JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-15, No.-3, March (2020) pp 72-85 ISSN (Print) 0973-8975

EFFECT OF THE LUBRICANT ADDITIVES ON THE DYNAMIC BEHAVIOUR OF ROTOR BEARING SYSTEMS

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https://doi.org/10.26782/jmcms.2020.03.00006

Abstract

The effect of using lubricant oil additives on the dynamic behaviour of rotor bearing system has been studied in this paper; the modified lubricant oil viscosity relation due to adding additives to oil has been used in the Reynolds equation to calculate the lubricant oil pressure and reaction forces and the calculate dynamic coefficients of journal bearings. The response of rotor was determined analytical and verified the results with ANSYS software. The results show that the viscosity ratio is increasing with increase of aggregate and volume fraction. The lubricant oil pressure is increasing with increase of nanoparticles aggregate and volume fraction up to 130^o *bearing angular position then decreasing with increase of aggregate and volume fraction. The dynamic response is generally decreasing with increase of aggregate and volume fraction*

Keywords: Rotor, Dynamic Response, Nanoparticles Additives, Dynamic Coefficients, ANSYS

I. Introduction

The dynamic response and critical speed of rotor systems represent the most important parameters which must be known to anyone who interested in or he is working on the rotating machines. The dynamic behaviour of rotor bearing systems is mainly depend on dynamic coefficients (stiffness and damping) of fluid film journal bearing as well as dimensions of Rotor. The dynamic coefficients can be calculated based on the Reynolds Equation [XV] which in turn depends on bearing radial clearance, lubricant oil film thickness and oil viscosity. The blended of nanoparticle additives with pure oil will changes the viscosity of lubricant oil and therefore the dynamic coefficients will be change. The change in dynamic coefficients mean the dynamic behaviour (dynamic response and critical speed of rotor) will be change. The adding of solid Nanoparticles to the lubricant oil enhance most parameters of fluid film journal bearings where there are many researchers have been investigated the effect of nanoparticle additives on the oil film thickness, load carrying capacity , friction force, oil pressure and oil viscosity.

The existence of rigid particles additives in the lubricant oil increases the viscosity of lubricant which enhances the minimum film thickness and improves the capacity of load-carrying [VI]. The load carrying capacity of fluid film journal bearings can be increased by adding TiO2 nanoparticle as lubricant additive [IV]. Nanoparticle additives when adding to the lubricant oil of Two-Axial Groove Journal Bearing Will lead to increase the load carrying capacity [X]. Nanoparticle concentration can be used with different combination to get High friction coefficient, high viscosity, high distribution of lubricant oil pressure and increasing the load carrying capacity of plain journal bearing [XVI]. The Nanoparticle additives can be used to decreases the dynamic coefficients of worn journal bearings [III]. The increasing in the concentration of TiO2 nanoparticle leads to increase in the dynamic coefficients (stiffness and damping), and improve the whirl instability features of journal bearings [V]. The nanoparticle additives enhanced lubricant oil causes higher damping ratios and f effective stiffness of journal bearings [XIII]. The nanoparticle additives presence in lubricant oil restricts the decrease in viscosity of lubricant with temperature increasing and hence enhances the performance of plain journal bearings [IX]. The two-lobe journal bearings load carrying capacity as well as flow co-efficient can be significantly increased while there is decreasing in the friction variable [I]. The lubricant oil when blended with nanoparticle and using with elliptical journal bearings improve the system performance over plain journal bearings operating with the same Nanolubricants [XIV]. The non-dimensional flow coefficient and load-carrying capacity of three-lobe journal bearings significantly rising due to adding nanoparticle additives to lubricant oil while there is decreasing in the friction variable as well as there is significantly improvement in the bearings dynamic coefficients [II]. In general, the using of lubricants that containing TiO2 as Nanoparticles additives can be enhanced the performance and static characteristics of different types of (two, three, and four) lobe journal bearings [XII].

This research aims to estimate the effect of nanoparticles in oil lubricants on the dynamic response and critical speed of rotor bearing systems

II. Dynamic Coefficients of Hydrodynamic Journal Bearings

The calculations of dynamic coefficients are based on reaction forces of journal bearing and they are can be found as following

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

Where, $K_{xy} = \partial F_x / \partial y$is a dynamic stiffness coefficient due to the variation of x component of lubricant oil force (F_x) with respect to the journal displacement in the y

direction and $K_{yx} = \partial F_y/\partial x$is a dynamic stiffness coefficient due to the variation of y component of lubricant oil force (F_y) with respect to the journal displacement in the x direction and so on for the other coefficients. The journal bearing dynamic coefficients ($K_{xx}, K_{yy}, K_{xy}, K_{yx}, C_{xx}, C_{yy}, C_{xy}, C_{yx}$)are illustrated in Figure 1.

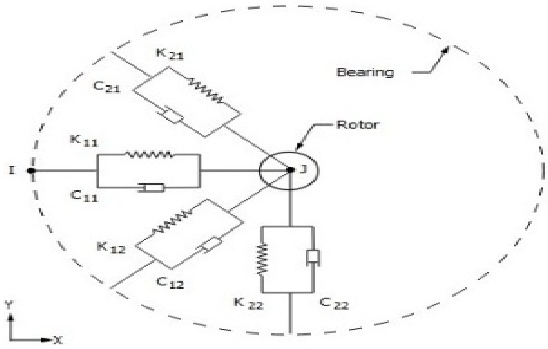

Fig. 1: Dynamic Coefficients of Fluid Film Journal Bearings

The pressure distribution over internal surface of journal bearings can be determined by solve Reynolds equation [XV] which depends on lubricant oil characteristics (pressure, oil film thickness) and rotor spin speed as shown in Equation 2;

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

Where; h, p, μ_f, are fluid film thickness, fluid pressure and base fluid viscosity respectively.

The lubricants oil forces can be calculated by direct Integration of the oil pressure field Equation 2, on the internal journal surface [XI] as follows;

$$\begin{bmatrix} F_r \\ F_t \end{bmatrix} = \int_{-L/2}^{L/2}\int_0^{2\pi} P(\theta, z, t)\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} Rd\theta dz \begin{bmatrix} F_x \\ F_y \end{bmatrix} = \int_{-L/2}^{L/2}\int_0^{2\pi} P(\varphi, z, t)\begin{bmatrix} \cos\varphi \\ \sin\varphi \end{bmatrix} Rd\varphi dz \quad (3)$$

Where; $\varphi, \theta, \emptyset$, as in Figure 2.

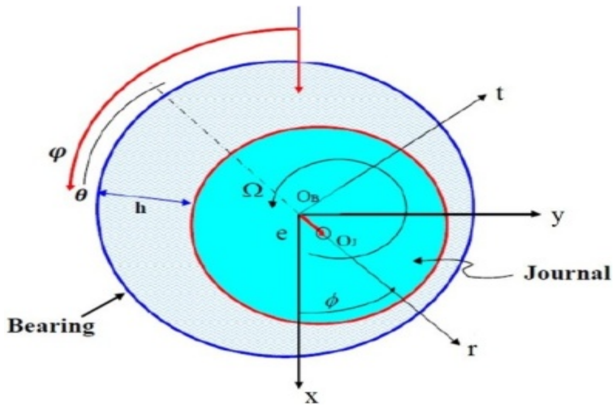

Fig. 2: Fluid Film Forces Applied to the Journal

III. Effect of Nanoparticles Additives

There are many analytical formulas to estimate the viscosity of nanolubricants oil due to existence of nanoparticles but the more suitable one was based on a modified Krieger and Dougherty is [VIII]

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{f}}\left(1-\frac{\emptyset_a}{\emptyset_m}\right)^{-\eta\emptyset_m} \quad \emptyset_a = \emptyset\left(\frac{a_a}{a}\right)^{3-D} \tag{4}$$

Where μ_{nf} is the nanofluid viscosity; $\emptyset$is solid nanoparticle volume concentration. $\emptyset_m$is the maximum nanoparticle concentration at which oil flow can take place and its value is 0.605 for high oil shear rate. η is the intrinsic viscosity and it has a typical value of 2.5. D is equal to 1.8, [VII], the Equation 3 can be rewritten as follows

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{f}}\left(1-\frac{\emptyset}{0.605}\left(\frac{a_a}{a}\right)^{1.2}\right)^{-1.5125} \tag{5}$$

Where (a_a) is the effective aggregates radii, (a) is the primary nanoparticles radii, see Figure 3.

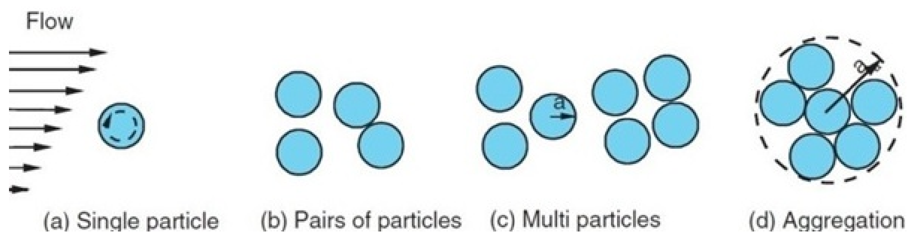

Fig. 3: Schematic llustrations of nanoparticles additives

By using Equation 3 and Equation 1 and take into account the value of viscosity as in Equation 5, the dynamic coefficients of fluid film journal bearings lubricated with Nanolubricants can be calculated.

IV. Dynamic Response and Critical Speed

The dynamic response of rotor journal bearing systems can be found by solving the Equation of motion of flexible rotor fluid film journal bearing systems as follows

$$M\ddot{x} + K(x_R - x_b) = me\Omega^2 \cos\Omega t \tag{6}$$

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

Where (x_R) and (y_R) are the rotor disk mass position, (x_b) and (y_b) are the bearing journal center position, $(me\Omega^2 \cos\Omega\mathrm{t}\ , me\Omega^2 \sin\Omega\mathrm{t})$ are the, $(x)$and (y) unbalance mass forces, (e) eccentricity of unbalance mass; (*M*) is the diskmass and K is rotor shaft stiffness. The Equation of motion of rotor can be solve with take into account the following relations

$$K(x_R - x_b) = 2\mathrm{F_x}$$

$$K(y_R - y_b) = 2\mathrm{F_y}$$

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

The solution of Equation 6 is as follows;

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

The dynamic response of rotor due to the unbalance mass is as follows,

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

$$r = r_f e^{i\Omega t} + r_b e^{-i\Omega t} (7)$$

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

Where, r_f ; forward whirl radius, r_b; backward whirl radius.

The maximum dynamic response of rotor is the major radii of rotor orbit at center of disc.

$$|r|_{maj} = |r_f| + |r_b| |r|_{min} = |r_f| - |r_b| (8)$$

So, the ***critical speed*** is the rotor speed at maximum radii of rotor whirl; $|r|_{maj}$.

V. Results and Discussion

The rotor bearing system with the mechanical specifications as in Table 1, Table 2 and Figure 4 has been used in this study.

Table 1: Mechanical Specifications of Rotor

Rotor Length mm	Rotor Dia. mm	Disk Dia. mm	Disk Thickness mm	Rotor / Disk Material Density Kg/m^3	Modulus of Elasticity	Unbalance Mass Kg	Mass Eccentricity mm
1200	40	700	40	7850	2.1×10^{11}	5×10^{-3}	350

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

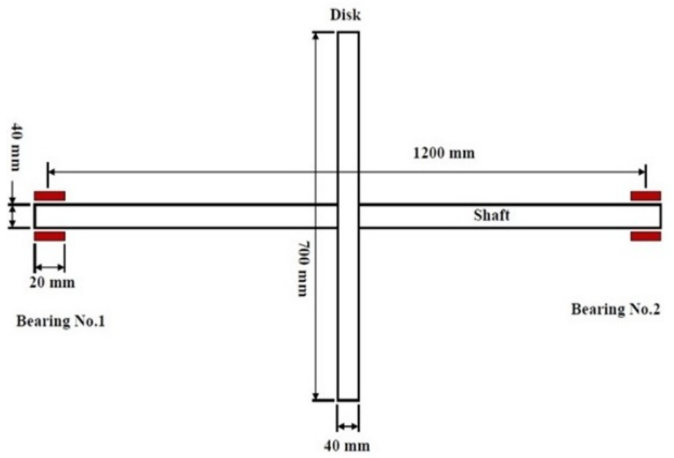

Fig. 4: Mechanical Specification of Rotor Bearing System

The adding of nanoparticle additives to the lubricant oils has a positive effect on the viscosity of Nanofluid whereas the viscosity ratio (μ_{nf}/μ_f) increases with increase of the volume fraction ($\emptyset$) for different aggregate fractions ($\frac{a_a}{a}$) as in Figure 5.a, also the viscosity ratio increase with increase of the aggregate fraction for different volume fractions as in figure 5.b

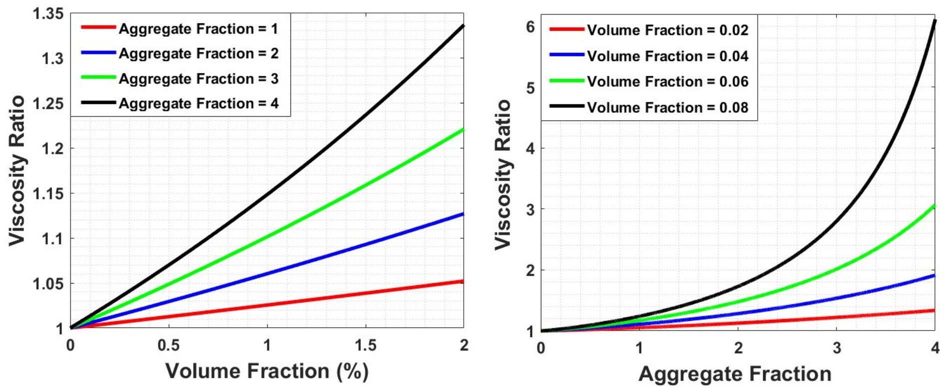

Fig. 5: Viscosity Ratio for Different Volume Fractions and Different Aggregate Fractions

At static equilibrium ($\frac{\partial h}{\partial t} = 0$) and constant rotor speed the lubricant oil pressure distribution over internal surface of bearing can be determined by double integration of Reynolds Equation 2 with respect to bearing length ($z = -L/2 \text{ to } L/2$) and bearing angular position ($\theta = 0 \text{ to} \pi$) , for constant rotor speed the pressure distribution at middle of bearing (z =0) and along angular position can be plotted fordifferent aggregate fraction and different nanoparticle volume fraction as in Figure 6, the lubricant oil pressure is increasing with increases in the aggregate fraction and volume fraction up to about 130^{o} then it is decreasing with increases in the aggregate fraction and volume fraction when angular position become greater than 130^{o}

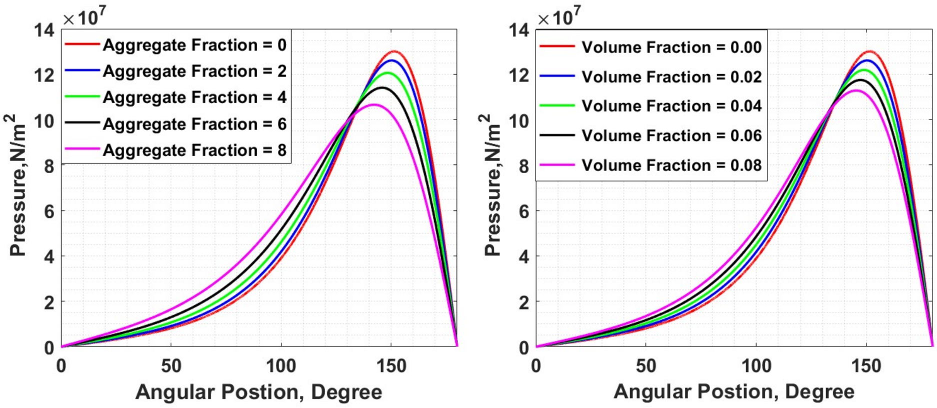

Fig. 6: Pressure Distribution along Angular Position

The dynamic coefficients of fluid film journal bearing in case of pure oil and nanofluid can be determined by using Equation (1). The dynamic coefficients of fluid film journal bearing are varying with rotor speed as shown in the semilog Figure 7; where the dashed line is represent the negative values of dynamic coefficients. The dynamic coefficients of journal bearing are depend on the bearing dimensions, lubricants oil viscosity and external applied force so that, the change in the lubricant oil viscosity will leads to change values of dynamic coefficients. The viscosity of nanoparticles lubricant oil can be calculated by using Equation (5). The all bearing stiffness types are approximately constant in spite of a change in rotor speed except the cross coupling stiffness (K_{xy}) becomes approximately constant at high rotor speed (above 1500 rpm in the case of rotor dimensions under study) as in Figure 7.

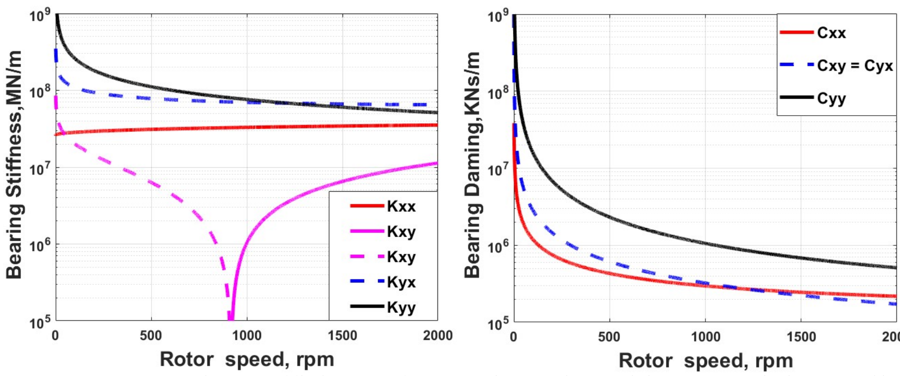

Fig. 7: Dynamic Coefficients of Journal Bearing with Pure Lubricant Oil

The effect of nanoparticles additives on the dynamic Stiffness of fluid film journal bearings is illustrated in Figure 8 with different nanoparticle aggregate fractions and constant volume fraction = 0.02, then illustrated in Figure 9 with different nanoparticle volume fraction and constant aggregate fraction = 2. In general, the dynamic coefficients; K_{xx} , K_{xy}, K_{yx} ,C_{xx} , C_{yy} are increasing with increases in the volume fraction or aggregate fraction as shown in Figure 10 and Figure 11 respectively while Direct stiffness in y direction, K_{yy} and cross coupling damping $(C_{xy} = C_{yx})$ are decreasing with increases in the volume fraction or in the aggregate fraction

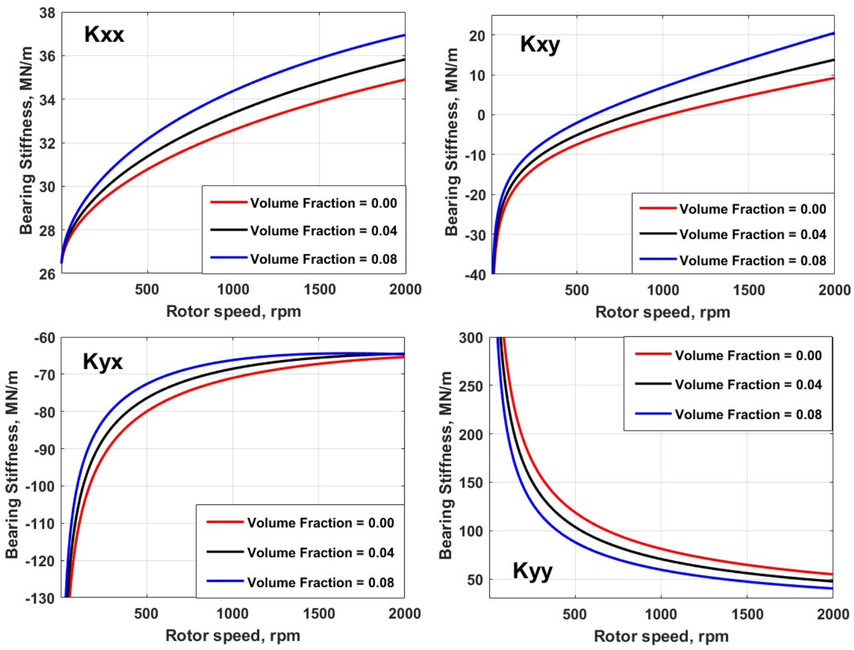

Fig. 8: Dynamic Stiffness of Bearing with Different Nanoparticles Aggregate fractions

Figure 10 shows the relation between nanoparticle aggregate fraction and bearing dynamic coefficients at 2000 rpm, the direct stiffness; K_{xx}, is slightly increasing with increase of aggregate fraction and K_{yy} is slightly decreasing with increase of aggregate fraction while cross coupling stiffness K_{xy} is slightly increasing up to 4 aggregate fraction value then strongly increasing. The cross coupling stiffness K_{yx} is constant up to 5 aggregate fraction then slightly decreasing up to 6 aggregatefraction then strongly decrease. The direct damping (C_{xx}) is slightly increasing up to 5 aggregate fraction then strongly increasing while the direct damping (C_{yy}) is very slightly increasing with increase of aggregate fraction up to 5 aggregate fraction then strongly increasing with increase of aggregate fraction. The cross coupling damping ($C_{xy} = C_{yx}$) is negative and almost constant.

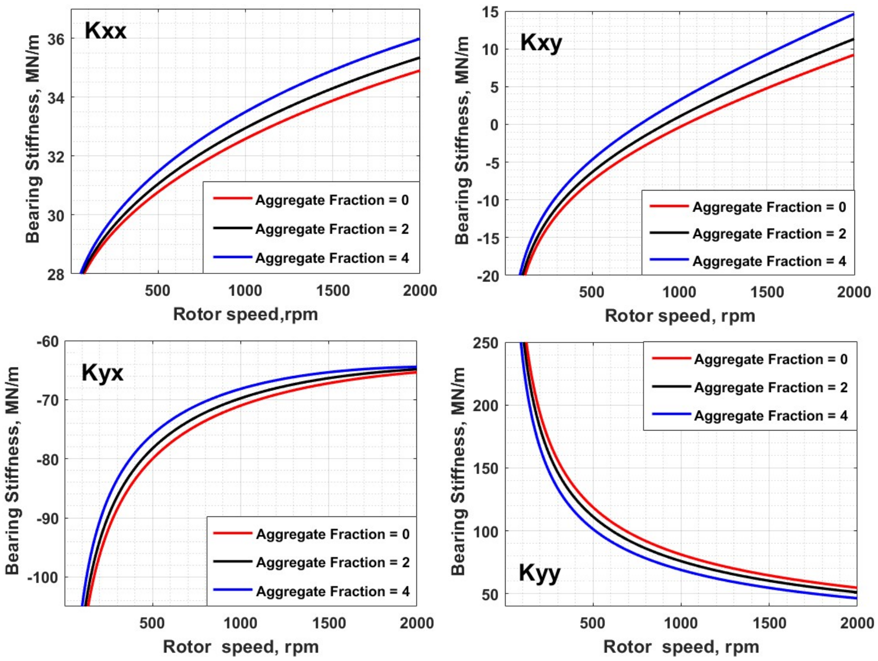

Fig. 9: Dynamic Stiffness of Bearing with Different Nanoparticles Aggregate fractions

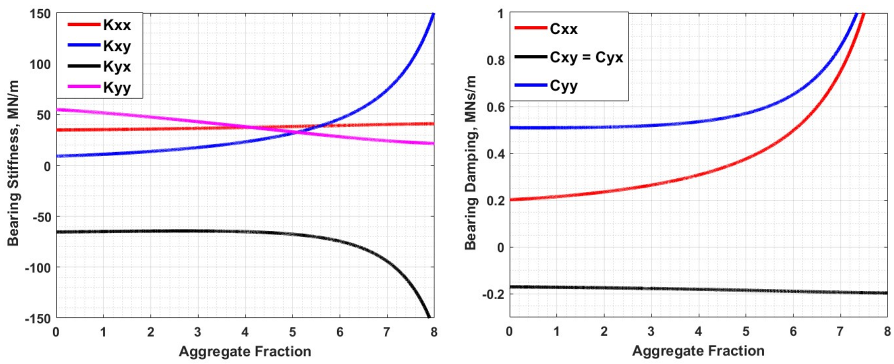

Fig. 10: Effect of Aggregate Fractions on the Dynamic Coefficients of Bearing

Figure 11 illustrates the effect of nanoparticle volume fraction on bearing dynamic coefficients at 2000 rpm, the direct stiffness; K_{xx}, is approximately constant for all values of volume fraction and K_{yy} is strongly decreasing with increase of volume fraction while cross coupling stiffness K_{xy} is increasing moderatelywith increase of volume fraction value and cross coupling stiffness K_{yx} almost constant. The direct damping coefficients (C_{xx}, C_{yy}) are slightly increasing with the increase of volume fraction while cross coupling damping $(C_{xy} = C_{yx})$ has negative value and is almost constant despite of increase of volume fraction.

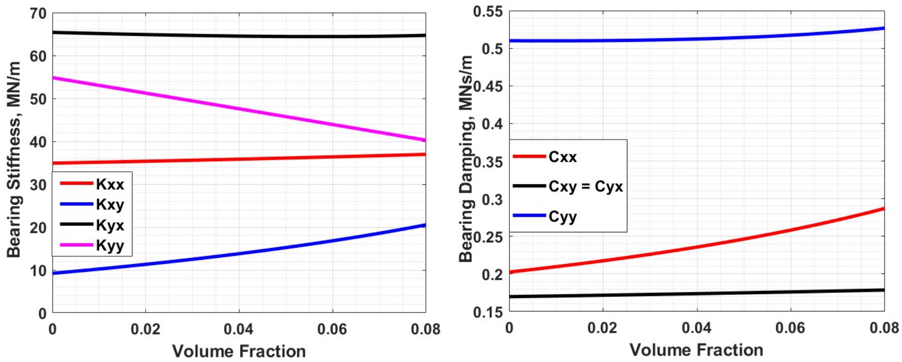

Fig. 11: Effect of Volume Fractions on the Dynamic Coefficients of Bearing

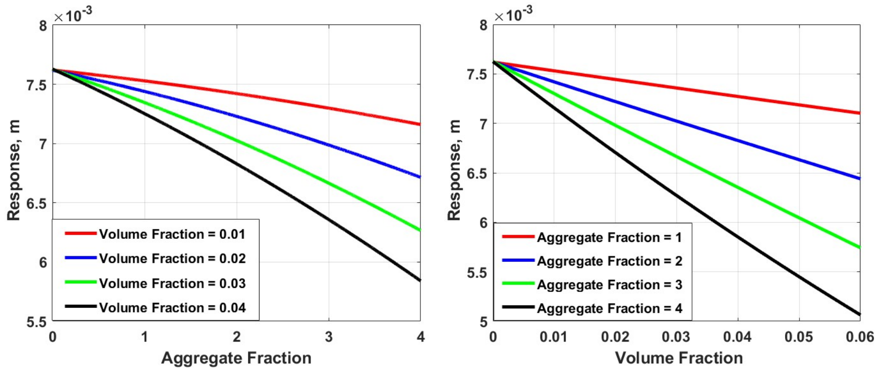

Fig. 12: Effect of Volume Fractions and Aggregate Fractions on the Rotor Response

Decreasing of the value of response displacement of rotor is representing aim of many researches. The using of lubricant oil additives to reduce response displacement with prevent the increasing of friction force of lubricant oil is one of easy way to enhance rotor operation with low cost. Generally, the response displacement is decreasing with increase of aggregate fraction for different volume fraction as well the response displacement is decreasing with increase of volume fraction for different aggregate fraction as shown in Figure 12.

The analytical repose displacement values which calculated by using Equation 8 had been verified with ANSYS software, the results show an acceptable compatibility as shown in Table 3 and Figure 13.

Table3: Comparison of response results between Analytical and ANSYS

Aggregate Fraction	Response, mm		
	Analytical	ANSYS	Ratio of Coincide
2	7.2	6	83%
4	6.6	5.5	83%

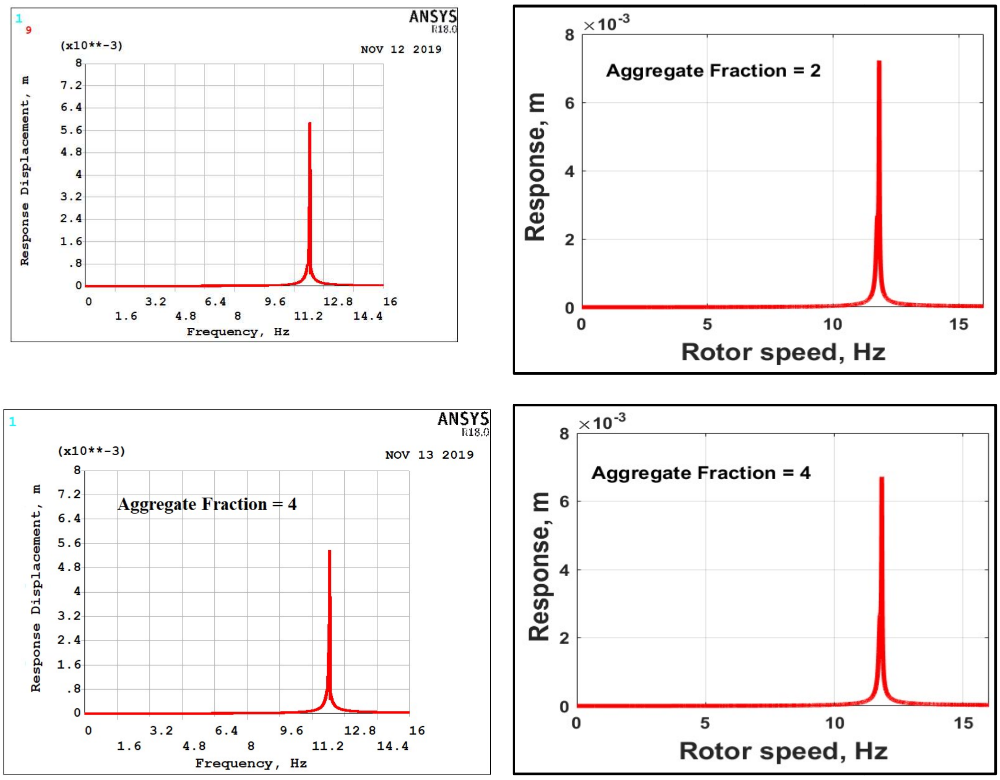

Fig. 13: Comparison of ANSYS and MATLAB Response Results

VI. Conclusions

I. Increasing of nanoparticles volume fraction leads to increase of viscosity ratio for different nanoparticles aggregate fraction. As well increasing of nanoparticles aggregate fraction leads to increase of viscosity ratio for different nanoparticles volume fraction.

II. The lubricant oil pressure is increasing with increase of nanoparticles aggregate fraction up to 130^o of angular bearing position then the pressure decreases with increases of aggregate fractionand the samething happens with increasing of nanoparticles volume fraction.

III. The stiffness coefficients are strongly increasing with increase of rotor speed up to 600 rpm then become slightly increasing with increase of rotor speed for different aggregate fraction and volume fraction except for direct stiffness in the vertical direction (K_{yy}) where the stiffness decreasing with increase of rotor speed approximately up to 600 rpm then becomes slightly decreasing with increase of rotor speed.

IV. The direct stiffness (K_{xx}) is slightly increasing with increase of aggregate fraction. The direct stiffness (K_{yy}) slightly decreasing with increase of aggregate fraction. The cross couple stiffness (K_{xy}) is slightly increasing up to 4 aggregate fraction then strongly increasing while ((K_{yx}) is almost constant up to 5 aggregate fraction then strongly decreasing.

V. The direct damping (C_{xx}) is slightly increasing up to 5 aggregate fraction then strongly increasing while the direct damping (C_{yy}) is very slightly increasing with increase of aggregate fraction up to 5 aggregate fraction then strongly increasing with increase of aggregate fraction. The cross coupling damping ($C_{xy} = C_{yx}$) is negative and almost constant

VI. the direct stiffness; K_{xx}, is approximately constant for all values of volume fraction and K_{yy} is strongly decreasing with increase of volume fraction while cross coupling stiffness K_{xy} is increasing moderatelywith the increase of volume fraction value and cross coupling stiffness K_{yx} almost constant. The direct damping coefficients (C_{xx}, C_{yy}) are slightly increasing with the increase of volume fraction while cross coupling damping ($C_{xy} = C_{yx}$) has negative value and is almost constant despite of increase of volume fraction.

VII. Generally, the increasing of nanoparticles aggregate fraction and increasing of nanoparticles volume fraction lead to decrease the response of rotor.

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