_a	Effective volume fraction
ϕ_m	Maximum particle packing fraction
ε	Eccentricity ratio
θ	Angular coordinates (rad)
ω	Angular velocity (rad/s)
ω_{cr}	Critical threshold speed
ω_p	Journal whirl speed
$[\eta]$	Intrinsic velocity
η	Material constant (couple stress)
Ω	Whirl ratio
Ω_{cr}	Critical Whirl ratio