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# Effect of Creating Surface Textures and Using Nanofluid Lubricant on the Dynamic Stability of Noncircular Journal Bearings

**Mahdi Zare Mehrjardi[1], Abolfazl Rasoolizadeh Shooroki[2], Mehran Rabani [3,*]**

**Reza Rashidi Meybodi[4]**

[1]Assoc. Prof., Department of Mechanical Engineering, Ardakan University, Iran.
[2] Ph.D., Department of Mechanical Engineering, Yazd University, Iran.
[3]Assist. Prof., Department of Mechanical Engineering, Ardakan University Iran.
[4]Assoc. Prof., Department of Mechanical Engineering, Meybod University Iran.

*Corresponding author: M.Rabani@ardakan.ac.ir

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## Abstract

Any change in the lubricant structure and the geometry of the components effectively impacts the performance of rotor-bearings supports as one of the common parts of industrial machines. Today, with technological advancements, the producing of nanofluids and textured surfaces are developed. In the present study, the effects of cylindrical textures depth and applying the titanium dioxide nanoparticles on the performance of hydrodynamic noncircular two lobe journal bearings are evaluated. For this purpose, after deriving the governing Reynolds equation, a linear dynamic analysis model is employed to investigate the stability condition of the bearing. Finally, various parameters such as the load-carrying capacity, attitude angle, critical mass and the whirl frequency ratio are examined as steady-state and dynamic performance characteristics of the system under the influence of cylindrical textures properties and the concentration of $\mathrm{TiO_2}$ nanoparticles. The results indicate an improvement in the performance characteristics of the bearing system when textures are created with optimized depth and surface location. Additionally, increasing the concentration of nanoparticles shows an enhancement in the steady-state performance of the system. Overall, the results indicate the possibility of optimizing and enhancing the performance of the two lobe bearings using surface textures and nanoparticle concentrations in a principled manner.

**Keywords:** Two Lobe Hydrodynamic Journal Bearing, Cylindrical Texture, Nanofluid, $TiO_2$, Dynamic Stability.

## 1. Introduction

In recent decades the increasing use of lubrication systems in various industrial machinery, particularly those involving journal bearings has led to significant advancements in this field researches. The design of efficient lubrication systems for bearings, which play a crucial role in the structure of diverse equipment, especially rotating systems, has improved their performance and can lead to substantial economic savings in materials and energy. Among the bearings used in machinery, journal bearings, due to their unique geometric shape, ease of lubrication, and optimal efficiency, have a special position.

In journal bearings, the thickness of the lubricant film between the rotor and the bearing shell, as well as the viscosity of the oil, are key factors affecting the efficiency of the system. Creating textures on the surface of the bearing shell and adding nanoparticles to the base lubricant are among the latest methods used to enhance the performance of journal bearings in recent years.

In line with the use of textured surfaces to improve the performance of oil-lubricated journal bearings, a new movement in this scientific field was created following the publication of Etsion et al.'s study on the impact of surface textures on improving the performance of interacting surfaces in 1996 [1]. Since then, many theoretical and experimental studies have been conducted by tribology researchers to improve the tribological performance of interacting surfaces. One of the most significant recent studies in this area is the numerical investigation by Manser et al. on the effect of square, triangular, and circular textured surfaces on the performance of hydrodynamic journal bearings with misalignment rotor [2]. The results show that the geometry and placement of textures on the inner surface of the bearing shell are crucial for improving journal bearing performance. Additionally, square, triangular, and circular textures are considered the best types of textures for enhancing the bearing performance, respectively. A study on the thermo hydrodynamic performance of noncircular, two lobe journal bearings with textured surfaces was conducted by Bhasker et al. in 2021 [3]. The results of this research show that noncircular bearings can provide higher load capacity and lower power losses compared to circular journal bearings.

Regarding the use of nanofluids to improve the performance of oil-lubricated journal bearings, a study by Suryawanshi and Pattiwar in 2018 examined the effect of adding $TiO_2$ nanoparticles to the base lubricant on the tribological performance of circular and elliptical journal bearings [4]. The results indicate that nanofluid lubrication improve the performance of bearing compared to the same system using the Newtonian lubricant. Another study by Hammza et al. in 2020 investigated the effect of solid nanoparticles in the lubricant composition on the static and dynamic performance of journal bearings [5]. The findings clearly show that nanofluid lubricants can be used to improve parameters such as pressure distribution, rotor attitude angle, load carrying capacity, friction force, equivalent stiffness and damping coefficients of the lubricant film and critical velocity of rotor center.

In 2021, Awasthi and Maan published a new study on the surface texture effects of on the performance of hydrodynamic journal bearings under turbulent lubrication regimes [6]. Their results demonstrate that using textures in appropriate locations can enhance the performance of hydrodynamic journal bearings in terms of increased load carrying capacity, reduced friction coefficient, and extended dynamic stability range. A review of the performance of textured bearings was conducted by Mishra and Aggarwal in 2023 [7]. Their research shows that the presence of textures on the bearing surface results in lower friction and higher load capacity. Profito et al. in 2024 presented a numerical and experimental evaluation of textured bearings for friction reduction [8]. The measured friction in the presence of textures was compared with a sample without textures. The study's results indicate that micro scale mechanisms of reducing shear stress and effective viscosity of the lubricant, due to cavitation caused by textures, simultaneously act to decrease the friction coefficient of textured shells.

Today, utilizing modern technologies such as laser techniques, lithography, anisotropic etching, reactive ion etching, chemical etching, abrasive jet machining, and mechanical methods like vibratory rolling and milling, it is possible to create complex three-dimensional textures on smooth surfaces, thereby enhancing their performance.

Based on the literature review, it appears that there is a gap in research regarding the static performance and dynamic stability analysis of non-circular two-lobe journal bearings with surface textures under nanofluid lubrication. The current study aims to address this gap by investigating the performance parameters of these bearings in steady-state conditions and their dynamic stability. Specifically, the focus is on non-circular, textured bearings with cylindrical textures, lubricated with a nanofluid composite consisting of titanium dioxide particles and SAE30 as the base oil.

## 2. Theory

The nondimensional governing Reynolds equation for hydrodynamic lubrication of a journal bearing, assuming constant temperature, an incompressible lubricant, and alignment of the rigid rotor and shell axes, is presented below:

$$\frac{\partial}{\partial\theta}\left[\bar{h}_n^3\frac{\partial\bar{P}}{\partial\theta}\right]+\left(\frac{D}{L}\right)^2\frac{\partial}{\partial\bar{z}}\left[\bar{h}_n^3\frac{\partial\bar{P}}{\partial\bar{z}}\right] = 6\mu_{rel}\frac{\partial\bar{h}_n}{\partial\theta}+12\mu_{rel}\frac{\partial\bar{h}_n}{\partial\tau} \quad (1)$$

The dimensionless parameters of the above equation are defined as follows:

$$\theta=\frac{x}{R},\ \bar{z}=\frac{z}{L/2},\ \bar{P}=\frac{C_m^2}{\mu_{bf}\omega R^2}P,\ \bar{h}_n=\frac{h_n}{C_m}, \quad u=R\omega,\quad \tau=t\omega,\quad \mu_{rel}=\frac{\mu_{nf}}{\mu_{bf}} \quad (2)$$

The relative viscosity of nanofluids ($\mu_{rel}$) is expressed as the ratio of the nanofluid viscosity to the viscosity of the base lubricant $(\mu_{nf}/\mu_{bf})$. Additionally, the lubricant film thickness at any point around the noncircular textured bearing as shown in Fig. 1 can be expressed using the following relationship [9].

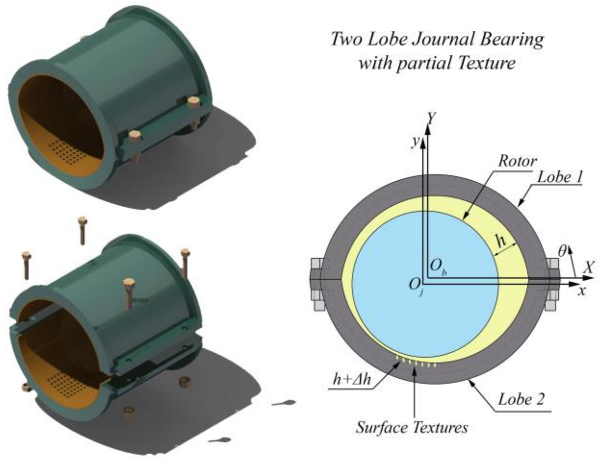


**Figure 1. Noncircular two lobe journal bearings with surface textures**

$$\bar{h}_n=\bar{h}_{n-smooth}+\Delta\bar{h}(\theta,z) \quad (3)$$

In equation (3), $\bar{h}_{n-smooth}$ represents the film thickness between the rotor and the shell in a smooth, non-textured state at any point around the circular bearing, which is defined by equation (4). Additionally, $\Delta\bar{h}(\theta,z)$ denotes the height of the cylindrical textures present on the inner surface of the bearing [10].

$$\bar{h}_n=\frac{h_n}{C_m}=\left(\frac{1}{\delta}-\frac{X_j}{C_m}\cos\theta-\frac{Y_j}{C_m}\sin\theta+\left(\frac{1}{\delta}-1\right)\cos(\theta-\theta_0^n)\right) \quad (4)$$

In equation (4), the index $n$ represents the number of lobes in the noncircular journal bearing, and the parameters $X_j$ and $Y_j$ denote the position of the journal center in the static equilibrium state relative to the coordinate axes. Additionally, $\theta_0^n$ indicates the angle of the lobe centerline relative to the $X$ axis. The parameter $\delta$ signifies the degree of noncircularity of the bearing, defined as the ratio of the minimum radial clearance $c_m$ to the maximum radial clearance $C$ when the bearing and rotor are concentric.

In the present study, the effect of the cylindrical dimples depth created within a fixed angular range around the bearing on the steady-state performance and dynamic stability of two lobe bearings are investigated. Also, $r_x$, $r_y$, and $r_z$ represent the radius in the circumferential direction, depth, and radius in the longitudinal direction of each cylindrical texture, respectively, along the $x$, $y$, and $z$ coordinate axes.

Considering the simulation of rotor center displacement as limited amplitude oscillatory disturbances in a closed loop around the static equilibrium point, the components of the rotor center displacement along the coordinate axes can be expressed as follows:

$$\bar{\mathrm{X}}' = \mathrm{Re}(|\bar{\mathrm{X}}'|\mathrm{e}^{\mathrm{j}\gamma\tau}) \quad \text{and} \quad \bar{\mathrm{Y}}' = \mathrm{Re}(|\bar{\mathrm{Y}}'|\mathrm{e}^{\mathrm{j}\gamma\tau}) \tag{5}$$

In this context, $\bar{X}'$ and $\bar{Y}'$ denote the components of the perturbed displacement of the rotor center along the coordinate axes. The parameter $\gamma$, referred to as the whirl frequency ratio, which is defined as the ratio of the angular velocity of the perturbed motion of the journal center around the static equilibrium point ($\omega_P$) to the angular velocity of the journal rotation around its longitudinal axis ($\omega$). The components of the dynamic pressure ($\bar{P}'_X$,$\bar{P}'_Y$) across the problem domain are determined by differentiating the dimensionless form of the Reynolds equation with respect to the dynamic coordinate components ($\bar{X}'$,$\bar{X}'$) and setting $\bar{X}'$ and $\bar{Y}'$ to zero. In the present study, the finite elements numerical solution method (FEM) based on the Galerkin model is used to solve the governing equations of lubrication for analyzed noncircular two lobe journal bearings [10].

## 3. Steady-state and Dynamic Performance Characteristic of Textured Two Lobe Bearing

**a) Load carrying capacity**

The components of the load-carrying capacity of the bearing along the coordinate axes can be calculated using equation (6).

$$\begin{bmatrix}\bar{W}_{X0}\\ \bar{W}_{Y0}\end{bmatrix} = \sum_{n=1}^{N}\begin{bmatrix}\bar{W}_{X0}^{n}\\ \bar{W}_{Y0}^{n}\end{bmatrix} = \sum_{n=1}^{N}\int_{\theta_1^n}^{\theta_2^n}\int_{-1}^{+1}\bar{P}_{0n}\begin{bmatrix}cos\theta\\ sin\theta\end{bmatrix}d\bar{z}d\theta \tag{6}$$

The overall load-carrying capacity of the bearing is also determined as follows:

$$\bar{W}_0 = \frac{2C_m^2}{\mu_{bf}\omega R^3 L}W_0 = \sqrt{\bar{W}_{0x}^2 + \bar{W}_{0y}^2} \tag{7}$$

**b) Dynamic Stability**

The determining factor for the magnitude of the dynamic stability parameters of noncircular journal bearings in a linear model depends on the equivalent stiffness and damping coefficients of the lubricant film, which are derived from solving the governing equations. The dynamic displacement equations of the rotor center supported by journal bearing for periodic rotational motion around the static equilibrium point are expressed in the form of the following equation.

$$\bar{M}_J\begin{Bmatrix}\ddot{\bar{X}}'\\ \ddot{\bar{Y}}'\end{Bmatrix} + \begin{bmatrix}\bar{B}_{XX} & \bar{B}_{XY}\\ \bar{B}_{YX} & \bar{B}_{YY}\end{bmatrix}\begin{Bmatrix}\dot{\bar{X}}'\\ \dot{\bar{Y}}'\end{Bmatrix} + \begin{bmatrix}\bar{S}_{XX} & \bar{S}_{XY}\\ \bar{S}_{YX} & \bar{S}_{YY}\end{bmatrix}\begin{Bmatrix}\bar{X}'\\ \bar{Y}'\end{Bmatrix} = 0 \tag{8}$$

In equation (8), the parameter $\bar{M}_J = M_J(2C_m^3\omega/\mu R^3 L)$ refers to the dimensionless mass of the rotor. A non-trivial solution of the equation is possible if the coefficient matrix is singular. Therefore, the characteristic equation of the linear dynamic system, assuming limited amplitude closed loop motion for the displacement of the rotor center at the threshold of instability, is as follows:

$$\left(-\bar{M}_J\gamma^2 + \bar{S}_{XX} + i\gamma\bar{B}_{XX}\right)\left(-\bar{M}_J\gamma^2 + \bar{S}_{YY} + i\gamma\bar{B}_{YY}\right) - (\bar{S}_{XY} + i\gamma\bar{B}_{XY})(\bar{S}_{YX} + i\gamma\bar{B}_{YX}) = 0 \tag{9}$$

Separating the real and imaginary parts of equation (9) and set them equal to zero yields two separate equations. These equations provide a measure for determining the dynamic stability margin of the system based on the dimensionless rotor mass and whirl frequency ratio $(\bar{M}_J,\gamma)$. Once the final corrected whirl frequency ratio is determined and the iterative method is completed, the stability region of the rotor and journal bearing assembly can be identified based on the linear dynamic model.

## 4. Results and Discussion

The design parameters of the noncircular journal bearing analyzed in this study are presented in Table 1.

Figure 2 shows the effect of the concentration of $TiO_2$ nanoparticles in the SAE30 base lubricant on the pressure distribution of the lubricant film at the central longitudinal line of two lobe bearing with a smooth surface. The diagrams in Fig. 2 suggest that increasing the concentration of $TiO_2$ nanoparticles enhances the pressure distribution of the bearing. This enhancement is due to the increased viscosity of the lubricant with higher concentrations of $TiO_2$ nanoparticles. According to the diagrams presented in Fig. 2, it is noted that the angular position of approximately 270 to 330 degrees is a critical location in the bearing, as the maximum pressure distributed in the lubricant film is created at this angle. Creating surface textures at this angular location could have the most significant impact on the bearing's performance. Therefore, the effect of $TiO_2$ nanoparticle concentration in the SAE30 base lubricant on the performance parameters of the bearing, such as the load carrying capacity, critical mass of the rotor and whirl frequency ratio, was further investigated for surface textures at angular positions of 270 to 300 and 300 to 330 degrees in two lobe journal bearings.

**Table 1. Specifications of analyzed noncircular journal bearing**

| Parameter | Definition | value |
|---|---|---|
| $N_{xD}$ | The number of textures in the circumferential direction | **5** |
| $N_{zD}$ | The number of textures in the longitudinal direction | **10** |
| $\bar{R}_x = r_x/R$ | The dimensionless radius of textures in the circumferential direction | **0.0476** |
| $\bar{R}_z = r_z/L$ | The radius of textures in the longitudinal direction | **0.0238** |
| $\bar{R}_y = r_y/C_m$ | nondimensional depth of textures | **0.5** |
| $\varepsilon$ | Eccentricity ratio | **0.5** |
| $\delta$ | Preload factor | **0.7** |
| $z_1$ | The starting border of textured domain in the longitudinal direction | **0.05** |
| $z_2$ | The end border of textured domain in the longitudinal direction | **0.95** |

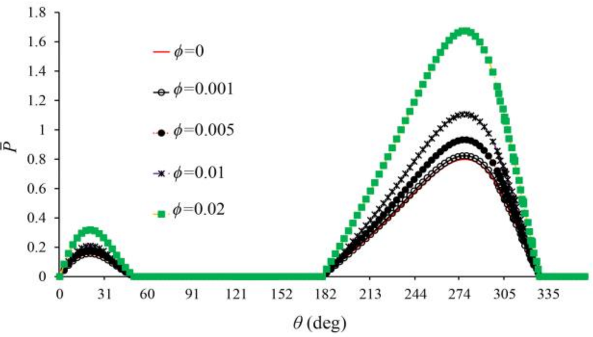


**Figure 2. The effect of $TiO_2$ nanoparticle on the pressure distribution at the central longitudinal plane of two lobe hydrodynamic journal bearings**

In Fig. 3, the concentration of $TiO_2$ nanoparticles is shown to affect the load carrying capacity of two lobe bearings based on the depth of cylindrical surface textures. Results indicate that in two lobe bearings with cylindrical textures positioned at an angular range of 270° to 300°, the load carrying capacity of the bearing increases. This increase appears with the creation of textures at low depths and stops after passing a specific depth, where the upward trend of the load carrying capacity in the bearing ceases. However, the analysis of the charts presented in Fig. 3 shows a decrease in the load carrying capacity of two lobe bearings with the creation and subsequent increase in texture depth when cylindrical textures are positioned at an angular range of 300° to 330°. In this case as well, the decrease in the mentioned load appears with the creation of textures at low depths and stops after passing a specific depth, where the downward trend of the load carrying capacity in the bearing ceases. From the charts in Fig. 3, it can also be concluded that increasing the concentration of $TiO_2$ nanoparticles in the base lubricant oil for two lobe journal bearings, with or without texture and at any depth or placement of surface roughness, increases the load carrying capacity of the bearing. The reason for this increase, which becomes more apparent with higher nanoparticle concentrations, can be attributed to the increase in the relative viscosity of the lubricant fluid by combining nanoparticles with the base oil.

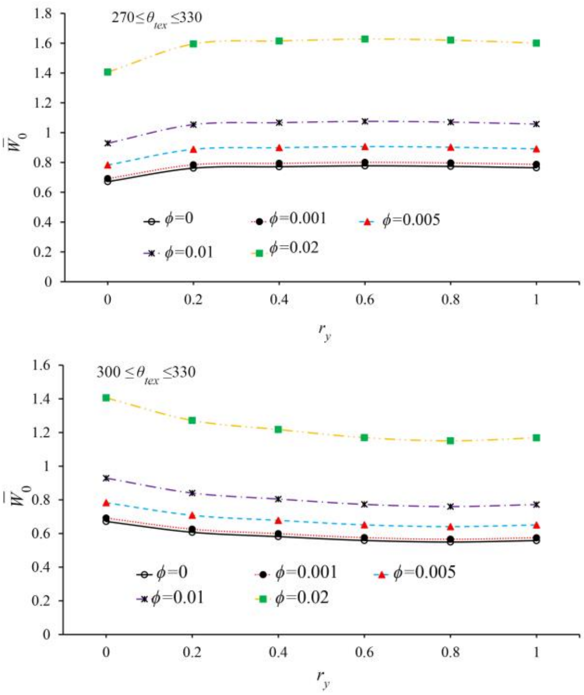


**Figure 3. Effect of $TiO_2$ nanoparticle concentration on load carrying capacity of textured two lobe bearing**

In Fig. 4, the effect of the volume fraction of $TiO_2$ nanoparticles on the critical mass parameter of the rotor is shown based on the depth of cylindrical textures placed at two angular ranges of 270° to 300° and 300° to 330°. The results presented in Fig. 4 show that with the placement of surface textures in the angular range of 300° to 330°, changing the depth of these dimples doesn't have a positive effect on increasing the stability of the bearing. With the creation of cylindrical textures, the stability of the system decreases in terms of reducing the critical mass of the rotor and upon reaching a specific depth, the critical mass of the rotor reaches a constant value with further reduction in texture depth within the range [0-1] and the trend of decreasing stability of the rotor-bearing system stops. This is while using surface textures in the angular range of 270° to 300°, as shown in Fig. 4, up to a certain depth, the stability of the system decreases compared to bearings without texture and upon reaching a specific depth this stability increases and then with passing a specific depth the stability of the system in terms of reducing the critical mass of the rotor decreases.

In other words, in two lobe bearings, using surface textures in the angular range of 270° to 300° with the creation and subsequent increase in texture depth, the stability of the bearing follows a decreasing, increasing and then decreasing trend again. Also, in the journal bearing under investigation adding $TiO_2$ nanoparticles to the base lubricant oil SAE30 doesn't affect the critical mass parameter of the rotor and the stability of the rotor-bearing system. Therefore, it can be concluded from this part that in two lobe bearings, using cylindrical textures with the appropriate depth and placement combined with $TiO_2/SAE30$ nano lubricant can achieve optimal performance in terms of static and dynamic behavior compared to bearings without texture using conventional Newtonian lubricants.

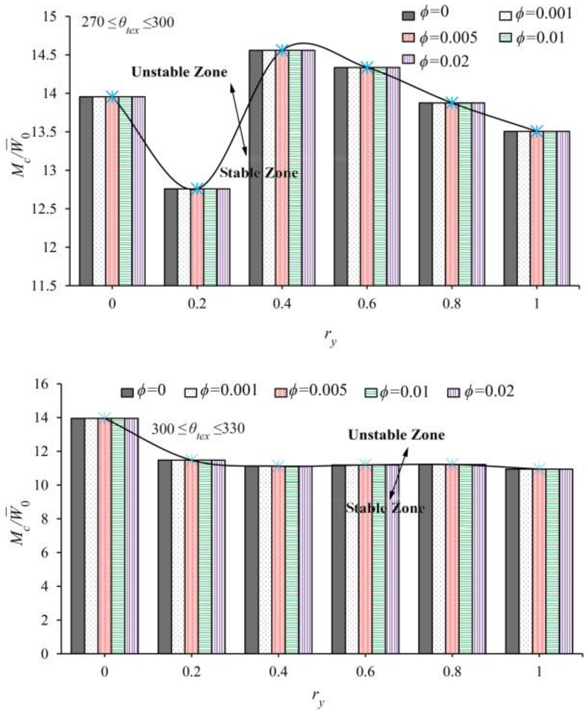


**Figure 4. Effect of $TiO_2$ nanoparticle volume fraction on critical mass of rotor of textured two lobe bearing**

The results of the investigation indicate that using cylindrical textures at an appropriate position and depth, as well as combining an optimal volume fraction of $TiO_2$ nanoparticles can be a suitable strategy for improving the steady state and dynamic stability performance of textured two lobe noncircular journal bearings.

## 5. Conclusions

This study investigates the effect of cylindrical surface textures with various depths and constant number in the high pressure region of the inner surface of noncircular two lobe hydrodynamic journal bearings, combined with the addition of $TiO_2$ nanoparticles to SAE30 base oil as a non-Newtonian lubricant. The effects of using texture surface and nano lubricant on the steady state performance and dynamic stability of two lobe bearings in terms of the load carrying capacity, attitude angle of the rotor center, critical mass of the rotor, and whirl frequency ratio are examined. For this goal, the governing Reynolds equation of textured two lobe journal bearings with incompressible nanofluids is evaluated using the finite element method (FEM). Also, the Reynolds boundary condition is applied to distinguish between converging and diverging pressure film regions or the beginning of cavitation zone in the lubricant film. The results of this study suggest the following:

**1-** The results indicate an increase in the distributed pressure in the lubricant film of two lobe journal bearings with an increase in the amount of $TiO_2$ nanoparticles. The main reason for this increase in pressure is the enhancement of the relative viscosity of the nano lubricant compared to the Newtonian SAE30 oil.

**2.** In non-circular two lobe journal bearings with cylindrical surface textures positioned at an angular range of 270° to 300° the load-carrying capacity of the bearing increases. This increase appears with the creation of textures at low depths and stops after passing a specific depth. Conversely, creating and increasing the depth of textures in the angular range of 300° to 330° reduces the load carrying capacity of analyzed bearings.

**3.** Creating cylindrical surface textures at any depth in the angular range of 300° to 330° decreases the dynamic stability of the rotor-bearing system. However, placing the textures in the angular range of 270° to 300°, results in an oscillatory trend in dynamic stability as the dimensionless texture depth varies within the range [0-1].

**4.** Selecting the appropriate volume fraction of nanoparticles and the position and depth of surface textures can play a crucial role in achieving optimal performance of noncircular two lobe journal bearings.

## 6. Nomenclature

| | |
|---|---|
| $\boldsymbol{C}$ | Conventional radial clearance, (m) |
| $\boldsymbol{C_m}$ | Minor clearance when journal and bearing centers are coincident, (m) |
| $\boldsymbol{\overline{M}_C}$ | Nondimensional critical mass parameter |
| $\boldsymbol{O_B}$ | Bearing center |
| $O_c$ | Center of the surface textures |
| $O_J$ | Journal center |
| $P$ | Fluid film pressure, $(\mathrm{N/m^2})$ |
| $\boldsymbol{r_x}, \boldsymbol{r_y}, \boldsymbol{r_z}$ | The radius and depth of surface texture along the Cartesian coordinate axis, (m) |
| $\boldsymbol{W_0}$ | Steady state resultant load carrying capacity, (N) |
| $\boldsymbol{x_c}, \boldsymbol{y_c}, \boldsymbol{z_c}$ | Local coordinate of textures |
| **Greek symbols** | |
| $\boldsymbol{\omega}$ | Angular velocity of the rotor,( $1/\mathrm{S}$) |
| $\boldsymbol{\omega_P}$ | Angular velocity of the rotor center perturbations,( $1/\mathrm{S}$) |
| $\boldsymbol{\gamma}$ | Whirl frequency ratio,$(\overline{\omega}_P/\overline{\omega})$ |
| $\boldsymbol{\mu_{bf}}$ | Absolute viscosity of the base oil, $(\mathrm{N.s/m^2})$ |
| $\boldsymbol{\mu_{nf}}$ | Absolute viscosity of the nano lubricant, $(\mathrm{N.s/m^2})$ |
| $\boldsymbol{\mu_{rel}}$ | Relative viscosity of the $\mathrm{Tio_2/SAE30}$ lubricant |
| $\boldsymbol{\phi_0}$ | Angle of journal and bearing line of centers with z axis |
| $\boldsymbol{\varepsilon}$ | Eccentricity ratio |
| $\boldsymbol{\lambda}$ | Bearing aspect ratio, $(\overline{\mathrm{L}}/\overline{\mathrm{D}})$ |
| $\boldsymbol{\delta}$ | Preload of the bearing, $(\overline{\mathrm{C}}_m/\overline{\mathrm{C}})$ |

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