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Effects of lubricant fluid with nanoparticle additive on the load capacity of a hydrostatic journal bearing

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Abstract: Hydrostatic journal bearings are recommended for supporting shafts operating at high speeds and under heavy loads in the industry. In the journal bearings, lubricant viscosity decreases with increasing temperature at high rotation speeds and hence, the fluid between the surfaces should be circulated using a pump to cool the lubricant. However, the lubricant supplying between the surfaces at the high flow rate causes the whirl instability and vibrations problems in the bearing-shaft system. These instability problems give rise to significant damage on the system during operating at the high speeds and under heavy loads. As a solution to this problem, it could be suggested to control the variation of the lubricant viscosity concerning the temperature by adding nanoparticle. In the present work, the effects of the lubricant with nanoparticle additives on the load carrying capacity of a hydrostatic journal bearing are theoretically investigated. The fluid film flow between the bearing and rotor surfaces are modelled with Reynolds equation and the viscosity term in Reynold's equation is defined as a function which depends on the nanoparticle properties. Then, the pressure distribution is obtained with solving the film flow equation and the load capacity is calculated for different nanoparticle parameters using this pressure distribution. The results show that the usage of the lubricant with nanoparticle increases the load performance of the hydrostatic journal bearing and the influences of the nanoparticle size on the load performance is more dominant for high volumetric ratio.

Keywords: Rotordynamics; load capacity; lubricant with nanoparticle; hydrostatic journal bearing.

Nanoparçacık Katkılı Yağlayıcı Akışkanın Radyal Hidrostatik Yatağın Yük Taşıma Kapasitesine Etkisi

Öz: Hidrostatik yataklar, endüstride, yüksek hızlarda ve ağır yükler altında çalışan şaftların yataklanması için önerilmektedir. Bu yataklarda, sıcaklığın artması akışkanın viskozitesini düşürmektedir ancak, akışkanın soğutulması için yüzeyler arasındaki akışkan, bir pompa ile devridaim ettirilebilir. Fakat yatak-şaft sistemlerinde, yüzeyler arasına akışkan iletilmesi, dolanım kararsızlıklarına ve titreşim problemlerine sebep olduğu bilinmektedir. Bu kararsızlık problemleri şaftın yüksek hızlarda dönüşü esnasında sisteme önemli hasarlar verebilecek kadar tehlikeli olabilir. Bu probleme çözüm önerisi olarak, yağlayıcı akışkanın viskozitesinin sıcaklığa bağlı değişiminin nanoparçacıklarla kontrol edilmesi önerilebilir. Bu çalışmada da, hidrostatik yataklarda nanoparçacık ilaveli yağlayıcı akışkan kullanımının yük taşıma kapasitesine etkisi teorik olarak araştırılmıştır. Yüzeyler arasındaki akışkan hareketi Reynold's denklemi ile modellenmiş ve denklem içerisindeki viskozite terimi nanoparçacık özelliklerine bağlı olarak ifade edilmiştir. Bunun ardından, yatak içerisindeki basınç dağılımı Reynold's denkleminin sayısal çözümü ile elde edilmiş ve bu basınç dağılımı kullanılarak, yatağın yük taşıma kapasitesi, farklı nanoparçacık özellikleri için hesaplanmıştır. Yapılan bu

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çalışmanın sonuçları, nanoparçacık takviyeli yağlayıcı kullanımının hidrostatik yatakların yük taşıma kapasitesini arttırdığını ve yüksek hacimsel oranlar için nanoparçacık boyutunun performansa etkisinin daha baskın olduğunu göstermiştir.

Anahtar Kelimeler: Rotor dinamiği; yük kapasitesi; nanaoparçacık takviyeli yağlayıcı; radyal hidrostatik yatak.

1. Introduction

Hydrostatic journal bearings are a type of fluid film bearing and paid regard to be a crucial part of rotating machinery. They are generally preferred to support the heavy load shafts and they could be an option in high-speed bearing-rotor application due to the externally supplied the lubricant. In the hydrostatic bearing-rotor system, externally pressurized lubricant fluid enters the radial clearance through the orifices, it flows between the bearing and rotor surfaces and it exhausts to the atmosphere at the end of the bearing. During the flow, the lubricant separates the moving and stationary surface and provides rotating of the shaft. Hence dynamic characteristics of a shaft with hydrostatic bearing are strongly related to the fluid flow. In the fluid film bearing, the lubricant flow between the surfaces determines the performance characteristic of the bearing and it depends on the viscosity of the lubricant, geometry of the bearing and operational conditions. Hence the performance characteristic of the bearing could be improved by optimization of the bearing parameters and lubricant properties [1-4].

In literature, a lot of researchers have investigated the performance properties of the hydrostatic journal bearing with Newtonian fluid in detail [5-13]. In these studies, effects of the bearing geometry [5-7] and structure of the orifice [8-10] on the static and dynamic characteristics of the bearing, as well as stability conditions of the hydrostatic journal bearing-shaft system [11-13] were theoretically and experimentally studied. In the hydrostatic bearing-rotor system, when the rotor operates at a high rotational speed, friction occurs between the layer of the lubricant film during the fluid flow and the friction leads to increase the temperature of the lubricant and decrease viscosity. And the changing at the viscosity of lubricant will be directly affected the performance of the system. Furthermore, alteration of the viscosity could cause instability problems such as half-speed whirl and whip phenomenon in the system. [1-2]. In order to solve these instability problems, controlling the viscosity of the lubricant could be suggested.

In recent years, the micro-polar lubricant has been preferred for controlling the lubricant characteristic in the industrial application. Micro-polar lubricant includes micro-structure solids such as microscopic metal particles [14] and it behaves as a non-Newtonian fluid due to solid particles in the base lubricant. In literature, a lot of researchers investigated the effects of the micro-polar fluids and the influences on the stiffness and damping of a hydrostatic journal bearing [15-17]. In these studies, the researchers modelled the micro-polar fluid flow with modified Reynold's equation, and they concluded that using micro-polar fluid as a lubricant in the hydrostatic bearings are significantly increased the performance [14]. However, micro-structure solid particle leads to thickening the base lubricant, moreover, affects the bearing performance. In order to controlled lubricant characteristics in the industrial bearing applications, using a lubricant with nanoparticle additives has been preferred also. Because nanoparticle additive is increased the viscosity of the base lubricant, in the bearing-rotor application, using the lubricant with nanoparticle additive significantly affects the thermo-hydrodynamic characteristic of the bearing and it improves the performance of the system [18]. In literature, the nanoparticle additive effects on the performance characteristics of a hydrodynamic bearing were investigated in detail. In these studies, effects of the parameters of the nanoparticle additive such as nanoparticle sizes, nanoparticle volume ratio, etc. on the viscosity of the lubricant were experimentally examined and a mathematical formula was derived for industrial lubricant [18-27]. In order to obtain the load performance of the hydrodynamic bearings, the fluid flow was modelled using Reynold's equation with viscosity formulation and a series simulation was performed for different nanoparticle parameters.

Comprehensive literature reveals show that the performance of the journal bearing is strongly related to the viscosity of the lubricant and it is controlled with suspended solid micro and/or nanoparticle in the base lubricant [29-31]. In the literature, the load capacity of the hydrodynamic and hydrostatic journal bearing with micro-polar lubricant have been analysed in detailed. In addition, a lot of researchers studied the investigation of the performance characteristic of the hydrodynamic bearing with nanoparticle additive, but the performance characteristic of the hydrostatic bearing with nanoparticle additive has not been analysed. This present work aims to shrink this vacancy. Consequently, in the present work, the effects of the lubricant with nanoparticle additives on the load capacity of a hydrostatic journal bearing were theoretically investigated. The fluid flow was modelled with Reynold's equation with the nanoparticle supplement having variable viscosity. Then, Reynold's equation expressed for fluid flow was discretized with the central finite difference method. Finally load capacity of the journal bearing was calculated with pressure distribution and the effects of TiO_2 nanoparticle additive in the lubricant on the load capacity were investigated for different nanoparticle sizes and volumetric ratios.

2. Mathematical Models

In fluid film bearings, lubrication film between the surfaces generates a pressure film force and this force supports the rotor. The film force known as the load capacity could be calculated using the pressure distribution function. Hence it could be computed from Eq. [1].

$$\begin{aligned} W_x &= \int_0^{L/R} \int_0^{2\pi} P(\theta,\xi)\cos(\theta)d\theta d\xi \\ W_y &= \int_0^{L/R} \int_0^{2\pi} P(\theta,\xi)\sin(\theta)d\theta d\xi \end{aligned} \tag{1}$$

where $P(\theta,\xi)$ is pressure distribution function. In order to obtain this function, the fluid flow could be modelled with the Reynold's equation under some assumption. These assumptions could be listed as follow;

- The viscosity of the fluid is constant
- Compared with the pressure force, inertial and body forces are very small and they could be neglected
- The film thickness is ultrathin and the pressure change at this direction could be ignored.
- Considering these assumptions, the Reynold's equation at the cylindrical coordinate for a hydrostatic journal bearing could be given as;

$$\frac{\partial}{R\partial\theta}\left(h^3\frac{\partial p}{R\partial\theta}\right) + \frac{\partial}{R\partial\xi}\left(h^3\frac{\partial p}{R\partial\xi}\right) = 6U\mu\frac{\partial h}{R\partial\theta} + 12\mu\frac{\partial h}{\partial t} \tag{2}$$

where θ is circumferential and ξ is axial coordinates (see Fig. 1), U is surface velocity, and h is film thickness function and this function could be computed from Eq. [3] for a journal bearing.

$$h(\xi,\theta) = 1 + e\cos(\theta - \theta_s) \tag{3}$$

Using the following dimensionless parameters,

$$\Lambda = \frac{\mu\Omega}{p_s}\left(\frac{R}{C}\right)^2, \sigma = \frac{\mu}{p_s}\left(\frac{R}{C}\right)^2 \qquad \bar{p} = \frac{p}{p_s}, \bar{h} = \frac{h}{C}, U = \Omega R$$

It could be addressed as in Eq. [4]

$$\frac{\partial}{\partial \theta}\left(\bar{h}^3 \frac{\partial \bar{p}}{\partial \theta}\right) + \frac{\partial}{\partial \xi}\left(\bar{h}^3 \frac{\partial p}{\partial \xi}\right) = 6\Lambda \frac{\partial \bar{h}}{\partial \theta} + 12\sigma \frac{\partial \bar{h}}{\partial t} \tag{4}$$

where $\bar{p}$ is dimensionless pressure, p_s is supply pressure, R is the radius of the bearing, Ω is the angular velocity of the shaft, c is the radial gap, and, $\bar{h}$ could be calculated from Eq. [5].

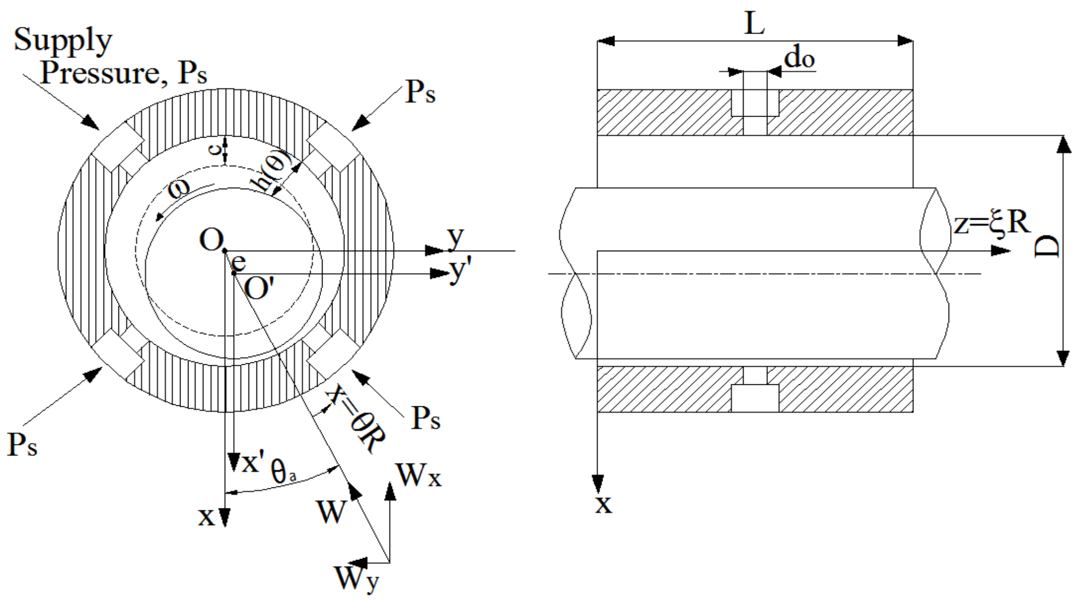

Figure 1. A hydrostatic journal bearing [28]

$$\bar{h}(\xi, \theta) = 1 + \epsilon cos(\theta - \theta_s) \tag{5}$$

and eccentricity ratio, ϵ could be given as follow;

$$\varepsilon = \frac{1}{C}\sqrt{{e_x}^2 + {e_y}^2} \tag{6}$$

2.1. Mass flow rate

In hydrostatic bearing, externally pressurized fluid supply to radial clearance through feeding holes. Hence a mass flow rate equation could be included in the Eq. [2] at the inlet. For a fluid film bearing, the mass flow is modelled with geometrical properties of the feeding holes. In this study, a hydrostatic bearing with orifice inlet is investigated, and hence dimensionless mass flow rate for orifice inlet could be written as following [26].

$$\bar{Q} = \bar{C}_S(1 - \bar{p}_c)^{1/2} \tag{7}$$

where $\bar{p}_c$ is concentric pressure ratio, $\bar{C}_S$ is dimensionless flow coefficient and it could be computed from Eq. [8].

$$\bar{C}_s = \frac{3\pi {d_o}^2 \mu\, C_d}{C^3}\sqrt{\frac{2}{\rho P_s}} \tag{8}$$

where d_o is the diameter of the orifice outlet, C_d is orifice coefficient.

2.2. Viscosity model of the lubricant with nanoparticle additive

Nowadays, the nanotechnology which is an important research area is increasingly common and use in several industrial applications [30-31,34]. In this study, the effects of the different size and volumetric ratio of TiO_2 nanoparticle additives on the load performance of the hydrostatic bearing are investigated. Nanoparticle additives directly affect the viscosity of the lubricant. Hence, it could be estimated using Eq. [9]. This mathematical model is known as the Krieger-Dougherty model and it depends on the size and volumetric ratio of the nanoparticle. [24].

$$\mu = \mu_o \left(1 - \frac{\emptyset}{0.605}\left(\frac{a_a}{a}\right)^{1.2}\right)^{-1.5} \tag{9}$$

where μ is viscosity of the lubricant with nanoparticle additives, μ_o is the lubricant viscosity, $\emptyset$ is the volumetric ratio of nanoparticle a_a is aggregate Radius and a is primary particle size ratio.

3. Numerical Solution

Reynolds equation is solved with finite difference method for obtaining the pressure distribution in this study. Before the Reynolds equation is discretized with finite difference scheme, the derivative terms could be rewritten as follow;

$$3\bar{h}^2\frac{\partial\bar{h}}{\partial\theta}\frac{\partial\bar{p}}{\partial\theta} + \left(\bar{h}^3\frac{\partial^2\bar{p}}{\partial\theta^2}\right) + 3\bar{h}^2\frac{\partial\bar{h}}{\partial\xi}\frac{\partial\bar{p}}{\partial\xi} + \left(\bar{h}^3\frac{\partial^2\bar{p}}{\partial\xi^2}\right) = 12\Lambda\frac{\partial\bar{h}}{\partial\theta} \tag{10}$$

After the derivation of the Reynold's equation is obtained, Eq. [10] is discritized with central finite difference scheme and $p_{i,j}$ could be calculated as Eq. [11].

$$\bar{p}_{i,j} = A_{i,j}\bar{p}_{i,j+1} + B_{i,j}\bar{p}_{i,j-1} + C_{i,j}\bar{p}_{i+1,j} + D_{i,j}\bar{p}_{i-1,j} + E_{i,j} \tag{11}$$

In this study, the pressure values on the computation grid which is composed of 65x97 nodes were calculated by using an iterative solution algorithm. This algorithm starts with geometric dimensions of the bearing and properties of the lubricant. Then the initial pressure distribution sets to atmospheric pressure and the pressure values are calculated from Eq. [11] and the pressure distribution is set to new initial pressure distribution for the next iteration step. In the solution, boundary condition could be given as follow.

- Pressure values at the end of the journal are equal to the atmosphere.
- The distribution function is periodic.
- Pressure values at the orifice inlet are equal to supply pressure.

4. Results and Discussion

The influences of the lubricant with TiO_2 nanoparticle additives on the load capacity are theoretically studied for a hydrostatic journal bearing. The flow model is numerically solved for different sizes and volumetric ratios of the TiO_2 nanoparticle and load capacity is obtained. In literature, there is no study which is considered the lubricant with nanoparticle additive effect on the load capacity of a hydrostatic journal bearing. Hence, to ensure the validity of developed the solution strategy, the results of the present study have been compared with the results of the Rowe et al. [32] and Ram et al. [33]. In Fig. 2, for the hydrostatic journal bearing whose detailed is given in Table 1, the fluid film forces are calculated and the results are illustrated. It could be observed from Fig. 2 that the values and trend of the load capacity are good agreement.

Table 1. Dimensions and geometric parameters of journal bearing [32, 33]

Description	**Value**
Land width ratio	0.25
L/D ratio	0.25
Number of orifices per row	12
Number of rows	2
Rotational speed	0
Concentric pressure ratio, β^*	0.5
Discharge coefficient, C_d	0.55
Viscosity of lubricant, μ_o	0.0264 Pa.s
Density of the lubricant, ρ	860 kg/m^3

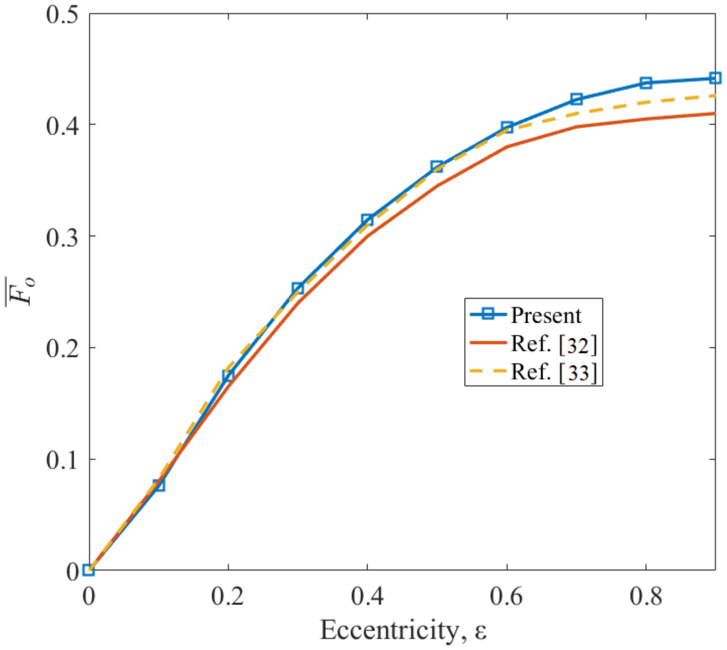

Figure 2. Variations of dimensionless fluid film forces with respect to eccentricity

For different nanoparticle size, the lubricant flow model is solved to analyse the influence of the nanoparticle size on the load capacity of the hydrostatic journal bearing, and the load capacities of the journal bearings whose detailed is given in Table 2 are calculated.

Table 2. Details of the hydrostatic bearing and lubricant

Description	**Value**
Clearance, c	75x10^{-6} m
Bearing length, L	0.1 m
Bearing radius, R	0.05 m
Diameter of the orifice, d_o	1x10^{-3} m
Number of the orifice	4
Supply pressure	4 bar
Discharge coefficient, C_d	0.5
Viscosity of lubricant, μ_o	0.0264 Pa.s
Density of the lubricant, ρ	860 kg/m^3
Density of the nanoparticle, ρ_n	4250 kg/m^3

Fig. 3 shows the alterations of the load capacity in regard to the eccentricity ratio for different nanoparticle sizes. It is seen from Fig. 1 that the load capacity increases when the eccentricity ratio grows up for all cases, as expected. Because the radial clearance shrinks with increasing the eccentricity ratio. On the other hand, the effects of the nanoparticle size on the load performance are almost invisible for a low eccentricity ratio. However, the nanoparticle size affects the load capacity for a higher eccentricity ratio (see Fig. 3a). In addition, the effects of the nanoparticle size on the load capacity is more dominant for higher volumetric ratio of the nanoparticle (see Fig. 3b-3c). Furthermore, the load capacity increases with increasing the nanoparticle size for higher volumetric ratio, because the value of the lubricant viscosity increases with the nanoparticle additive and the viscosity is higher for the coarse grain of the nanoparticles.

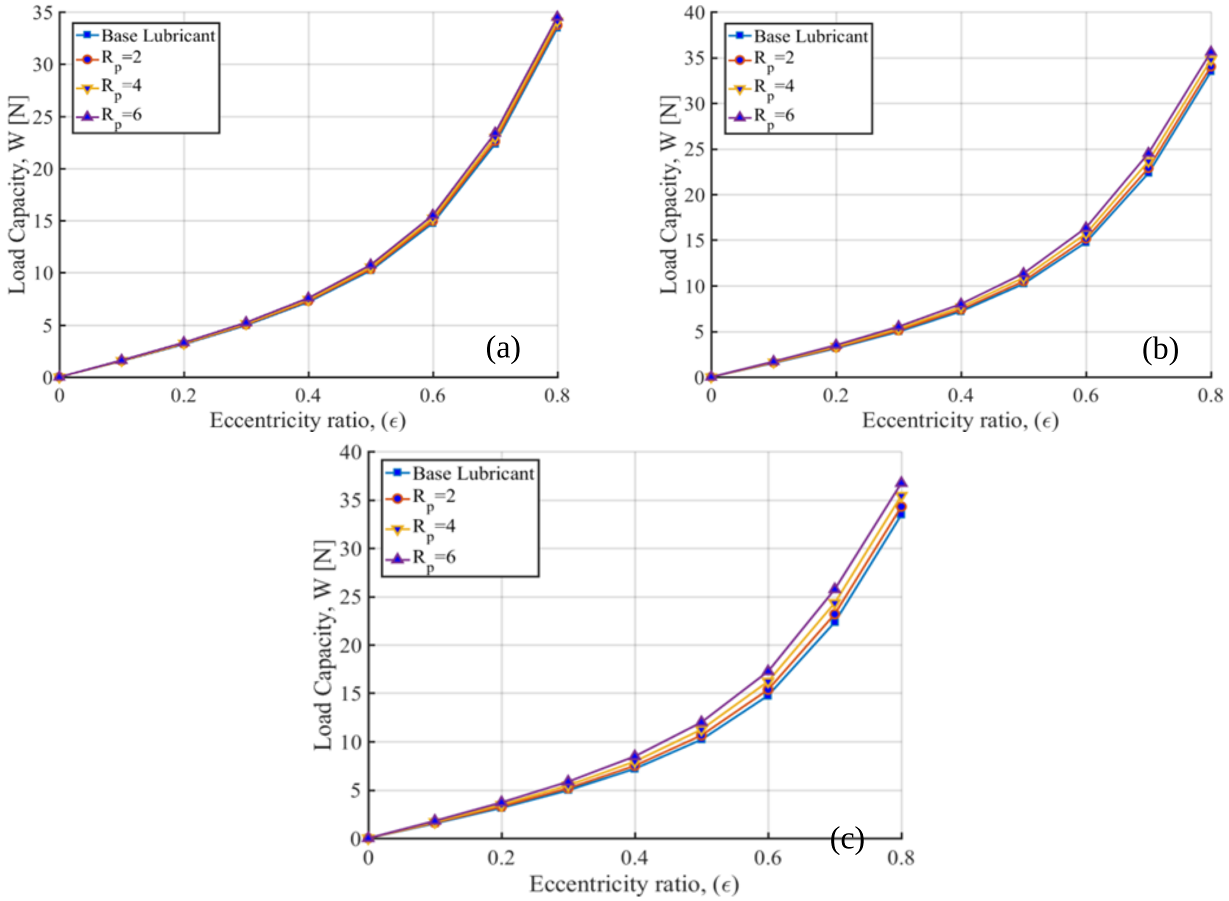

Fig. 3. Variations of the load capacity in regard to eccentricity ratio for different nanoparticle size, a) φ=0.25%, b) φ=0.5%, c) φ=0.75%

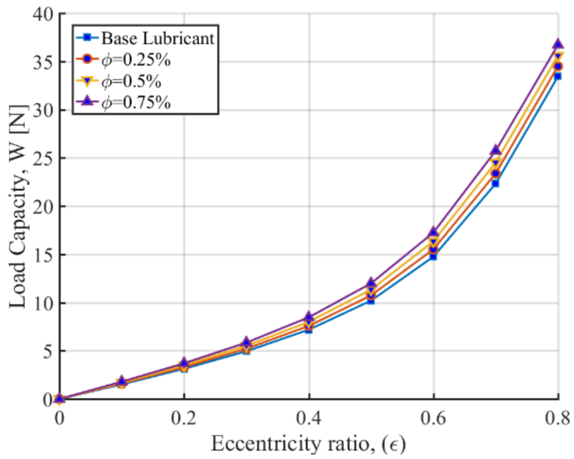

Fig. 4 Variations of the load capacity in regard to the eccentricity ratio for different volumetric ratios of the nanoparticle additive

The flow model is solved for different volumetric ratios of the nanoparticle and the load capacities of the journal bearings are calculated to study the effects of the volumetric ratio on load performance. Fig. 4 shows the variations of the load capacity with respect to the eccentricity ratio for different volumetric ratios of the nanoparticle and nanoparticle size of R_p=6. It is seen from Fig. 3 that the fluid film force is higher for high volumetric ratio due to the improvement of the lubricant viscosity.

5. Conclusions

In this study, the influences of the lubricant with nanoparticle additives on the performance of the hydrostatic bearing were theoretically investigated. In order to obtain the load capacity, the fluid flow is modelled with the Reynolds equation and the lubricant viscosity is estimated from the Krieger-Dougherty model. Then the load capacity is calculated for different nanoparticle sizes and volumetric ratios. From the simulation results, the conclusions could be listed as follows,

- The lubricant with nanoparticles additives increases the load carrying capacity and the performance of the hydrostatic journal bearing.
- The performance of the hydrostatic bearing is higher for high volumetric ratio and larger size of the nanoparticle additives.
- The growth of the nanoparticle size is improved the load capacity of the hydrostatic journal bearing. Moreover, the influences of the nanoparticle size on the load capacity is more dominant for high volumetric ratio of the nanoparticle.

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