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On the Performance Characteristics of Rough Short Bearing Considering Thin Film Lubrication at Nano Scale

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Abstract This article discusses the effect of transverse surface roughness on the behaviour of a magnetic fluid based short bearing considering thin film lubrication at nano-scale. The model of Christensen and Tonder has been adopted to evaluate the effect of surface roughness. The stochastically averaged Reynolds type equation is solved with appropriate boundary conditions leading to the calculation of pressure distribution, in turn, which gives load carrying capacity. The graphical results underline that although, the effect of transverse roughness is adverse in general, this effect reduces when considered with thin film lubrication at nano-scale. The thin film lubrication at nano-scale leads to a sustained improvement in bearing performance characteristics even for lower values of magnetization parameter. Further, this study makes it clear that the formidable combination of couple stress and magnetization goes a long way in minimizing the adverse effect of standard deviation associated with roughness, in case variance (-ve) occurs.

Keywords: *short bearing, magnetic fluid, rough surfaces, nano-scale, load carrying capacity*

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1. Introduction

During these last few years a considerable amount of progress has been made in the research for thin film lubrication. Thin film lubrication has been well studied as a new lubrication regime since 1990s. [1,2,3] studied the transition from elastohydrodynamic lubrication to thin film lubrication, the transition from thin film lubrication to boundary lubrication, failure of liquid film at nano scale, the properties of fluid film at nano scale and the mechanism of thin film lubrication. [4] investigated the effect of liquid crystal additives in the construction of thin film. [5] analyzed the lubrication characteristics of thin film lubrication in two phase fluid. Here, it was shown that the existence of couple stress improved the load carrying capacity.

[6] analyzed the problem of lubrication of finite hydrodynamic journal bearing lubricated by magnetic fluids with couple stress, based upon the Stokes micro-continnum theory. It was established that the bearing characteristics enhanced due to the magnetic effects. [7] dealt with the work carried out in the domain of hydrodynamic lubricated journal bearings with magnetic fluids. Here, it was mooted that magnetic fluids could be used to develop active journal bearings. By applying an external magnetic field, ferrofluids can be confined, positioned, shaped and controlled at a desire location. [8] reported a discussion on the ferrofluid lubrication with an external magnetic field and found that the load carrying capacity of a lubricant film of a magnetic fluid increased with an appropriate magnetic field. [9] considered the performance of a hydrodynamic short journal bearing under the presence of a magnetic fluid lubricant. It was found that the magnetization turned in a favorable effect on the performance of the bearing system. The coefficient of friction decreased significantly for a large range of the magnetization parameter.

[10] discussed the random nature of roughness orientation and used a stochastic method to describe the surface roughness. Later on, this was developed by Christensen and Tonder [11,12,13] to propose a more general method for analyzing the effect of both the roughness patterns(transverse as well as longitudinal). This method was deployed by [14] to conduct an analysis for the performance of a rough spherical bearing. On the basis of Stokes theory and Christensen stochastic model, [15] theoretically investigated the combined effect of couple stresses and surface roughness on the instability thresholds of a rough short journal bearing lubricated with non-Newtonian fluids. Here the couple stress escorted with longitudinal roughness to provide an increase in the stability threshold speed. [16] discussed the characteristics of lubrication at nano scale on the performance of transversely rough slider bearing. [17] studied the roughness and thermal effect on different characteristics of finite rough tilted pad slider bearings. It was noticed that for non-parallel slider bearings the load carrying capacity due to combined effect was less than the load

capacity due to roughness effect for both longitudinal and transverse roughness model. [18] theoretically analyzed the problem of magneto hydrodynamic couple stress fluid film lubrication between rough circular stepped plates. It was observed that the radial roughness patterns on the bearing surface decreased the mean load capacity and squeeze film time. Further, the applied magnetic field increased the load carrying capacity. [19] proposed a model to investigate the mixed nano lubrication regime expected during light contact or “surfing”, recording in magnetic storage. In fact, they discussed an advanced rough surface continuum based contact and sliding model in the presence of molecularly thin lubricant. [20] investigated an analytical solution for the performance characteristics of a magnetic fluid based double layered porous rough slider bearing. It was noticed that the increased load carrying capacity owing to double layered got enhanced due to the magnetic fluid lubricant and this went a long way in reducing the adverse effect of roughness in the case of Kozeny-Carman model.

Here, it has been deemed appropriate to study and analyze the performance characteristics of a magnetic fluid based rough short bearing considering the thin film lubrication at nano scale.

2. Analysis

The geometry and configuration of the short bearing system is displayed in Fig. 1. The slider moves with the uniform velocity u in the X-direction. The length of the bearing is L and breadth B is in Z-direction where $B << L$, necessitating dimension of B to be very small. The pressure gradient $\partial p/\partial Z$, is much larger as compared to the pressure gradient $\partial p/\partial X$ and hence the latter can be neglected.

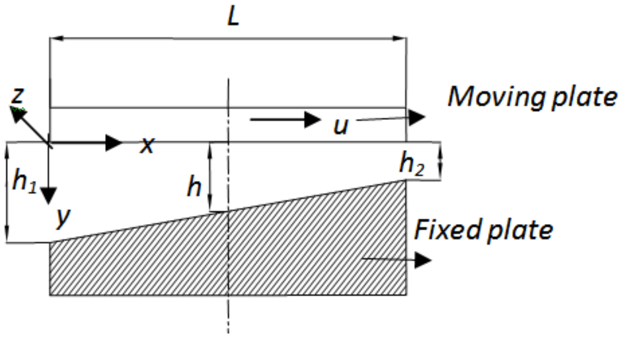

Figure 1. Configuration of the bearing system

It is considered that the bearing surfaces are transversely rough. In view of the discussions of Christensen and Tonder [11,12,13], the thickness h(x) of the lubricant film is taken as

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

where $\bar{h}(x)$ is the mean film thickness and h_s denotes the deviation from the mean film thickness characterizing the random roughness of the bearing surfaces. h_s is considered to be stochastic in nature and governed by the probability density function

$$f(h_s) = \begin{cases} \dfrac{35}{32c}\left(1 - \dfrac{h_s^2}{c^2}\right)^3, & -c \le h_s \le c \\ 0, & elsewhere \end{cases}$$

wherein c represents 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 variable h_s, are defined and discussed in Christensen and Tonder [11,12,13].

It is assumed that the lubricant film is isoviscous and incompressible and the flow is laminar. Following [21] the magnetic field is considered to be oblique to the stator. [22] carried out the investigation of the effect of various forms of magnitude of the magnetic field. Following his emphasis on certain forms of the magnitude in this study, the magnitude of the magnetic field is taken as

$$M^2 = KB^2\left\{\left(\frac{1}{2}+\frac{z}{B}\right)\sin\left(\frac{1}{2}-\frac{z}{B}\right)+\left(\frac{1}{2}-\frac{z}{B}\right)\sin\left(\frac{1}{2}+\frac{z}{B}\right)\right\}$$

where K is a suitably chosen constant from dimensionless point of view ([23,24])

In view of usual assumptions of hydro dynamic lubrication ([5,22,25,26,27]) the modified Reynolds’ equation with couple stress effect governing the pressure distribution is obtained as

$$\frac{d^2}{dz^2}\left(p - \frac{\mu_0\bar{\mu}M^2}{2}\right) = \frac{6\mu u}{g(h)\varphi(\gamma)}\frac{dh}{dx} \tag{1}$$

where

$$C = \sqrt{\eta/\mu}, \gamma = h/C, \varphi(\gamma) = 1 - \frac{12}{\gamma^2} + \frac{44}{\gamma^3},$$

and

$$g(h) = h^3 + 3h^2\alpha + 3(\sigma^2 + \alpha^2)h + 3\sigma^2\alpha + \alpha^3 + \varepsilon$$

while C is the characteristic length which contributes to the couple stress effect, μ_0 is the magnetic susceptibility, $\bar{\mu}$ is the free space permeability, μ is the lubricant viscosity and η is the material constant responsible for couple stress parameter.

The concerned boundary conditions are

$$p = 0; z = \pm\frac{B}{2}$$

and

$$\frac{dp}{dz} = 0; z = 0 \tag{2}$$

Introducing the non dimensional quantities

$$m = \frac{h_1 - h_2}{h_2}, h = h_2\left\{1 + m\left(1 - \frac{x}{L}\right)\right\}, \bar{L} = \frac{L}{h_2},$$

$$P = \frac{h_2^3}{\mu u B^2}p, \mu^* = \frac{h_2^3 K\mu_0\bar{\mu}}{\mu u}, Z = \frac{z}{B}, X = \frac{x}{L}, \bar{\varepsilon} = \frac{\varepsilon}{h_2^3},$$

$$A = \{1 + m(1 - X)\}, \bar{B} = \frac{B}{h_2}, \bar{\sigma} = \frac{\sigma}{h_2}, \bar{\alpha} = \frac{\alpha}{h_2},$$

$$g(\bar{h}) = A^3 + 3A^2\bar{\alpha} + 3\left(\bar{\sigma}^2 + \bar{\alpha}^2\right)A + 3\bar{\sigma}^2\bar{\alpha} + \bar{\alpha}^3 + \bar{\varepsilon} \quad (3)$$

and using boundary conditions (2), the dimensionless form of the pressure distribution
is found to be

$$P = \frac{\mu^*}{2}\left\{\left(\frac{1}{2}+Z\right)\sin\left(\frac{1}{2}-Z\right)+\left(\frac{1}{2}-Z\right)\sin\left(\frac{1}{2}+Z\right)\right\} + \frac{3m}{\bar{L}}\left(\frac{1}{4}-Z^2\right)\frac{1}{g(\bar{h})\varphi(\gamma)} \quad (4)$$

The dimensionless load carrying capacity of the bearing system then is obtained as

$$W = \frac{h_2^3}{\mu u B^4} w = \int_{-B/2}^{B/2}\int_0^1 p(x,z)\,dx\,dz = \mu^*\frac{\bar{L}}{\bar{B}}\left(1-\sin(1)\right) + \frac{m}{2}\frac{1}{\bar{B}}\int_0^1 \frac{dx}{g(\bar{h})\varphi(\gamma)} \quad (5)$$

3. Results and Discussion

It is clearly seen that the pressure distribution is given by equation (4) while equation (5) determines the non dimensional load carrying capacity. As the equation (5) is linear with respect to magnetization parameter, an increase in the magnetization would lead to increased load carrying capacity.

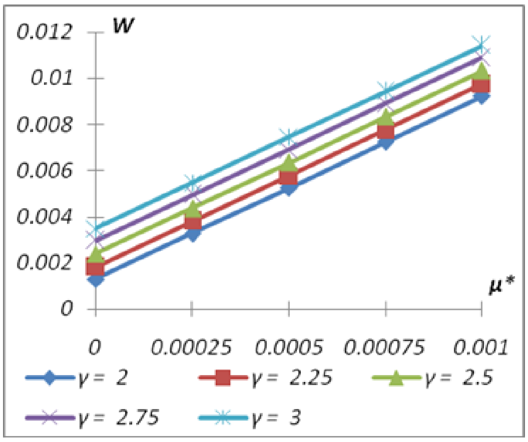

Figure 2. Variation of Load carrying capacity with respect to μ^* and γ

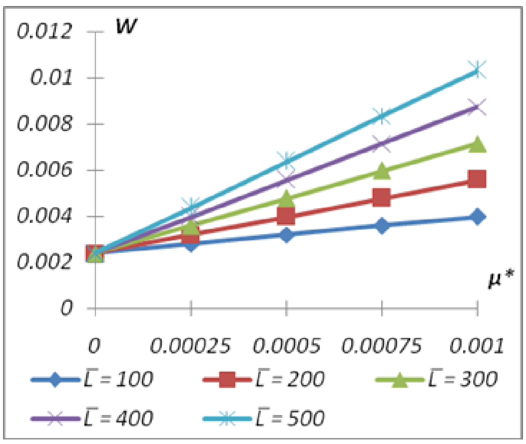

Figure 3. Variation of Load carrying capacity with respect to μ^* and $\bar{L}$

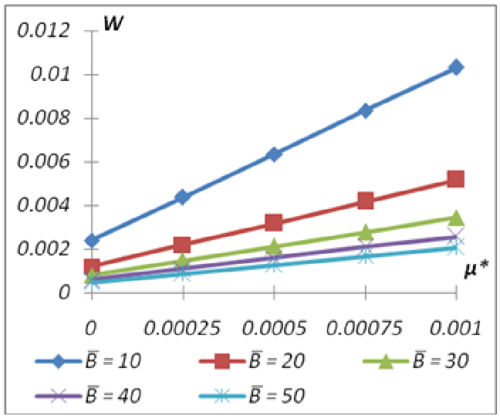

Figure 4. Variation of Load carrying capacity with respect to μ^* and $\bar{B}$

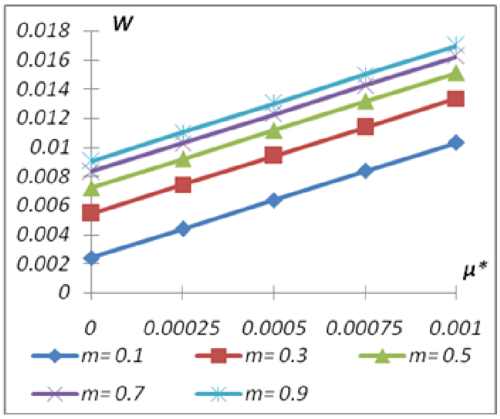

Figure 5. Variation of Load carrying capacity with respect to μ^* and m

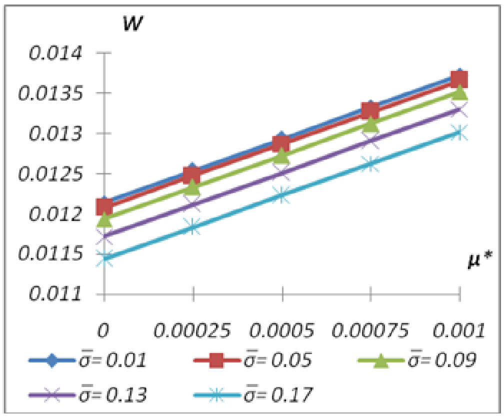

Figure 6. Variation of Load carrying capacity with respect to μ^* and $\bar{\sigma}$

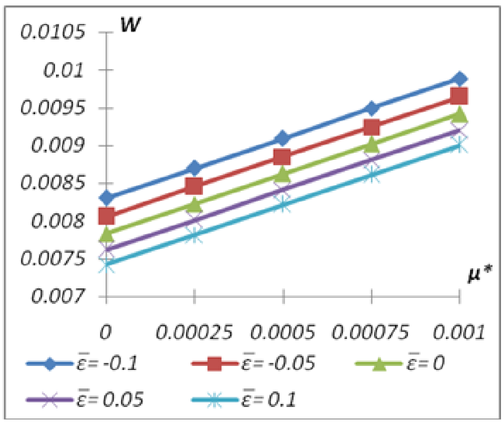

Figure 7. Variation of Load carrying capacity with respect to μ^* and $\bar{\varepsilon}$

The effect of magnetization parameter on the load carrying capacity is presented in Figure 2-Figure 8. It is observed that the magnetization parameter causes increased load carrying capacity.

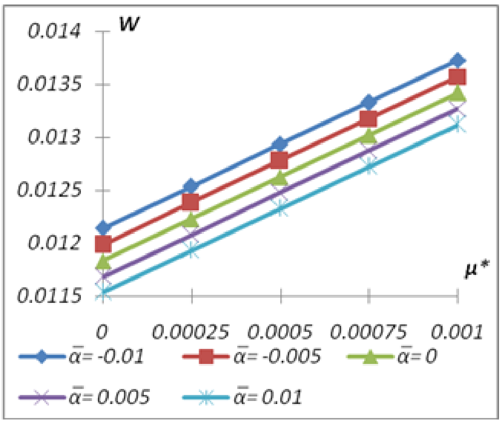

Figure 8. Variation of Load carrying capacity with respect to μ^* and $\bar{\alpha}$

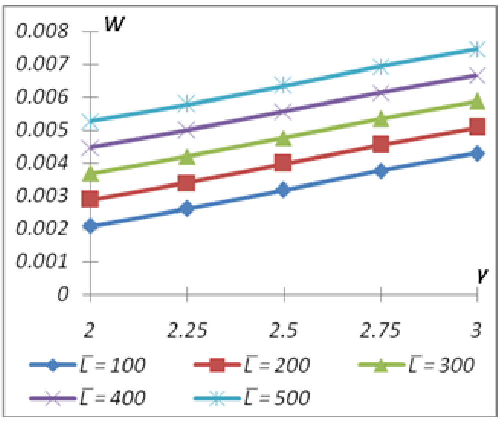

Figure 9. Variation of Load carrying capacity with respect to γ and $\bar{L}$

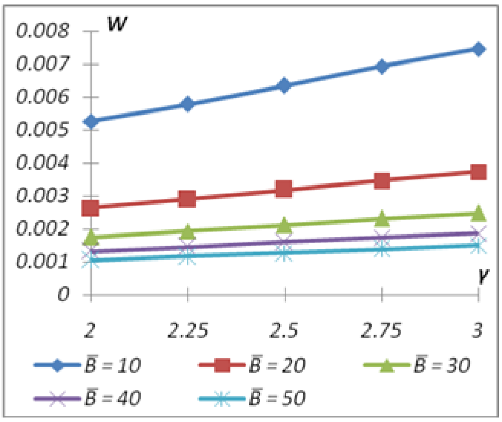

Figure 10. Variation of Load carrying capacity with respect to γ and $\bar{B}$

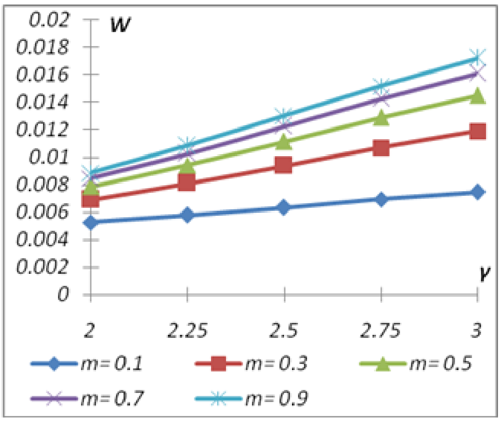

Figure 11. Variation of Load carrying capacity with respect to γ and m

The effect of γ is discussed in the Figure 9-Figure 14 where the load carrying capacity gets increased due to γ.

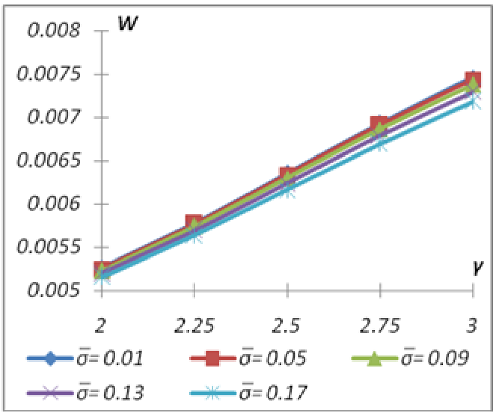

Figure 12. Variation of Load carrying capacity with respect to γ and $\bar{\sigma}$

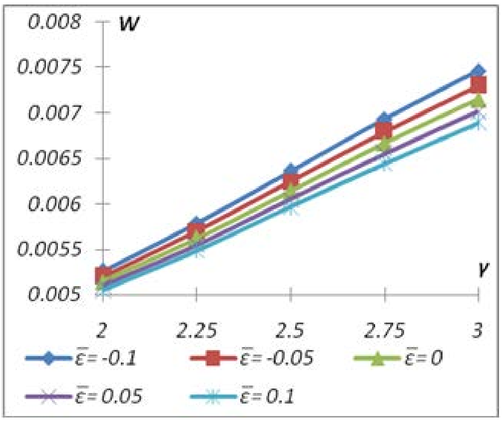

Figure 13. Variation of Load carrying capacity with respect to γ and $\bar{\varepsilon}$

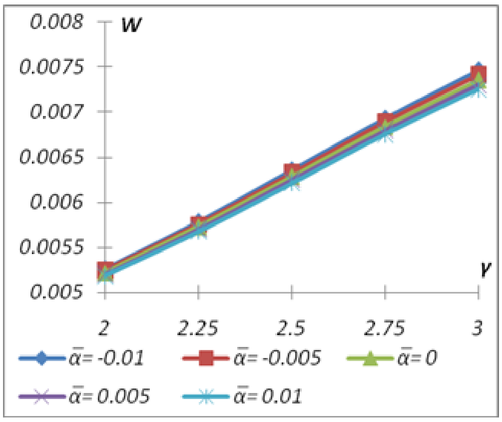

Figure 14. Variation of Load carrying capacity with respect to γ and $\bar{\alpha}$.

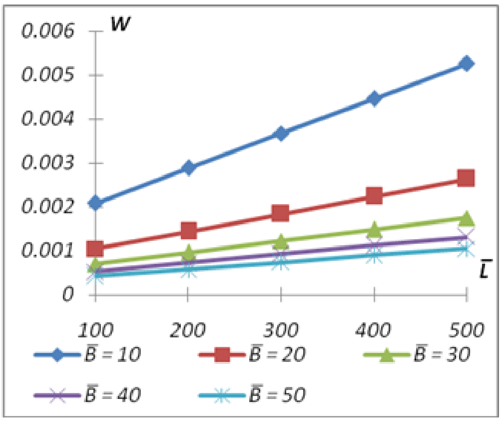

Figure 15. Variation of Load carrying capacity with respect to $\bar{L}$ and $\bar{B}$

The influence of $\bar{L}$, $\bar{B}$ and m can be examined from the Figure 15-Figure 19, Figure 20-Figure 23 and Figure 24 - Figure 26 respectively.

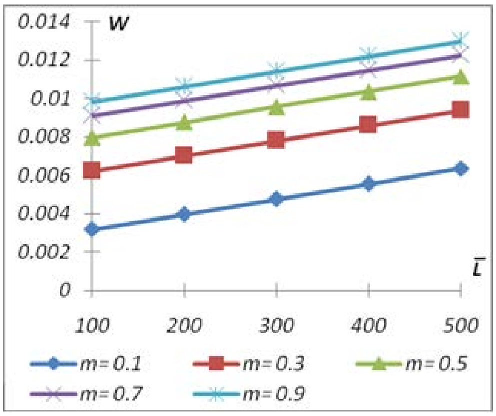

Figure 16. Variation of Load carrying capacity with respect to $\bar{L}$ and m

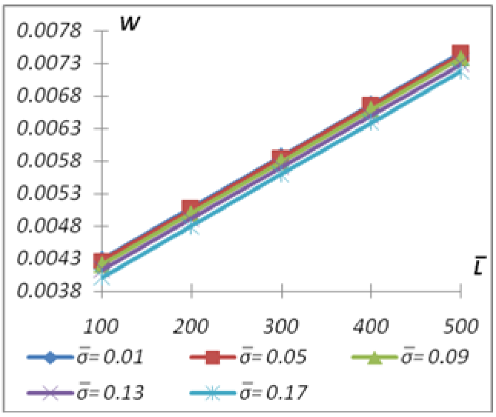

Figure 17. Variation of Load carrying capacity with respect to $\bar{L}$ and $\bar{\sigma}$

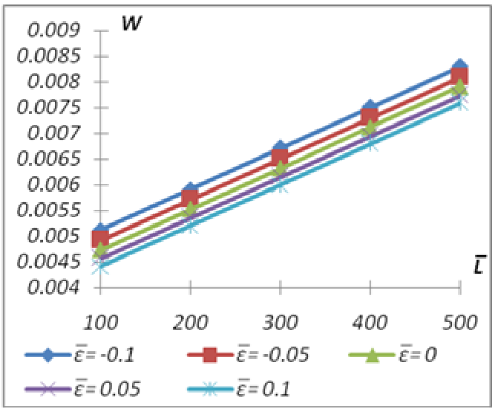

Figure 18. Variation of Load carrying capacity with respect to $\bar{L}$ and $\bar{\varepsilon}$

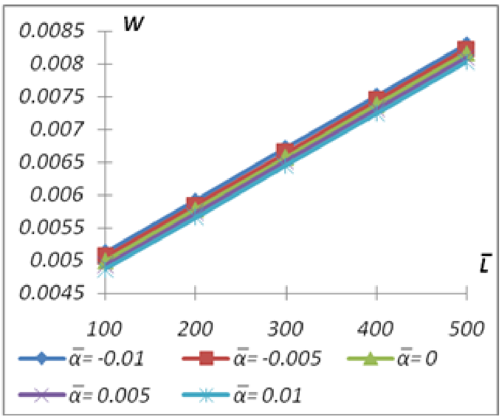

Figure 19. Variation of Load carrying capacity with respect to $\bar{L}$ and $\bar{\alpha}$.

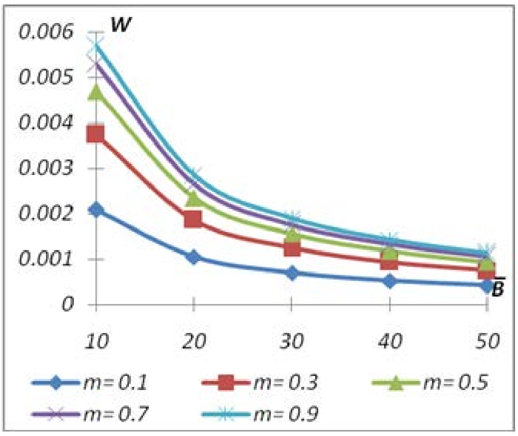

Figure 20. Variation of Load carrying capacity with respect to $\bar{B}$ and m.

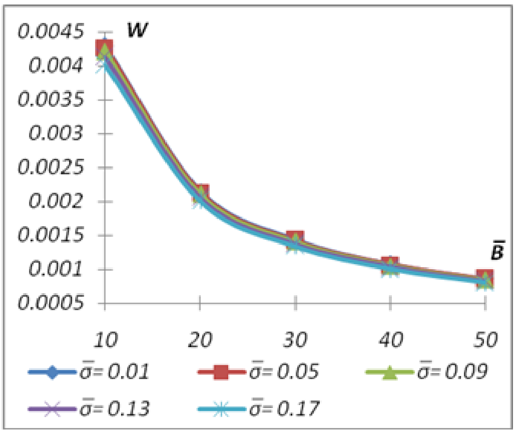

Figure 21. Variation of Load carrying capacity with respect to $\bar{B}$ and $\bar{\sigma}$.

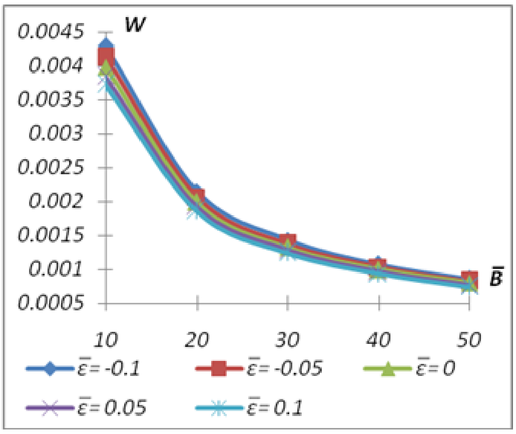

Figure 22. Variation of Load carrying capacity with respect to $\bar{B}$ and $\bar{\varepsilon}$.

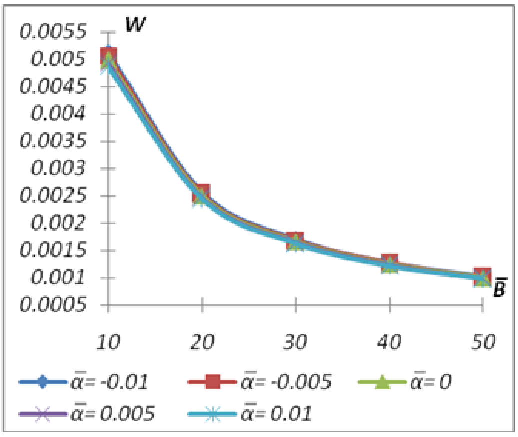

Figure 23. Variation of Load carrying capacity with respect to $\bar{B}$ and $\bar{\alpha}$

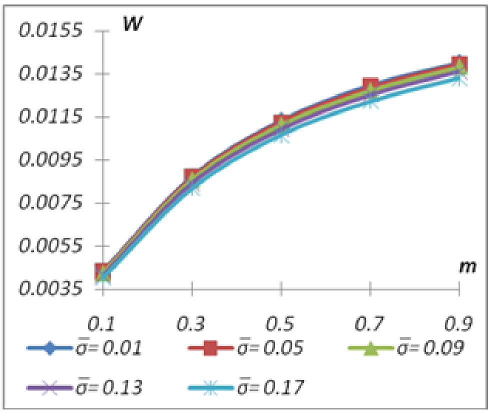

Figure 24. Variation of Load carrying capacity with respect to m and $\bar{\sigma}$

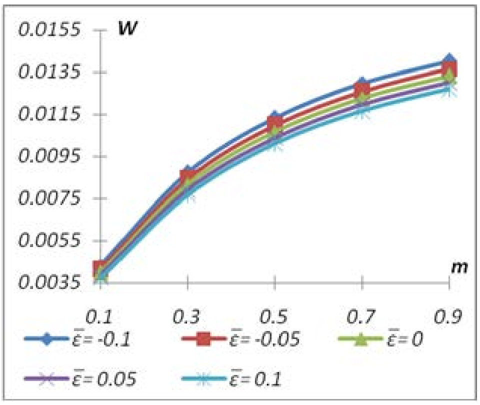

Figure 25. Variation of Load carrying capacity with respect to m and $\bar{\varepsilon}$

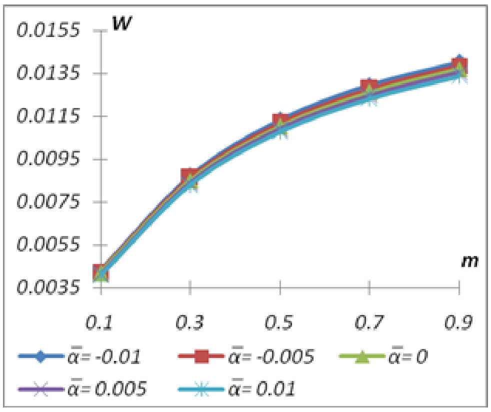

Figure 26. Variation of Load carrying capacity with respect to m and $\bar{\alpha}$

Figure 27-Figure 28 suggest that the standard deviation decreases the load carrying capacity for various values of variance and skewness.

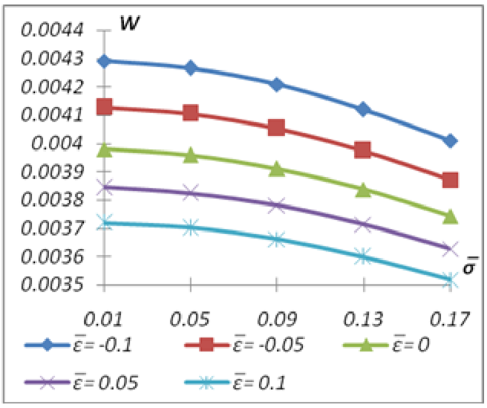

Figure 27. Variation of Load carrying capacity with respect to $\bar{\sigma}$ and $\bar{\varepsilon}$

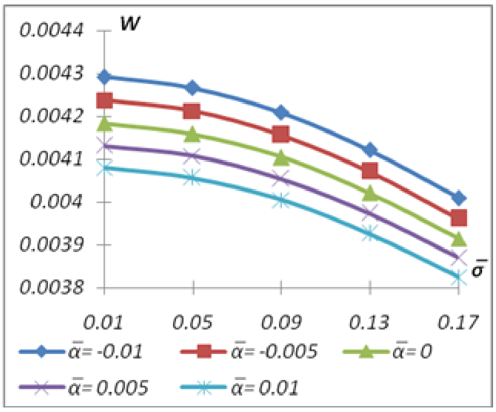

Figure 28. Variation of Load carrying capacity with respect to $\bar{\sigma}$ and $\bar{\alpha}$

Lastly, the effect of skewness on the load carrying capacity is depicted in Figure 29.

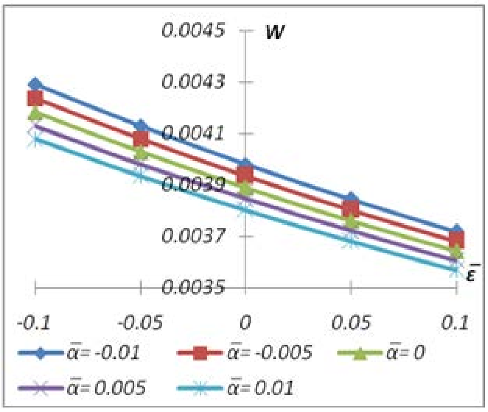

Figure 29. Variation of Load carrying capacity with respect to $\bar{\varepsilon}$ and $\bar{\alpha}$

The graphical representations reveal the following:

The effect of roughness is more sharp in the case of short bearing in comparison with the slider bearing at the nano-scale.

The thin film lubrication at nano scale induced increased load carrying capacity with gets further augmented due to magnetization. This effect further advances the influence of couple stresses.

Indeed the effect of magnetization and couple stress is to improve the effective viscosity which increases the load carrying capacity of the fluid film up to certain extent. This influence becomes more significant as the characteristics length increases.

Although, bearing suffers due to transverse surface roughness, this investigation offers ample measures for improving the bearing performance when variance (-ve) is involved, which is very much unlike to the situation studied in [16].

The negative effect induced by the standard deviation can be compensated to a large extent by considering the thin film lubrication at nano scale, in case variance (-ve) occurs. This compensation increases further in the case of negatively skewed roughness.

The effect of magnetization and couple stress does not allow the load carrying capacity to fall rapidly owing to transverse surface roughness.

5. Conclusion

This study establishes that the thin film lubrication at nano-scale may turn out to be more effective with a moderate to higher values of coupe stress parameter suitably choosing the magnetic strength. This article further indicates that even if thin film lubrication at nano scale is considered and suitable magnetic strength is in place, the roughness aspect must be duly respected while designing the bearing system. This study reveals that consideration of nano-scale film thickness may not be much favorable, especially after a long run of the ferrofluid based rough short bearing.

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