Effect of Bearing Deformation on the Performance of a Magnetic Fluid-Based Infinitely Rough Short Porous Journal Bearing

M. E. Shimpi and G. M. Deheri

Abstract An attempt has been made to investigate theoretically the performance of a transversely rough porous infinitely short journal bearing considering bearing deformation under the presence of a magnetic fluid lubricant. Christensen and Tonder's stochastic model has been used to develop the stochastic Reynolds' type equation. This associated equation is solved to obtain the pressure distribution paving the way for the calculation of the load carrying capacity. The results indicate that the roughness pattern and the height of the roughness have significant effects on the performance characteristics. It is noticed that the bearing deformation further influences the adverse effect rendered by transverse roughness. However, for a suitable choice of eccentricity, the magnetization relatively improves the performance of the bearing system for a long range of deformation, at least in the case of negatively skewed roughness. Lastly, it is revealed that higher bearing deformation hampers the positive effect of eccentricity ratio.

Keywords Deformation · Short bearing · Magnetic fluid · Squeeze film · Surface roughness

1 Introduction

Lin [1] theoretically analyzed the squeeze film behaviour in a finite journal bearing in the presence of a couple stress fluid. It was found that the couple stress effects not only increased the load carrying capacity significantly but also lengthened the response time of the squeeze film.

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Turaga et al. [2] adopted the model of Christensen and Tonder [3–5]; to study the influence of roughness patterns on the steady state and dynamic characteristics of hydrodynamic journal bearing with rough surfaces. It was concluded that the transverse surface roughness induced a significant effect on the performance of the bearing system.

In order to analyze the effect of using current carrying wear model in the design of a hydrodynamic journal bearing lubricated with Ferrofluid et al. [6] developed the modified Reynolds type equation for a Ferrofluid under an applied magnetic field. The results established that the magnetic lubrication resulted in higher load carrying capacity and reduced friction coefficient as compared to that of a conventional fluid based lubrication.

Gururajan and Prakash [7] extended the investigation carried out by Gururajan and Prakash [8] by incorporating the velocity slip in a thin walled infinitely short rough porous journal bearing operating under the steady conditions in a hydrodynamic regime. It was found that a strong interaction between roughness and slip effects was in place. However, for an effective performance the slip parameter deserved to be minimized.

The numerical analyses of very narrow journal bearings were presented by Stahil [9]. A number of relevant dimensionless design quantities were computed for each combination of different width, diameter ratio and eccentricities.

Hsu et al. [10] theoretically studied the combined influence of couple stress and surface roughness on the lubrication performance of a short journal bearing. It was established that the couple stress effect and the longitudinal roughness improved the load carrying capacity and decreased the friction parameters.

Deheri et al. [11] considered the performance of a longitudinally rough slider bearing with squeeze film formed by a magnetic fluid adopting the Christensen and Tonder's stochastic modeling of roughness. It was concluded that the longitudinal surface roughness resulted in an improved load bearing capacity.

Haque and Guha [12] theoretically investigated the performance characteristics isotropically rough porous hydrodynamic journal bearing of finite width with the effect of slip flow on the basis of Beavers-Joseph criterion. The results obtained in this article confirmed that the influence of roughness on the steady state performance of the journal bearing could not be neglected.

Chen et al. [13] derived a modified Reynolds equation in order to study the effects of non Newtonian lubricants. A comparison showed that surface roughness had less effect on performance results as compared to lubricants with non Newtonian property.

Nada et al. [14] investigated the lubrication of a finite hydrodynamic journal bearing under the presence of magnetic fluid taking couple stress effect into consideration. It was observed that the combined influence of couple stress and magnetic effects on the bearing performance characteristics were significant. The results indicated that fluids with couple stress were better than Newtonian fluids and the performance characteristic enhanced owing to magnetic effect.

Urreta et al. [15] carried out a discussion on the solution of the Reynolds' Equation to obtain the pressure distribution in a hydrodynamic journal bearing, based on viscosity modulation for Ferrofluid. It was conclusively established that magnetic fluid could be used to manufacture active journal bearings.

Shimpi and Deheri [16] analyzed the performance of a magnetic fluid based transversely rough short bearing. The graphical representation made it clear that the negative effect of standard deviation could be compensated largely due to the magnetization parameter in the case of negatively skewed roughness resorting to suitable values of eccentricities ratio.

Recently, Patel et al. [17] theoretically investigated the behaviour of a magnetic fluid based squeeze film for a hydrodynamic short bearing. It was found that the load carrying capacity increased nominally due to magnetic fluid lubricant while the coefficient of the friction decreased significantly. Besides, this study confirmed the importance of forms of the magnitude of the magnetic field.

1.1 Analysis

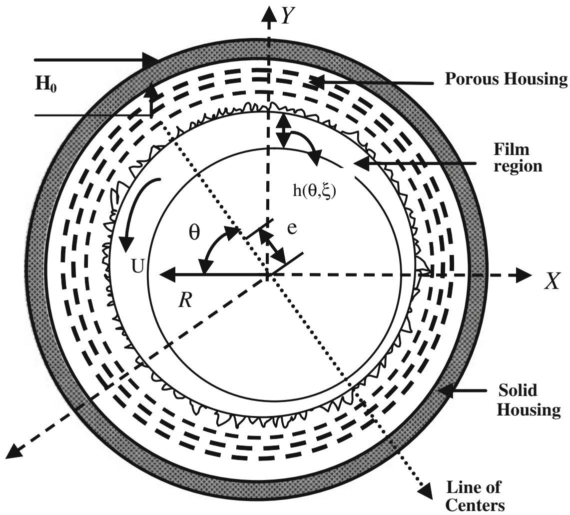
The geometry and configuration of the bearing system is in Fig. 1.

The assumptions of usual hydrodynamics lubrication theory are taken into consideration in the development of the analysis. The following Christenson and Tonder [3–5] bearing surfaces are assumed to be transversely rough. The expression for film thickness is considered as

$$h(x) = \overline{h(x)} + h_s$$

where $\overline{h}$ is the mean film thickness, h_s is assumed to have the probability density function

Fig. 1 The configuration of the bearing system



$$F(h_s) = \begin{cases} \frac{32}{35b}\left[1 - \left(\frac{h_s}{b}\right)^2\right]^3, & -b \le h_s \le b \\ 0, & otherwise \end{cases}$$

where b is the maximum deviation from the mean film thickness. The mean α, the standard deviation σ and the parameter ε, which is the measure of symmetry of the random variableh_s are defined by the relationships

$$\alpha = E(h_s),\ \sigma^2 = E\left[(h_s - \alpha)^2\right],\ \varepsilon = E\left[(h_s - \alpha)^3\right],$$

where E denotes the expected value defined as

$$E(R) = \int_{-b}^{b} RF(h_s)dh_s$$

Stochastically averaging and adopting the properties of magnetic fluid lubrication [16, 18], the associated generilized Reynolds equation is derived as

$$\frac{\partial}{\partial z}\left[g(h)\frac{\partial}{\partial z}\{p - 0.5\mu_0\overline{\mu}H^2\}\right] = \frac{6\mu U}{R}\frac{\partial}{\partial \theta}(h + p_a p'\delta) \tag{1}$$

where,

$$\begin{aligned} h = h_0(1 + e\cos\theta); \quad H^2 = k\left(z - \frac{B}{2}\right)\left(z + \frac{B}{2}\right) \\ g(h) = (h + p_a p'\delta)^3 + 3\alpha(h + p_a p'\delta)^2 \\ + 3\left(\sigma^2 + \alpha^2\right)(h + p_a p'\delta) + \alpha^3 + 3\sigma^2\alpha + \varepsilon + 12\phi H_0, \end{aligned},$$

μ_0 is permeability of free space, $\overline{\mu}$ is the magnetic susceptibility of particles,μ is the viscosity of the lubricant,ϕ is the permeability of porous facing and H_0 is the thickness of porous medium, δ is the local elastic deformation of the porous facing, p_a is the reference ambient pressure. For the details regarding the deformation aspects one is requested to refer [18]. The concerned boundary conditions are

$$p\left(\pm\frac{B}{2}\right) = 0. \tag{2}$$

In view of the following non-dimensional quantities,

$$P = \frac{h_0^3 p}{\mu UB^2},\ \overline{\sigma} = \frac{\sigma}{h_0},\ \overline{\alpha} = \frac{\alpha}{h_0},\ \overline{\varepsilon} = \frac{\varepsilon}{h_0^3},\ \psi = \frac{\phi H_0}{h_0^3},$$

$$\mu^* = -\frac{\mu_0\,\overline{\mu}h_0^3}{\mu U},\ \ \overline{p} = p'p_a,\ \overline{\delta} = \frac{\delta}{h},\ Z = \frac{z}{B}.$$

integrating the stochastically averaged Reynolds Eq. (1) under the boundary conditions (2) one obtains the expression for the non-dimensional pressure distribution as

$$P = \left[-0.5\mu^* - \frac{3h_0^3\, e}{RG(h)}\left(1+\overline{p\delta}\right)\sin\theta\right]\left(Z^2 - 0.25\right) \tag{3}$$

where,

$$\begin{aligned} G(h) &= h_0^3\left[A_1 + A_2\cos\theta + A_3\cos^2\theta + A_4\cos^3\theta\right]; \\ A_1 &= \left(1+\overline{p\delta}\right)^3 + 3\overline{\alpha}\left(1+\overline{p\delta}\right)^2 + 3\left(\overline{\sigma}^2+\overline{\alpha}^2\right)\left(1+\overline{p\delta}\right) \\ &\quad + 3\overline{\sigma}^2\overline{\alpha} + \overline{\alpha}^3 + 12\psi + \overline{\varepsilon} \\ A_2 &= 3e\left[\left(1+\overline{p\delta}\right)^3 + 2\overline{\alpha}\left(1+\overline{p\delta}\right)^2 + \left(\overline{\sigma}^2+\overline{\alpha}^2\right)\left(1+\overline{p\delta}\right)\right] \\ A_3 &= 3e^2\left[\left(1+\overline{p\delta}\right)^3 + \overline{\alpha}\left(1+\overline{p\delta}\right)^2\right];\ A_4 = e^3\left(1+\overline{p\delta}\right)^3. \end{aligned}$$

The load carrying capacity in non-dimensional form then, is calculated as

$$W = \int_0^{\pi}\int_{-0.5}^{0.5} P\, dZ\, d\theta$$

which leads to

$$\begin{aligned} W &= \frac{\mu^*\pi}{12} \\ &\quad + \frac{2\pi h_0^3\, e\overline{\alpha}\left(1+\overline{p\delta}\right)}{9Rh_0^2}\left[\frac{8(4A_1+3A_3)}{4(4A_1+3A_3)^2 - 3(4A_2+3A_4)^2}\right] \\ &\quad + \frac{2\pi h_0^3\, e\overline{\alpha}\left(1+\overline{p\delta}\right)}{9Rh_0^2}\left[\frac{1}{A_1} + \frac{16\sqrt{3}(4A_1+A_3)}{4(4A_1+A_3)^2 - (4A_2+A_4)^2}\right]. \end{aligned} \tag{4}$$

1.2 Results and Discussion

It is clearly seen that the load carrying capacity enhances by $0.261\mu^*$ due to magnetization as compared to that of a conventional lubricant. As the expression for non-dimensional load carrying capacity is linear in μ^*, it is easily observed that increasing values of magnetization cause increased load carrying capacity.

It is noticed that in the absence of magnetization this investigation gives the deformation effect on the behaviour of a rough porous infinitely short journal bearing. Further, for a smooth surface this reduces to the performance of a infinitely short bearing in the absence of deformation. In addition, if there is no deformation this essentially turns to the effect of porosity on infinitely short journal bearing. It is revealed from the Eq. (4) that the bearing can support a load even in the absence of flow.

A comparison of this study with the investigation of Patel et al. [17] tends to indicate that the load carrying capacity is relatively reduced here due to transverse roughness and deformation. Probably, this may be due to the fact that the roughness retards the motion of the lubricant thereby reducing the pressure distribution. However, this situation is slightly improved in the case of negatively skewed roughness.

It is easily observed from Figs. 2, 3, 4 and 5 that the parabolic profile of the pressure is significantly affected by roughness and deformation.

The variation of load carrying capacity with respect to the magnetization presented in Figs. 6, 7, 8, 9, 10 and 11 makes it clear that the load carrying capacity rises sharply due to the magnetic fluid lubricant. However, the effect of variance on the load carrying capacity with respect to magnetization is marginal.

Figures 12, 13, 14, 15 and 16 deal with the variation of load carrying capacity with respect to the standard deviation associated with the roughness. It is clear that

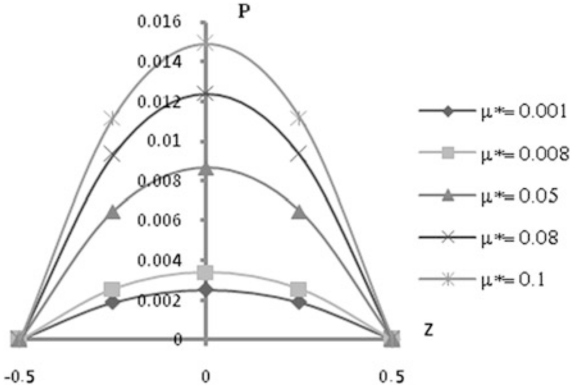


Fig. 2 Distribution of pressure with respect to Z and μ^*

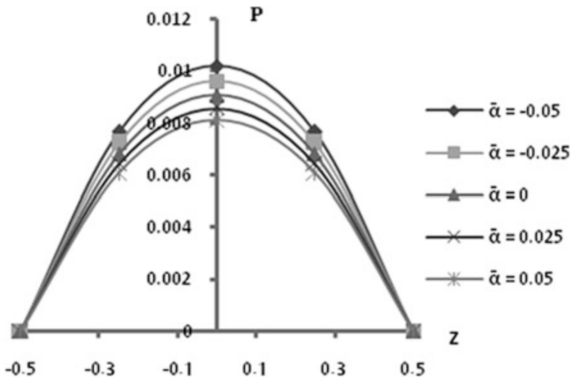


Fig. 3 Distribution of pressure with respect to Z and $\overline{\alpha}$

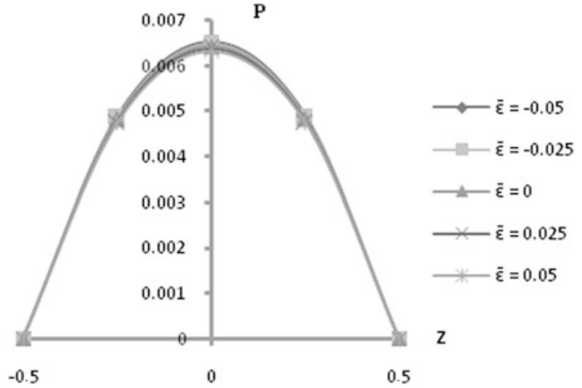


Fig. 4 Distribution of pressure with respect to Z and $\overline{\varepsilon}$

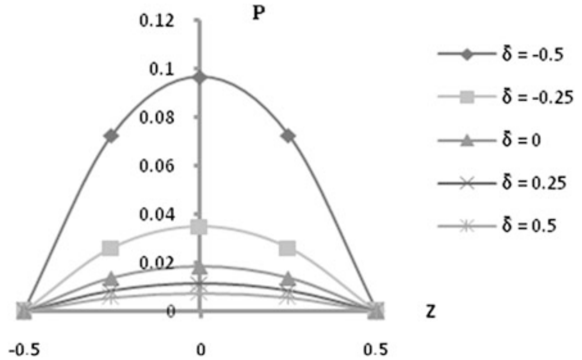


Fig. 5 Distribution of pressure with respect to Z and $\overline{\delta}$

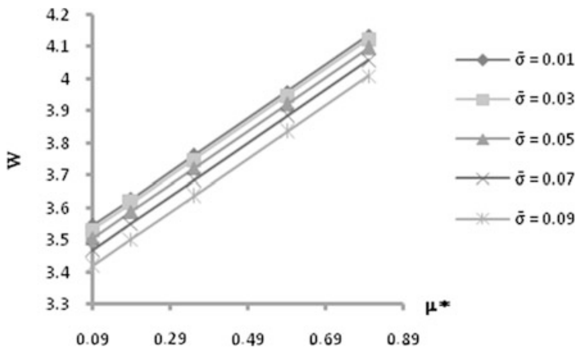


Fig. 6 Variation of Load carrying capacity with respect to μ^* and $\overline{\sigma}$

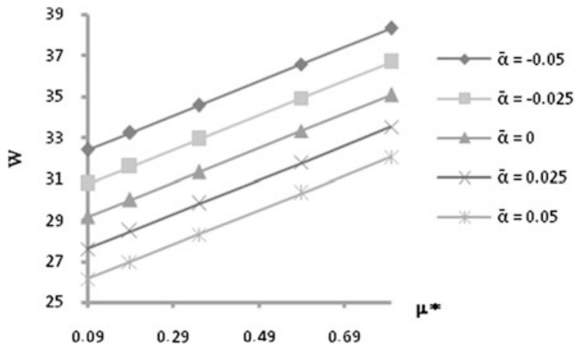


Fig. 7 Variation of Load carrying capacity with respect to μ^* and $\overline{\alpha}$

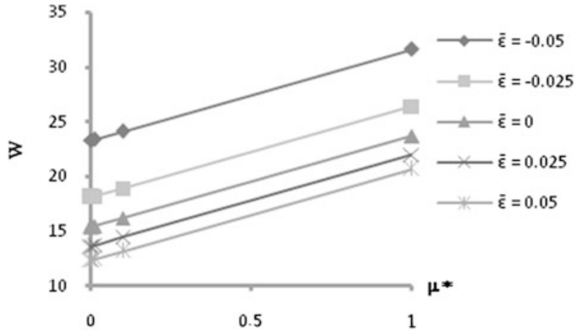


Fig. 8 Variation of Load carrying capacity with respect to μ^* and $\overline{\varepsilon}$

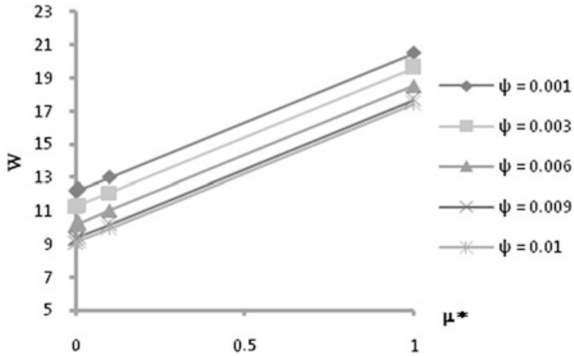


Fig. 9 Variation of Load carrying capacity with respect to μ^* and ψ

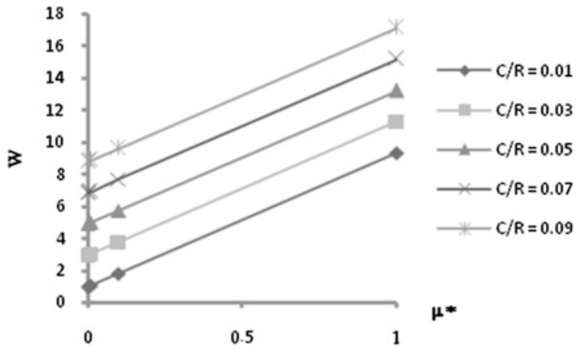


Fig. 10 Variation of Load carrying capacity with respect to μ^* and C/R

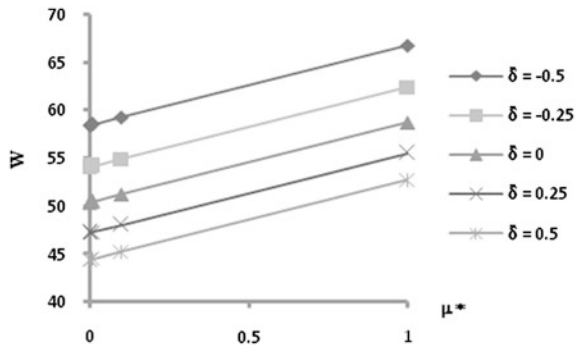


Fig. 11 Variation of Load carrying capacity with respect to μ^* and $\overline{\delta}$

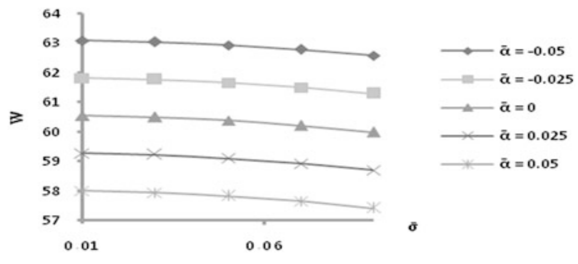


Fig. 12 Variation of Load carrying capacity with respect to $\overline{\sigma}$ and $\overline{\alpha}$

standard deviation has a considerable adverse effect on the performance of the bearing system in the sense that it decreases the load carrying capacity considerably. Interestingly, however it is noticed that the rate of reduction in the load carrying capacity with respect to standard deviation gets decreased for higher values of porosity.

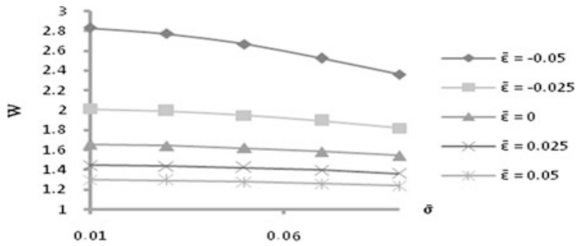


Fig. 13 Variation of Load carrying capacity with respect to $\overline{\sigma}$ and $\overline{\varepsilon}$

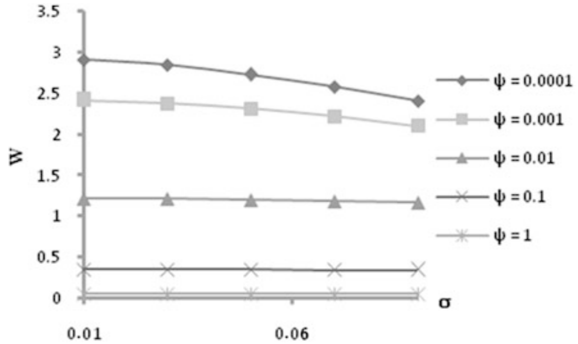


Fig. 14 Variation of Load carrying capacity with respect to $\overline{\sigma}$ and ψ

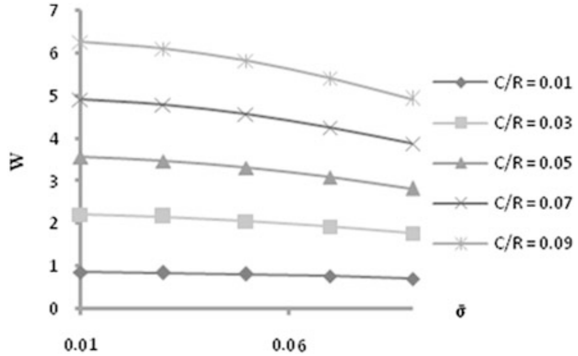


Fig. 15 Variation of Load carrying capacity with respect to $\overline{\sigma}$ and C/R

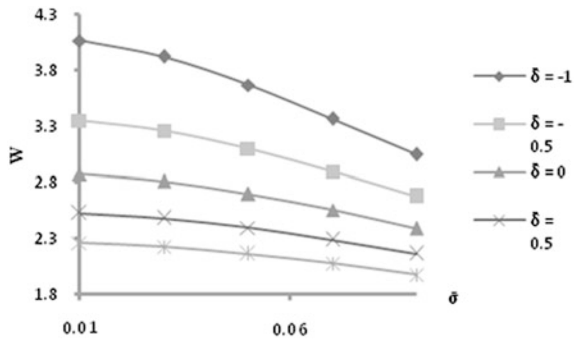


Fig. 16 Variation of Load carrying capacity with respect to $\overline{\sigma}$ and $\overline{\delta}$

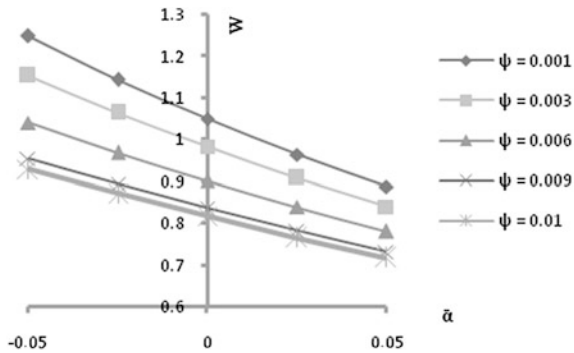


Fig. 17 Variation of Load carrying capacity with respect to $\overline{\alpha}$ and ψ

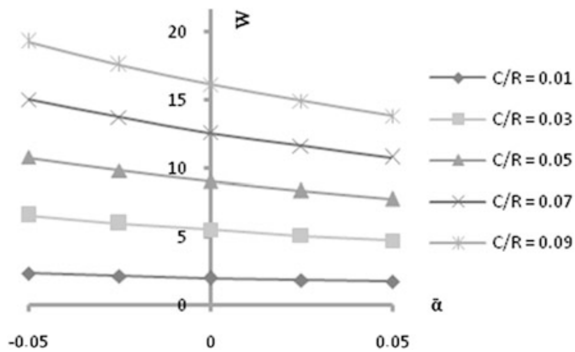


Fig. 18 Variation of Load carrying capacity with respect to $\overline{\alpha}$ and C/R

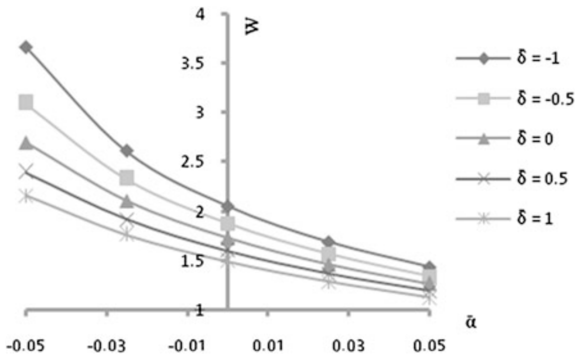


Fig. 19 Variation of Load carrying capacity with respect to $\overline{\alpha}$ and $\overline{\delta}$

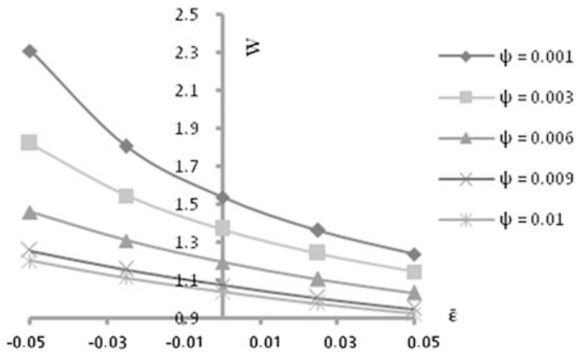


Fig. 20 Variation of Load carrying capacity with respect to $\overline{\varepsilon}$ and ψ

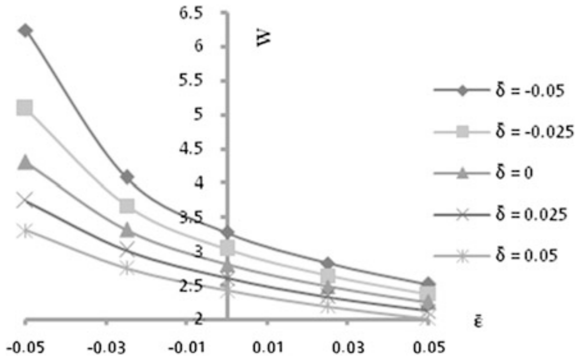


Fig. 21 Variation of Load carrying capacity with respect to $\overline{\varepsilon}$ and $\overline{\delta}$

Fig. 22 Variation of Load carrying capacity with respect to ψ and C/R

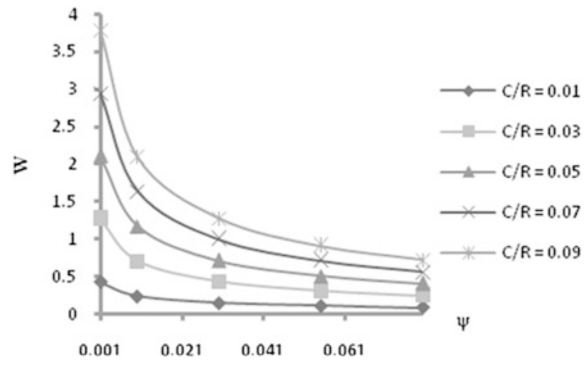


Fig. 23 Variation of Load carrying capacity with respect to ψ and $\overline{\delta}$

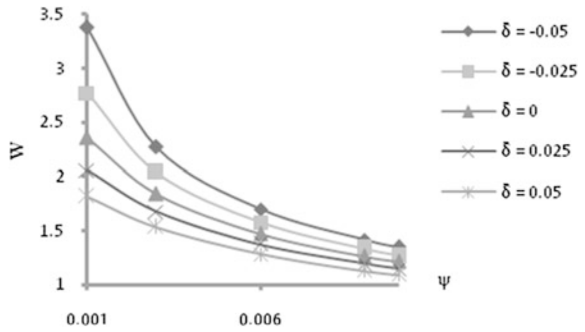
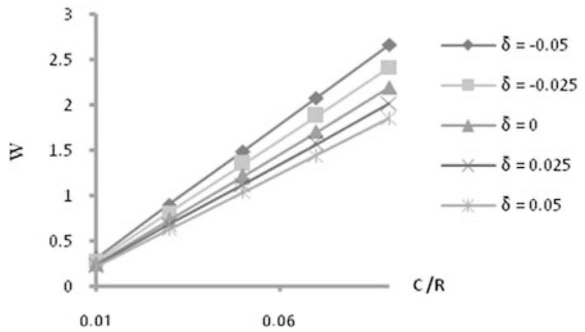


Fig. 24 Variation of Load carrying capacity with respect to C/R and $\overline{\delta}$



The effect of variance on the distribution of load carrying capacity is presented in Figs. 17, 18 and 19. These figures suggest that the load carrying capacity decreases when variance (positive) increases while variance (negative) increases the load carrying capacity. The effect of variance is relatively sharp with the increase in the eccentricity.

Figures 20 and 21 dealing with the variation of the load carrying capacity with respect to skewness make it clear that the skewness follow the trends of the variance. Thus, the combined effect of negatively skewed roughness and the variance (negative) is significantly positive. The fact that the load carrying capacity decreases significantly due to the porosity can be seen from Figs. 22 and 23. Figure 24 says that the effect of deformation cannot be disregarded for all values of the ratio C/R because the load carrying capacity increases sharply with respect to C/R.

2 Conclusion

Although, the effect of transverse surface roughness and deformation is relatively adverse, this investigation provides some measures to mitigate this negative effect at least in the case of negatively skewed roughness. Thus, the roughness must be accounted for while designing this type of bearing system, even if suitable magnetic strength is taken into consideration. In addition, this type of bearing system can support a load even when there is no flow while fails to happen in the case of traditional lubricants. It is interesting to note that the effect of magnetization goes a long way in reducing the adverse effect of porosity and standard deviation choosing suitably the eccentricity ratio, for a large range of deformation.

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