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Dynamic Effect of the Nano-Lubricant Oil on the Performance of Rotating Systems

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Abstract

The influence of adding nanoparticles to lubricating oils on the dynamic parameters of bearings, as well as their effect on the response of the rotor and its critical speedhas been investigated. The modified lubrication oil viscosity due to adding nanoparticles additives to the lubricant oil is used to calculate the lubrication oil pressure, reaction forces and dynamic coefficients of journal bearing theoretically based on the solution of the Reynold equation. The computational fluid dynamics (CFD) fluent Ansys software is used to verify the theoretical results. The results show that the lubrication oil pressure is increased with the increase of nanoparticles volume fraction as well as aggregate fraction up to the angular position130°, then is decreased with the increasing of both the volume fraction and aggregate fraction. Generally, the bearing dynamic coefficients (stiffness and damping) have been improved.The rotor dynamic response is decreased with the rising of both volume ratioand aggregate ratiofractions while, the adding nanoparticles has no effect on the rotor critical speed.

Keywords : Computationalfluid dynamics (CFD), dynamic response, Dynamic Coefficients

1 Introduction

The dynamic stiffness and damping of the journal bearing are depend on the pressure that initiates in the bearing due to the existence of oil in the bearing clearance. The journal bearing dynamic coefficients under use of the lubricant oil with nanoparticles can be determinedby theoretically based on the Reynolds equation with take into account the nano-lubricant viscosity.

The minimumoil film thickness as well as load-carrying capacity of the bearings can be improved by adding nanoparticles additives [1]. The bearing load carrying capacity is increased remarkably by addingsome types of nanoparticle as lubricant additive such as TiO2 [2]. The load capacity for different bearing types can be improved with use of nanoparticles additives [3]. The increasing of concentration of nanoparticles in the lubricant oil is caused high friction coefficient, high viscosity and high lubrication oil pressure as well as it increases the load carrying capacity [4].The using of nanoparticle additives aredecreased the dynamic coefficients ofthe worn bearings [5]. The increasing of the concentration of some nanoparticlesuch as TiO2 increases the dynamic coefficients as well as improves the instability of the journal bearings operation [6]. The adding of nanoparticlestothe lubricant oil will increasethe bearing damping ratioas well asimproving their stiffness [7]. The presence of nanoparticles in the lubricant oil restricts the decreasing of lubricantviscosity withthe temperature increasing thus, the performance of the journal bearings is improved [8]. The load carrying capacity of the two-lobe journal bearings is considerably increased while the friction variable is decreasing [9]. The performance of system with the elliptical bearings is more improvedthan the system performance with plain journal bearings when using the same nanolubricants as lubricant oil additives [10]. The three-lobe journal bearings dynamic parameters like load-carrying capacity and nondimensional flow coefficient are considerably rising by adding nanoparticles additives while the friction variable is decreasing as well as the dynamic coefficients are significantly improving [11]. Generally, the use of lubricants oils that containing the nanoparticle type TiO2 as additives is enhanced the static featuresand performance of the different types of the lobe journal bearings (two, three, and four) [12].

Themain objectives of thisresearchareinvestigating the effect of adda nanoparticles to thelubricant oils on the bearing dynamic coefficients (stiffness and damping) as well as their effect on the critical spin speed and the dynamical response of the rotating parts

2 Hydrodynamic BearingsDynamic Coefficients

The journal bearing dynamic coefficients calculationsare based on the reaction forces of the lubricant oil. The dynamic cofficients can be found as following;

$$K_{ab} = \frac{\partial F_a}{\partial b} \quad ; \quad C_{ab} = \frac{\partial F_a}{\partial \dot{b}} \quad ; \quad ab = x, y \qquad (1)$$

Where, (F_x, F_y), are the hydrodynamic reaction forces which supported journal. The hydrodynamic journal bearings have four stiffness and four daming coefficients, where there are four parameters are direct parameters and four parameters are cross coupled-parameters as illustrated in Fig.1.

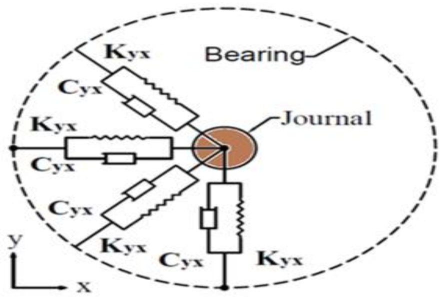

Fig 1. Dynamic coefficients of fluid film journal bearings

Where, $K_{xy} = \partial F_x / \partial y$is a stiffness coefficient that result of the change in the reaction force (F_x) in the x-direction with respect to the displacement in the y-direction and $K_{yx} = \partial F_y / \partial x$is a stiffness coefficient that result of the change in the reaction force (F_y) in the y-direction with respect to the displacement in the x-direction and the other coefficients are in the same way can be calculated.

The hydrodynamic pressure distribution of journal bearings due to use nano-lubricant can be calculated theoretically by solvethe Reynolds equation as following, [13]

$$\frac{\partial}{\partial z}\left(\frac{h^3}{12\mu_{nf}}\frac{\partial P}{\partial z}\right) = \frac{\partial h}{\partial t} + \frac{\Omega}{2}\frac{\partial h}{\partial \theta} \qquad (2)$$

Where;$p,\ \mu_{\mathrm{nf}}, h$, are the pressure, viscosityand thicknessof the nano-lubricant respectively.

The lubricant oil reaction forces can be calculated using the direct Integration for the lubricant oil pressure in Eq.(2)along the bearing length and bearing angular direction as following [14];

$$\begin{bmatrix} F_r \\ F_t \end{bmatrix} = \int_{-L/2}^{L/2}\int_0^{2\pi} P(\theta, z, t) \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} R d\theta dz \qquad (3)$$

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \int_{-L/2}^{L/2}\int_0^{2\pi} P(\phi, z, t) \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix} R d\phi dz \qquad (4)$$

Where; ϕ, θ, as in Fig.2.

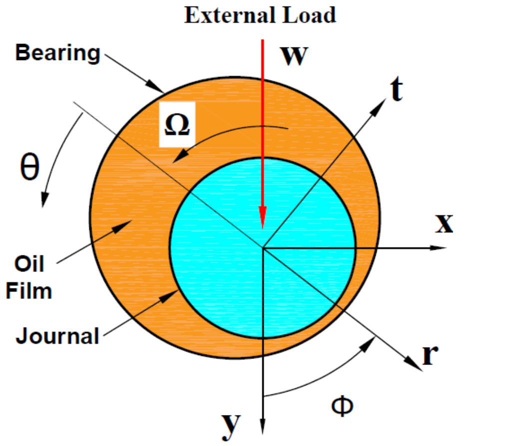

Fig 2. Journal bearing model

3 Nano-lubricant oil viscosity

There are many mathematical formulas to calculate the nano-lubricant oils viscosity but the more convenient one is a modified Krieger and Dougherty equation [7]

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{f}}\left(1 - \frac{\emptyset_a}{\emptyset_m}\right)^{-\eta\emptyset_m} \quad \emptyset_a = \emptyset\left(\frac{a_a}{a}\right)^{3-D} \qquad (5)$$

Where $\emptyset$ is the nanoparticle volume concentricity,$\emptyset_m$ is the maximum concentricityof nanoparticles wherethe oil flow can be occurred and it 0.605 for the high oil shear rate. η is the oil substantial viscosity and its value 2.5. D is 1.8, [15], the Eq.(3) can be rewritten as follows

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{f}}\left(1 - \frac{\emptyset}{0.605}\left(\frac{a_a}{a}\right)^{1.2}\right)^{-1.5125} \qquad (6)$$

Where (a_a) the nanoparticles effective aggregates radius and (a) the primary nanoparticles radius, see Fig. 3.

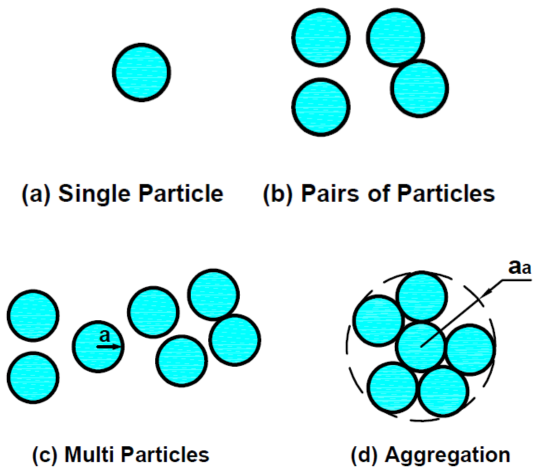

Fig 3. Schematic illustrations of nanoparticles additives

The dynamical coefficients fortheNano-lubricated bearings are analyticallydeterminedby using Eq.(1) after calculate the nano-lubricant viscosityusing Eq.(6) and substitute its value in Eq.(4) to calculate the reaction forces.

4 Rotor dynamic response and critical speed

The rotor bearings arrangement which adopted in present study is as in Fig,4.

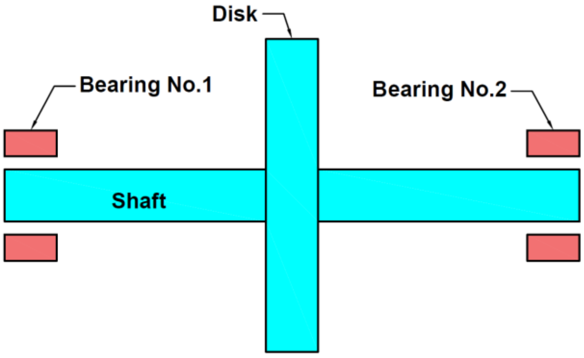

Fig 4. Rotor Bearings model

The rotor dynamic response can be calculatedvia solve the equation of motion of the rotor model that shown in Fig,4

$M\ddot{x} + K(x_R - x_b) = me\Omega^2 \cos \Omega t$ (7)

$M\ddot{y} + K(y_R - y_b) = me\Omega^2 \sin \Omega t$(8)

Where (x_R) and (y_R); the disk center location, (x_b) and $(y_b)$the journal center location. $(me\Omega^2 \cos \Omega t\ , me\Omega^2 \sin \Omega t)$ The unbalance force components, (e)unbalance masseccentricity; (M) the disk mass, (K) the rotor shaft stiffness. The equation of motion can be solve as following;

$K(x_R - x_b) = 2F_x$ (9)

$K(y_R - y_b) = 2F_y$ (10)

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} x_b \\ y_b \end{Bmatrix} + \begin{bmatrix} C_{xx} & C_{xy} \\ C_{yx} & C_{yy} \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{y}_b \end{Bmatrix}$$

The solution of Eq.(9) and Eq.(10) are as follows;

$$x_R = Ae^{i\Omega t} + Be^{-i\Omega t} y_R = Ce^{i\Omega t} + De^{-i\Omega t}$$

The rotor dynamic response under the unbalance mass is;

$r = x_R + iy_R = (A + iC)e^{i\Omega t} + (B+iD)e^{-i\Omega t}$

$r = r_f e^{i\Omega t} + r_b e^{-i\Omega t}$ (11)

$r_f = (A + iC) r_b = (B + iD)$

Where, $r_f$and r_b are the forward andbackward whirl radii respectively.

The maximum rotor dynamical response is equal to the large radius of the rotororbital path at the disk center.

$|r|_{maj} = |r_f| + |r_b| |r|_{min} = |r_f| - |r_b|$ (12)

Therotor critical spin speed is speed of the rotor at the maximum response.

5 Results and discussion

The mechanical propertiesof the rotor bearing system which used in present study are asin Table 1 and Table 2

Table 1: Mechanical specifications of rotor

Rotor Length mm	Rotor Dia. mm	Disk Dia. mm	Disk Thickness mm	Unbalance Mass Kg	Mass Eccentricity mm
1200	40	700	40	$5\text{x}10^{-3}$	350

The rotor material has density (7850 Kg/m^3) and modulus of elasticity (2.1x10^{11})

Table 2: Mechanical Specifications of Bearings

Bearing Length mm	Bearing Diameter mm	Radial Clearance mm	Lubricant Viscosity Pa.s
20	40	0.04	0.032

The use of nanoparticle with the lubricant oils is increased the viscosity ratio ($\mu_{\mathrm{nf}}/\mu_{\mathrm{f}}$) with the increasing of the volume fraction ($\emptyset$) for different nanoparticles aggregate fractions ($\frac{a_a}{a}$), as in Fig.5, also the viscosity ratio is increased with the increasing of the aggregate fractions for different nanoparticles volume fractions as in Fig.6.

The CFD fluent Ansys software is used to prove the theoretical results at rotor speed 1500 rpm, eccentricity ratio 0.6 and volume fraction ($\emptyset = 0.02$).

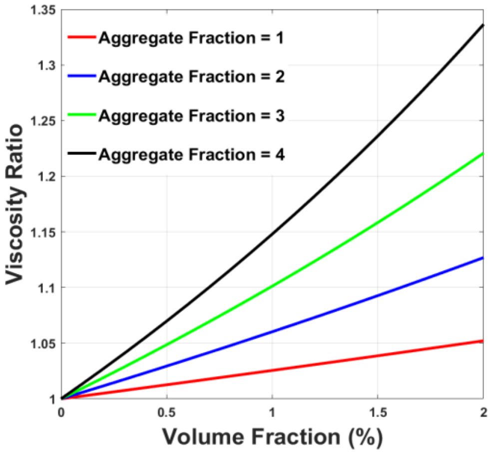

Fig 5. Viscosity ratio for different volume fractions

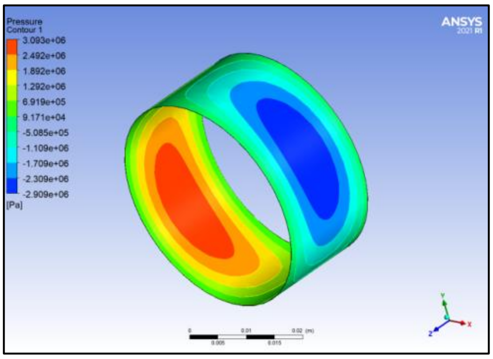

Fig 6. Viscosity ratio for different Aggregate fractions

The CFD pressure distribution shown in Fig.7 for aggregate fraction 2 and Fig.8 for aggregate fraction 6 have been compared with the analytical pressure distribution shown in Fig.9 and Fig.10 for aggregate fraction 2 and 6. The comparison results are clearly identical with different percentage less than 7% , therefore the using of the theoretical method to investigate the effect of adding the nanoparticles to lubricant oil can be adopted.

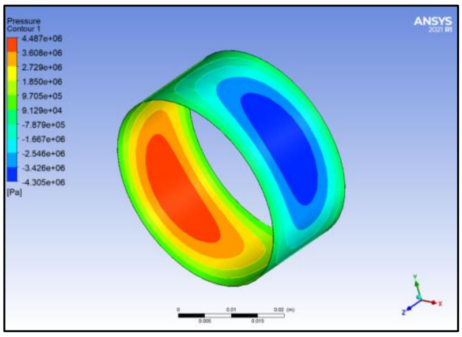

Fig 7. CFD Pressure distribution, Aggregation=2

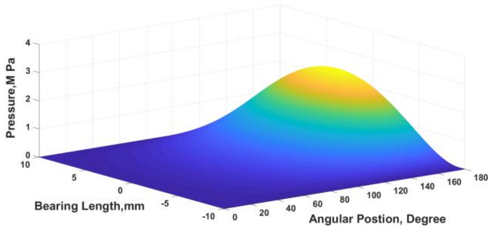

Fig8.CFD Pressure distribution, Aggregation=6

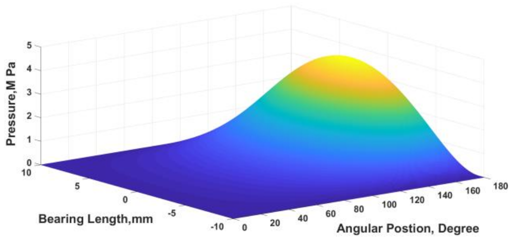

Fig 9. Theoretical Pressure distribution, Aggregation = 2

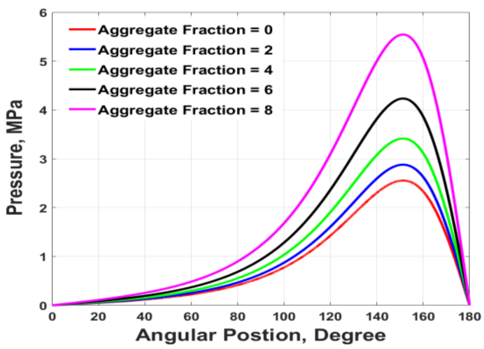

Fig 10. Theoretical Pressure distribution, Aggregation = 6

The nano-lubricant oil pressure is increased with the increasing of the aggregate fractions and the nanoparticles volume fractions up to 130^{o} then isdecreased with the increasing of the aggregate fractionsas in Fig.11. The same thing can be said about the pressure distribution with different nanoparticles volume fractions as in Fig.12.

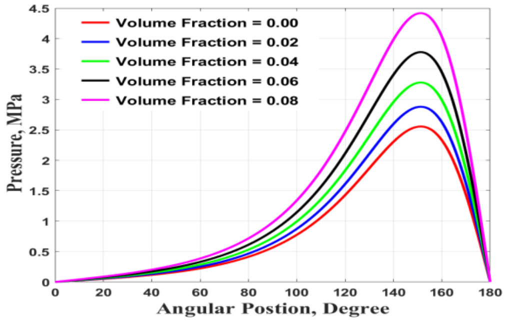

Fig.11. Oil pressure for different aggregate fractions

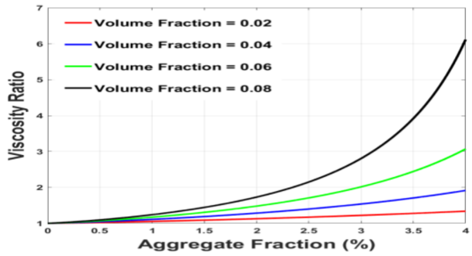

Fig.12. Oil pressure for different volume fractions

The dynamic coefficients are varied with rotor speed as shown in semilog Fig.13 and Fig,14, where the dashed line is the negative values of the coefficients. The coefficients (stiffness and damping) are approximately have constant valuesfor all rotor speed range except the cross-coupling stiffness (K_{xy})has negative value with rotor speed less than 1000 rpm then becomes positive and has approximately constant value at rotor speed about 1500 rpm in Fig.9 and Fig.14.

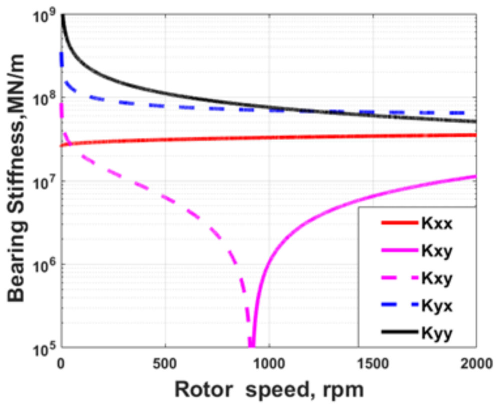

Fig.13. Journal bearing stiffness

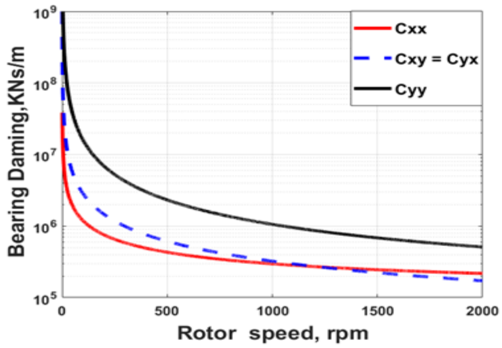

Fig.14. Journal bearing damping

Generally, the bearing dynamic coefficients(K_{xx} , K_{xy} , C_{xx} , C_{yy}) are increasing with the aggregate fractionincreasing as shown in Fig.15 and Fig.16 respectively while the direct stiffness (K_{yy}) and the cross-coupling damping ($C_{xy} = C_{yx}$) slightly decrease with the increasing in the aggregate fraction. The cross-coupling stiffness (K_{yx}) is has constant value up to 4 aggregate fraction then starts decrease with the increasing in the aggregate value.

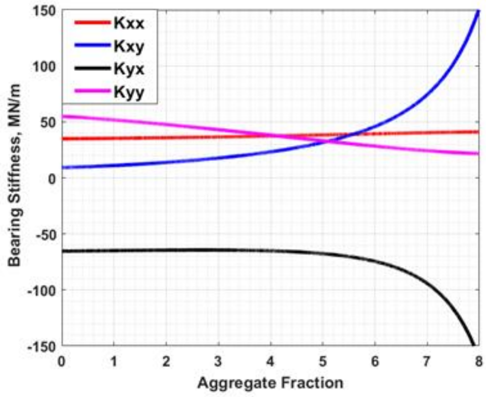

Fig 15. Effect of aggregate fractions on the bearing stiffness

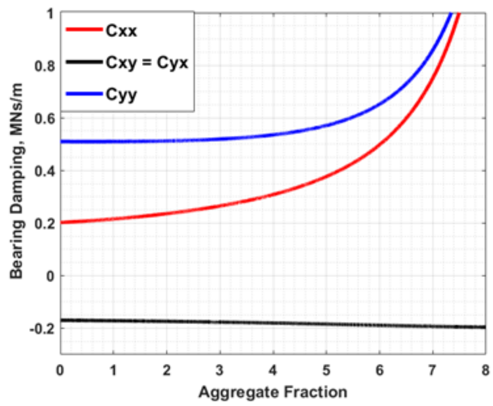

Fig 16. Effect of aggregate fractions on the bearing damping

Fig.17, shows the volume fraction influence on the dynamic coefficients at speed 2000 rpm. The direct stiffness(K_{xx}), is approximately does not change for all values of volume fraction while(K_{yy}) is strongly decrease with the increasing of volume fraction. The cross-coupling stiffness (K_{xy}) is moderatelyincreasewith the increasingof thevolume fraction. The cross-coupling stiffness (K_{yx})is constant with different volume fraction. The bearing damping coefficients (C_{xx}, C_{yy}) are slightly increase with the increasing of volume fraction, while cross-coupling damping ($C_{xy} = C_{yx}$) are negative and approximatelydon't changewith changing of volume fraction as in Fig.18.

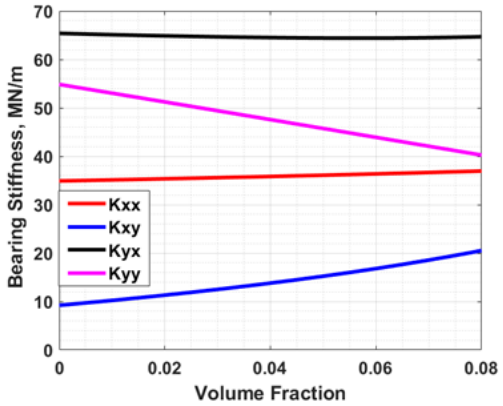

Fig 17. Effect of volume fractions on the bearing stiffness

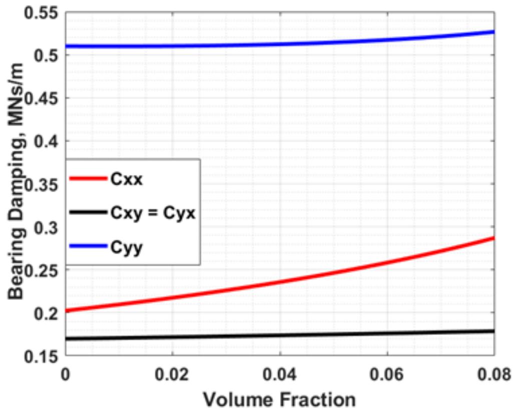

Fig 18. Effect of the volume fractions on the bearing damping

Generally, the rotor dynamic response is decreased with the aggregate fraction increasing for the different volume fractionratio as in Fig.19,also the dynamic response is decreased with the volume fractionincreasing for the different aggregate fraction ratioas in Fig.20**.**

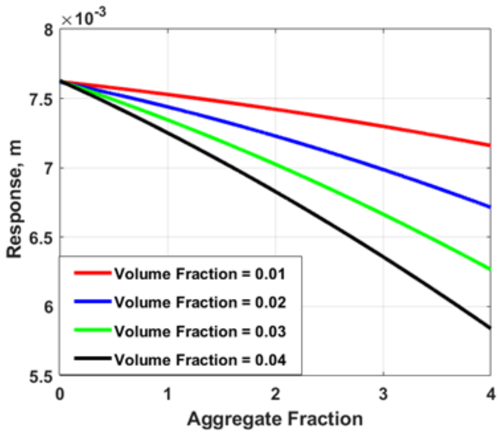

Fig 19. Effect of aggregate fractions on the rotor response

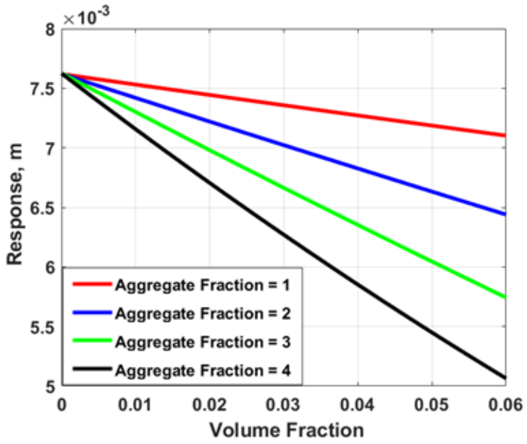

Fig 20. Effect of volume fractions on the rotor response

The critical spin speed is the speed of rotor when the maximum dynamical response occurring and it hasthe same value for the different aggregate fractions (volume fraction=0.02) as in Fig.21, and for different volume fraction (aggregate fraction=2) as in Fig.22.

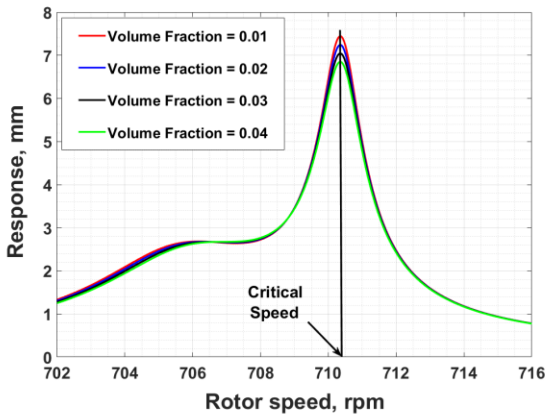

Fig 21.Effect of aggregate fractions on the rotor critical speed

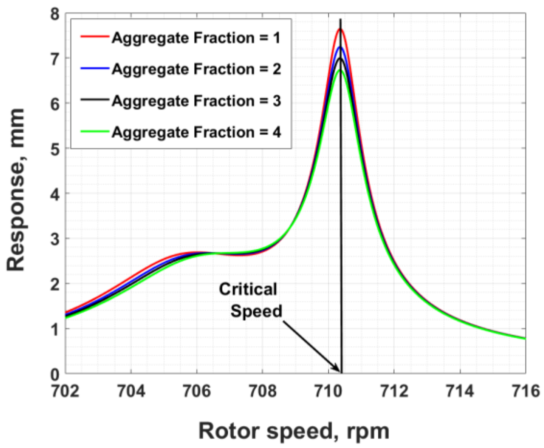

Fig 22. Effect of volume fractions on the rotor critical speed

6 Conclusion

1. The viscosity of blended pure oil with nanoparticles is increased with the increasing of volume fraction and with the increasing of aggregate fraction
2. The nano-lubricant oil pressure is increases with the increasing of aggregate fraction and with the increasing of volume fraction up to 130^{o} of angular bearing position then it decreasing.
3. Generally, the bearing stiffness coefficients are increase with the increasing of rotor speed for different volume fraction and aggregate fraction except, the direct stiffness ($\boldsymbol{K_{yy}}$) is reducing with the rising of the rotor speed.
4. Generally, the direct damping ($\boldsymbol{C_{xx}}, \boldsymbol{C_{yy}}$) are increase with the increasing of the aggregate fraction and with the increasing of volume fraction while the cross-coupling damping ($\boldsymbol{C_{xy}} = \boldsymbol{C_{yx}}$) are almost constant.
5. The dynamic response of rotor is decreasing due to the increasing of the aggregate ratio and volume ratio fractions.
6. The variation of aggregate ratio and volume ratio fractions have no effect on the rotor critical speed

References

[1] Benyebka Bou-Saïd, Hamid Boucherit and Mustapha Lahmar, “On the influence of particle concentration in a lubricant and its rheological properties on the bearing behavior”, Mechanics & Industry, EDP Sciences, DOI: 10.1051/meca/2012006, 2012.

[2] Binu K.G, Shenoy B.S, Rao D.S and Pai R., “A variable Viscosity Approach for the Evaluation of load Carrying Capacity of oil lubricated Journal Bearing with TiO2 Nanoparticles as lubricant Additives”, Procedia Materials Science 6, 1051 – 1067, ScienceDirect, Elsevier Ltd. 2014.

[3] K. Yathish, K. G. Binu, B. S. Shenoy, D. S. Rao and R. Pai, “Study of TiO2 Nanoparticles as Lubricant Additive in Two-Axial Groove Journal Bearing”, World Academy of Science, Engineering and Technology International Journal of Aerospace and Mechanical Engineering, Vol: 8, No: 11, 2014.

[4] Tushar P. Gundarneeya, “Theoretical Analysis of Journal Bearing With Nanolubricants”, International Journal of Scientific Research in Science, Engineering and Technology, IJSRSET | Volume 1 | Issue 3 | Print ISSN: 2395-1990 | Online ISSN: 2394-4099, 2015.

[5] Bassim A. Abass, Amal K. A., “Effect of nano-lubrication on the dynamic coefficients of worn journal bearing”, International Journal of Energy and Environment, Issue on applied mechanics research, Volume 8, Issue 6, pp.557-566, 2017.

[6] Binu, K. G, Yathish, K, Shenoy, B. S, Rao, D. S.and Pai, R, “Dynamic Performance Characteristics of Finite Journal Bearings Operating on TiO_2 based Nanolubricants”, Pertanika, Journal of Science & Technol. 25 (3): 963 – 976, University Putra Malaysia Press, 2017.

[7] Mohammad Yaghoub Abdollahzadeh Jamalabadi, “Effects of Nanoparticle Enhanced Lubricant Films in Dynamic Properties of Plain Journal Bearings at High Reynolds Numbers”,International Journal of Engineering and Technologies, Vol. 13, pp 1-23 doi:10.18052/www.scipress.com/IJET.13.1, SciPress Ltd, Switzerland, 2017.

[8] K. Yathish and K. G. Binu, “Static Characteristics of Two-Axial Groove Journal Bearing Operating on TiO2 Nanolubricants Using a Temperature Dependent Viscosity Model”, Journal of Mechanical Engineering and Automation, 7(5): 150-154 DOI: 10.5923/j.jmea.20170705.05, 2017.

[9] Ashutosh Kumarand and Sashindra K Kakoty, “Effect of couple-stress parameter on the steady state performance parameters of two-lobe journal bearing operating with non- Newtonian lubricant”, ScienceDirect, Elsevier, 2018.

[10] S.R. Suryawanshi and J.T. Pattiwar, “Effect of TiO2 Nanoparticle Blended with Lubricating Oil on the Tribological Performance of the Journal Bearing”, Tribology in Industry, Vol. 40, No. 3, p; 370-391, DOI: 10.24874/ti.2018.40.03.04, 2018.

[11] Ashutosh Kumar and SK Kakoty, “Effect of couple stress parameter on steady-state and dynamic characteristics of three-lobe journal bearing operating on TiO2 Nanolubricants”, Journal of Engineering Tribology 1994-1996 (vols 208-210), DOI: 10.1177/1350650119866028, 2019.

[12] Maleki Varnoosfaderani, Dashti Rahmatabadi A. and Dehghan A.A, “Analysis of Static Performance of Noncircular Lobed Journal Bearings with Lubricants Containing TiO2 Nanoparticles Using Couple Stress Fluid Model”, ISSN: 2476-6909; Modares Mechanical Engineering;19(1):151-157, Copyright TMU Press, 2019

[13] D. A. Bompos and P. G. Nikolakopoulos, “Journal Bearing Stiffness and Damping Coefficients Using Nanomagnetorheological Fluids and Stability Analysis”, Journal of Tribology, Copyright VC 2014 by ASME OCTOBER 2014, Vol. 136 / 041704-1.

[14] Luis San Andres, “kinematics of journal bearings”, notes 3, https://rotorlab.tamu.edu/me626/Notes_pdf/Notes03%20Kinematics%20JBs.pdf, 2012.

[15] Haisheng Chen, Yulong Ding and Chunqing Tan, “Rheological behaviour of nanofluids”, New Journal of Physics 9, 367, Online at http://www.njp.org/, doi:10.1088/1367-2630/9/10/367, 2007.