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Performance of a magnetic fluid based infinitely long rough parallel surface bearing: A comparison of forms of magnitude of the magnetic field

Sejal J. Patel and G.M. Deheri

Department of Mathematics,
Sardar Patel University,
V.V.Nagar, Gujarat, India

ABSTRACT: An attempt has been made to study and analyze the performance of a magnetic fluid based infinitely long parallel rough surface bearing. A comparison has been made with two different forms of the magnitude of the magnetic field. The stochastic model of Christensen and Tonder has been used to account for the effect of surface roughness, considering a different type of probability distribution function. The concerned stochastically averaged Reynolds type equation is solved with suitable boundary conditions to obtain the pressure distribution leading to the calculation of the load carrying capacity. Further, the expressions for volume flow rate and response time are derived. The graphical representations make it clear that the adverse effect of porosity and roughness can be minimized by the positive effect of magnetization particularly, in the case of negatively skewed roughness. However, this compensation is found to be more when the magnitude of the magnetic field is described by a trigonometric function. This investigation establishes that the bearing system sustains certain amount of load even in the absence of flow which does not happen in the case of conventional fluid based bearing system. It is found that the volume flow rate is comparatively augmented in the case of trigonometrical form as compared to the algebraic form of the magnitude of the magnetic field. It is appealing to note that the response time does not change for both the forms of magnitude of the magnetic field.

KEYWORDS: Long bearing, porosity, roughness, magnetic fluid, load carrying capacity.

1 INTRODUCTION

In fact, the infinite long slider bearing is the idealization of a single sector shaped pad of a hydrodynamic thrust bearing. Such a bearing consists of a fixed or pivoted pad and a moving pad which may be plane, stepped, curved or composite shaped (such bearings are widely used in hydrodynamic generators and turbines).

Reference [1] analyzed the performance of magneto-hydro-dynamic squeeze film, by considering infinitely long rectangular plates. It was observed that the squeeze action got altered significantly when the electric field was symmetrical about the centre of the bearing. Reference [2] derived the load carrying capacity and time-height relations for squeeze films between porous plates of various shapes. The geometries considered were circular, annular, elliptical, rectangular and conical. The circular shape recorded the highest load carrying capacity as compared to the other shapes. Reference [3] considered ferro fluid based porous squeeze films in bearings of various geometrical shapes including infinitely long rectangular plates. The bearing working with magnetic fluid as a lubricant was found to be better than that of an identical bearing working with a conventional lubricant. Reference [4] analyzed the effects of surface roughness by using Christensen stochastic theory in infinitely long porous journal bearing. The surface roughness considerably affected the bearing performance, the direction of the influence depending on the type of roughness. Reference [5] made a comparison of squeeze film behavior in an infinitely long journal bearing using the ferrofluid flow models of Neuringer- Rosensweig, Jenkin and Shliomis with uniform and non-uniform magnetic fields. An uniform magnetic field failed to produce magnetic pressure in the Neuringer- Rosensweig model, but it could affect the bearing characteristics in the Shliomis model owing to the rotational viscosity.

Reference [6] conducted a study of ferrofluid based squeeze film between infinitely long rough rectangular plates. For this type of bearing system it was established that magnetic fluid failed to deliver in reducing the adverse effect of surface roughness. Reference [7] observed the squeeze film performance between rough porous infinitely long parallel plates with porous matrix of variable film thickness under the presence of a ferrofluid. This investigation suggested that considerable increase in the load carrying capacity was possible with a suitable choice of film thickness ratio in the case of negatively skewed roughness. Reference [8] also discussed the magnetic fluid lubrication of a squeeze film in infinitely long bearing. Here, it was shown that the magnetization failed to respond favourably because the form of the magnitude of the magnetic fluid was quit unusual. Reference [9] investigated the squeeze film performance between rough porous infinitely long parallel plates with porous matrix of non uniform thickness. This study revealed that the thickness ratio played a crucial role for improving the bearing performance besides providing an additional degree of freedom, from design point of view. Further, the magnetic fluid lubrication compensated the adverse effect of porosity and roughness up to certain extent with a suitable choice of thickness ratio parameter. Reference [10] considered the lubrication performance of rough short journal bearings under the presence of a magnetic fluid. It was shown that the longitudinal roughness enhanced the load capacity and reduced the modified friction coefficient.

Reference [11] made a comparison of various porous structures on the performance of a magnetic fluid based transversely rough short bearing. The Kozeny-Carman model was found to be superior to Irmay's model. Reference [12] discussed the combined effect of couple stress and magneto-hydro-dynamic lubrication on squeeze film between two parallel plates. It was shown that the load carrying capacity increased with increased couple stress parameter and Hartmann number as compared to the classical Newtonian case. Reference [13] made an attempt to discuss the squeeze film performance between infinitely long rough porous rectangular plates in the presence of a ferrofluid. The negatively skewed roughness increased the already increased load carrying capacity owing to magnetization. This load further advanced with a suitable range of thickness ratio parameter. Reference [14] evaluated the effect of surface roughness on the performance of ferrofluid based parallel plate porous slider bearing considering the effect of slip velocity. It was established that the friction remained unchanged. However, for an enhanced performance the slip parameter was required to be kept at minimum. Reference [15] studied combined effect of magnetic fluid and surface roughness on the performance of a long journal bearing. It was noted that under a higher power-law index and induced magnetic force the transverse roughness could enhance the load capacity while reducing the attitude angle and modified friction coefficient.

Here it has been proposed to compare the effects of various forms of the magnitude of the magnetic field on the performance of a magnetic fluid based infinitely long rough parallel surface bearing.

2 ANALYSIS

The geometry and configuration of the bearing system is given in Figure-1.

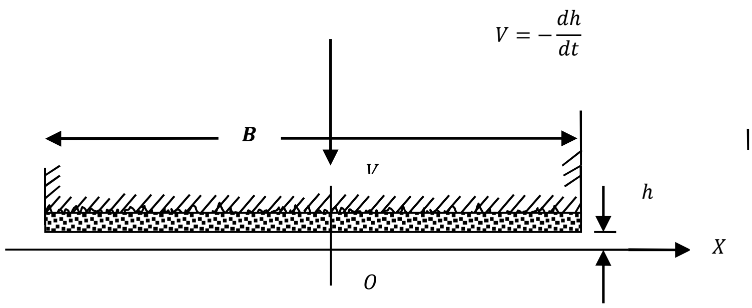

Fig. 1. Parallel Surface Bearing

It is well-known that for an isoviscous incompressible fluid the Reynolds equation can be written as

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(h^3\frac{\partial p}{\partial z}\right)=-12\,\eta V \quad (1)$$

where V is the squeeze velocity $V=-\frac{dh}{dt}$, η is the viscosity of the lubricant.

Assuming that the length in the z-direction is infinitely long, this differential equation for the bearing reduces to

$$\frac{\partial^2 p}{\partial x^2}=\frac{-12\eta V}{h^3} \quad (2)$$

It is assumed that the porous region is homogeneous and isotropic. The flow in the porous region is governed by Darcy's law. In corporation of porosity transforms the equation(2) into

$$\frac{\partial^2 p}{\partial x^2}=\frac{-12\eta V}{h^3+12\varphi H} \quad (3)$$

where φ is the permeability and H is a thickness of the porous facing.

Reference [16] proposed a mathematical model to describe the steady flow of magnetic fluids, in the presence of slowly changing external magnetic fields. This model and related aspects has also been discussed in [17]. Following the model outlined in [17], equation(3) takes the following form when a magnetic fluid is considered as a lubricant.

$$\frac{\partial^2}{\partial x^2}\left(p-\frac{\bar{\mu}\mu_0}{2}H^2\right)=\frac{-12\eta V}{h^3+12\varphi H} \quad (4)$$

where μ_0 is the magnetic permeability, $\bar{\mu}$ is the magnetic susceptibility of the magnetic particles and H is the magnitude of the applied external magnetic field.

Christensen and Tonder recognized the random character of roughness and characterized the surface roughness by a random variable with non zero mean, variance and skewness. In view of the deliberations of [18], [19], [20], [21] the roughness of the bearing surfaces is governed by a beta density function of the form

$$f(h_s)=\frac{15}{16c}\left(1-\frac{{h_s}^2}{c^2}\right)^2; \quad -c<h_s\le c$$
$$=0; \quad \text{elsewhere}$$

where c is optimum value of h_s. This form has been considered in [21].

In view of the stochastic model of Christensen and Tonder , stochastically averaging equation(4) one arrives at

$$\frac{\partial^2}{\partial x^2}\left(p-\frac{\bar{\mu}\mu_0}{2}H^2\right)=\frac{-12\eta V}{g(h)} \quad (5)$$

where

$$g(h)=h^3+4(\sigma^2+\alpha^2)h+2\alpha^2h+2\alpha^3+3\sigma^2\alpha+\varepsilon+12\varphi H$$

where σ is the standard deviation, α is the variance and ε is the measure of symmetric of the random roughness.

The associated boundary conditions are

$$p=0 \text{ at } x=\pm\frac{B}{2} \quad (6)$$

Considering

$$H^2=k(x^2-\frac{B^2}{4}) \quad (7)$$

and solving equation(5) in view of the boundary conditions(6), the governing equation for the pressure distribution in dimensionless form is obtained as

$$P=\left(\frac{\mu^*}{8}+\frac{3}{2g(\bar{h})}\right)(1-4\bar{x}^2) \quad (8)$$

where

$$g(\bar{h}) = 1 + 4(\bar{\sigma}^2 + \bar{\alpha}^2) + 2\bar{\alpha} + 3\bar{\sigma}^2\bar{\alpha} + 2\bar{\alpha}^3 + \bar{\varepsilon} + 12\bar{\psi}$$

while the dimensionless quantities are

$$P = \frac{p{h_2}^3}{\eta V B^2}, \bar{x} = \frac{x}{B}, \bar{\sigma} = \frac{\sigma}{h_2}, \bar{\alpha} = \frac{\alpha}{h_2}, \bar{\varepsilon} = \frac{\varepsilon}{{h_2}^3}, \bar{\psi} = \frac{\varphi H}{{h_2}^3}, \mu^* = \frac{-k\bar{\mu}\mu_0 h^3}{\eta V}$$

wherein k is a suitably choosen constant for preparing a required magnetic strength.([17])

One can see that the expression for maximum value of the non dimensional pressure distribution turns out to be

$$P = \frac{\mu^*}{8} + \frac{3}{2g(\bar{h})} \tag{9}$$

Then, the load carrying capacity of the bearing given by

$$w = L\int_{-B/2}^{B/2} p\,dx$$

in dimensionless form is obtained as

$$W = \frac{\mu^*}{12} + \frac{1}{g(\bar{h})} \tag{10}$$

where $W = \frac{{h_2}^3 w}{\eta V L B^3}$

The volume flow rate in dimensionless form is derived as

$$\bar{Q} = \left(\frac{\mu^*}{12} + \frac{1}{g(\bar{h})}\right)\bar{x} \tag{11}$$

The dimensionless time of approach starting from a initial film thickness h1 at t1 to final film thickness h2 at t2 is calculated in dimensionless form as

$$\Delta\bar{t} = \frac{1}{Wg(\bar{h})}(1 - \overline{h_1}) \tag{12}$$

Wherein $\overline{h_1} = \frac{h_1}{h_2}$ and $\Delta\bar{t} = \frac{-{h_2}^3}{\eta L B^3}\Delta t$

For the comparison a trigonometric function has also been choosen to describe the magnitude of the magnetic field, namely

$$H^2 = kB^2 \cos\frac{\pi x}{B} \tag{13}$$

This form has been discussed and used in [21] and [22].

For this case the non-dimensional pressure distribution is obtained as

$$P = \frac{\mu^*}{2}\cos\pi\bar{x} + \frac{3}{2g(\bar{h})}(1 - 4\bar{x}^2) \tag{14}$$

Further, the maximum value of non-dimensional pressure distribution is

$$\frac{1}{2}\left[\mu^* + \frac{3}{g(\bar{h})}\right]$$

The non dimensional load carrying capacity associated with this form comes out to be

$$w = \frac{\mu^*}{\pi} + \frac{1}{g(\bar{h})} \tag{15}$$

The dimensionless flow rate is described by

$$\bar{Q} = \frac{\mu^*}{24}\pi\sin\pi\bar{x} + \frac{\bar{x}}{g(\bar{h})} \tag{16}$$

A little computation shows that the maximum value of $\overline{Q}$ is

$$\frac{1}{2}\left[\frac{\pi\mu^*}{12}+\frac{1}{g(\overline{h})}\right]$$

Lastly, the non dimensional response time is found to be

$$\Delta\bar{t}=\frac{1}{Wg(\bar{h})}(1-\overline{h_1}) \tag{17}$$

It is interesting to note from equations(12) and (17)that the dimensionless time of approach remains same for both the forms of magnitude.

3 Results and Discussion

It is easily seen that, the non dimensional load carrying capacity for both the forms can be determined from equations(10) and (15).One can observe that the expressions involved in both the equations are linear with respect to the magnetization parameter. Accordingly, an increase in the magnetization parameter would lead to increased load carrying capacity. Probably, this may be due to the fact that the magnetization increases the viscosity of the lubricants. Further, it is noticed that the load carrying capacity enhances by $\frac{\mu^*}{12}$ in the algebraic form of the magnitude of the magnetic field and $\frac{\mu^*}{\pi}$ for the trigonometric form as compared to the case of conventional lubricant. It is clearly seen that the load carrying capacity is comparatively more in the case of the trigonometrical form of the magnitude of the magnetic field. It is established from equations (12) and (17) that the squeeze time remains same for both the forms of the magnitude. From equations (11) and (15) it is found that the volume flow rate increases by $\frac{\mu^*}{\pi}\bar{x}$ for the algebraic form of the magnitude, while the increase in the flow rate with respect to the trigonometrical form is $\frac{\mu^*}{24}\pi\sin\pi\bar{x}$ as compared to the case of conventional lubricant.

When the bearing surfaces are smooth this study reduces to the performance of a magnetic fluid based squeeze film in infinitely long porous plates. Further, taking $\mu^*=0$ one gets the behavior of a squeeze film in infinitely long porous plates. This study reduces to the performance of a squeeze film in infinitely long parallel plates in the absence of porosity([23]).

Fig. 2-7 are concerned with algebraic form of the magnitude of the magnetic field, while the fig. 8-13 are associated with the trigonometric form of the magnitude. It can be easily seen that the effect of porosity on the distribution of load carrying capacity with respect to the roughness parameters $\bar{\alpha}$ and $\bar{\varepsilon}$ is negligible for the value of porosity less than or equal to 0.001. Further, increasing value of standard deviation causes severe reduction in the load carrying capacity. Likewise, the load carrying capacity decreases when variance [+ve] and skewness[+ve] increase. Besides, the combined effect of variance (-ve) and negatively skewed roughness is to increase the load carrying capacity, significantly. Also, the combined effect of porosity and standard deviation is relatively adverse.

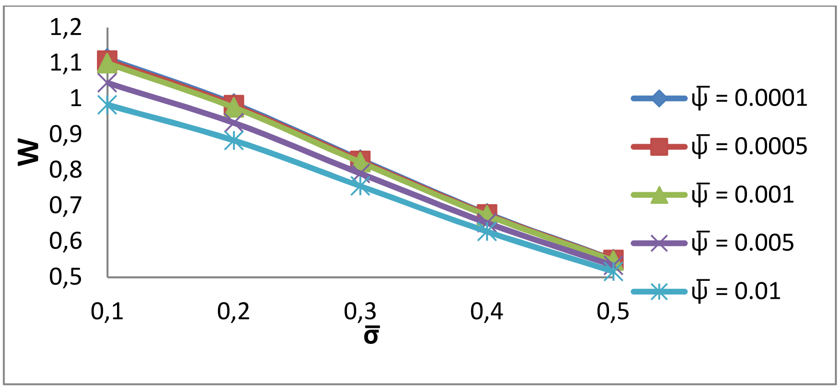

Fig. 2. Variation of Load Carrying capacity with respect to $\bar{\sigma}$ and $\bar{\psi}$

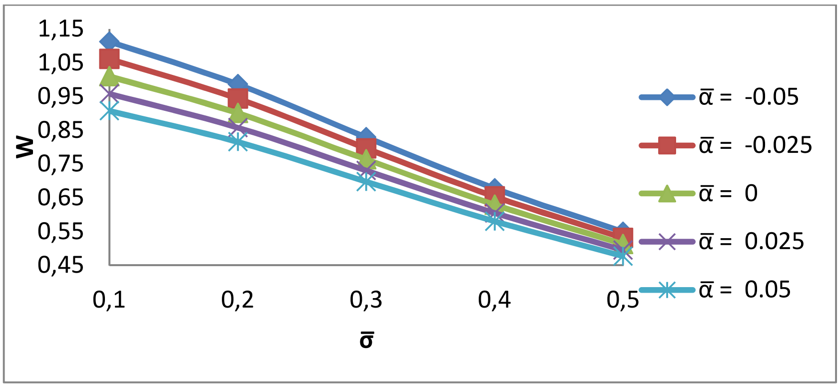

Fig. 3. Variation of Load Carrying capacity with respect to $\bar{\sigma}$ and $\bar{\alpha}$

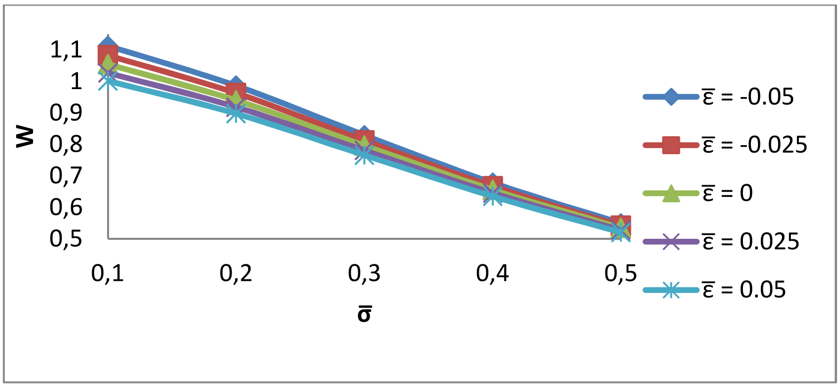

Fig. 4. Variation of Load Carrying capacity with respect to $\bar{\sigma}$ and $\bar{\varepsilon}$

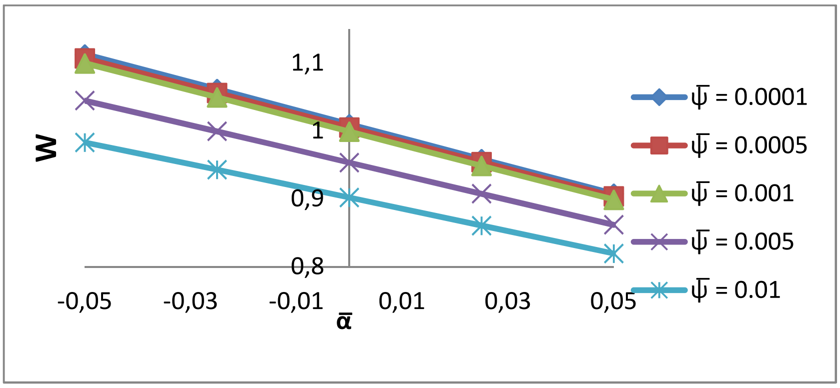

Fig. 5. Variation of Load Carrying capacity with respect to $\bar{\alpha}$ and $\bar{\psi}$

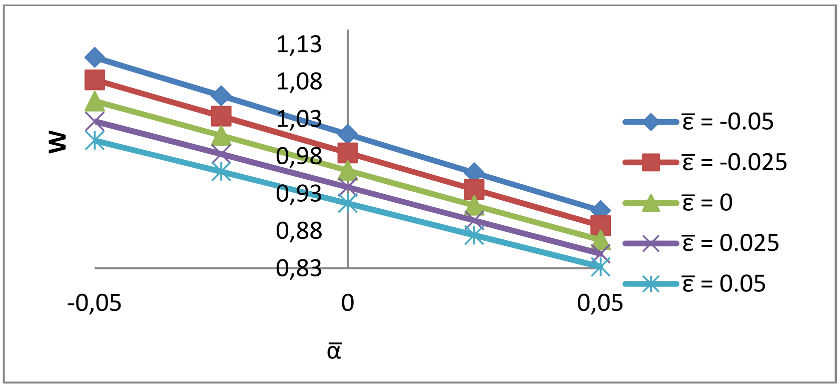

Fig. 6. ***Variation of Load Carrying capacity with respect to $\bar{\alpha}$ and $\bar{\varepsilon}$***

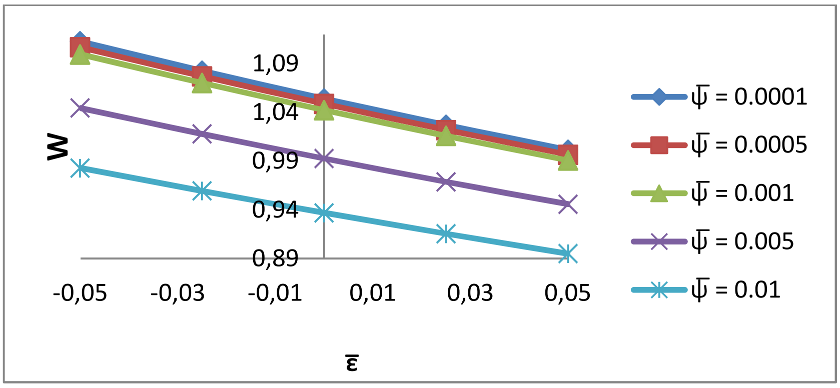

Fig. 7. ***Variation of Load Carrying capacity with respect to $\bar{\varepsilon}$ and $\bar{\psi}$***

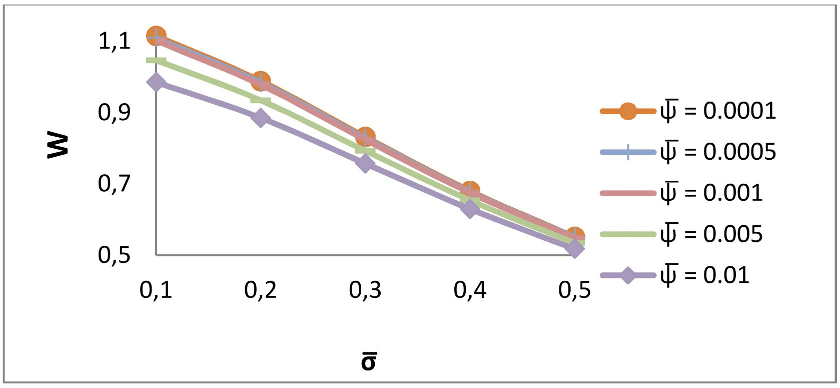

Fig. 8. ***Variation of Load Carrying capacity with respect to $\bar{\sigma}$ and $\bar{\psi}$***

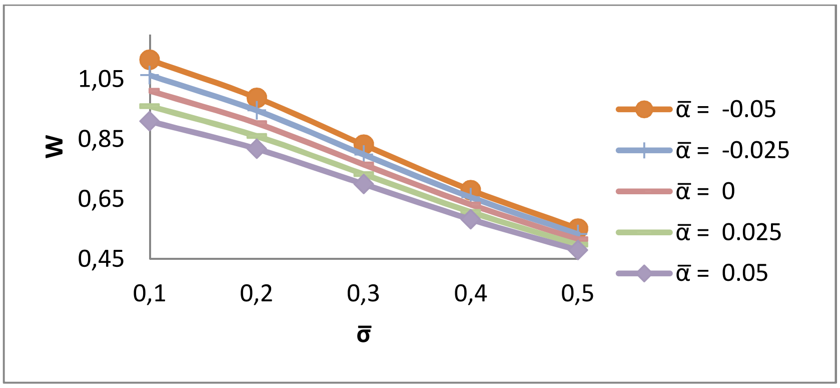

Fig. 9. Variation of Load Carrying capacity with respect to $\bar{\sigma}$ and $\bar{\alpha}$

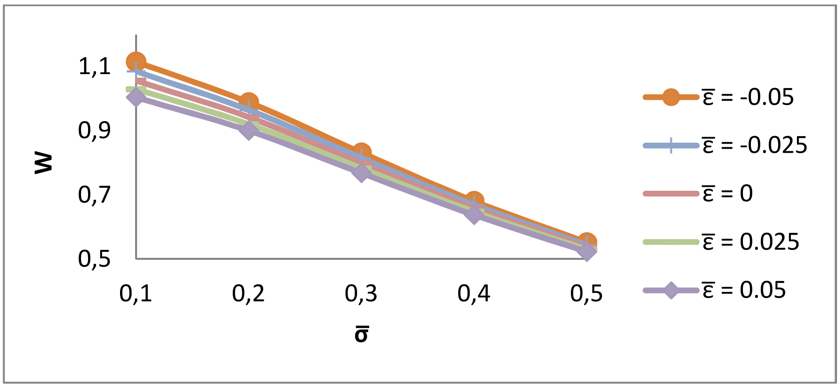

Fig. 10. Variation of Load Carrying capacity with respect to $\bar{\sigma}$ and $\bar{\varepsilon}$

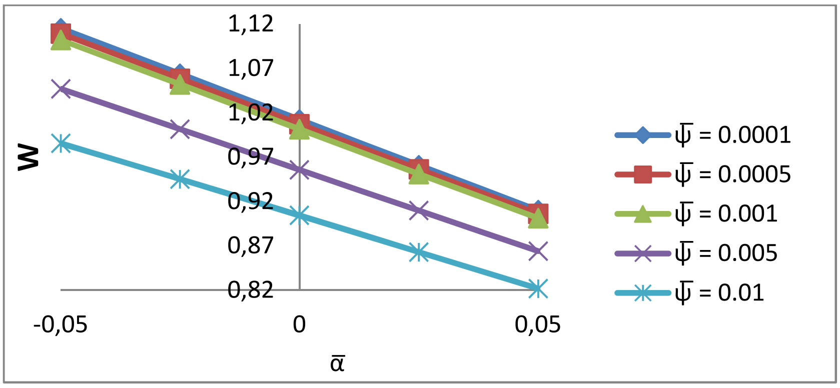

Fig. 11. Variation of Load Carrying capacity with respect to $\bar{\alpha}$ and $\bar{\psi}$

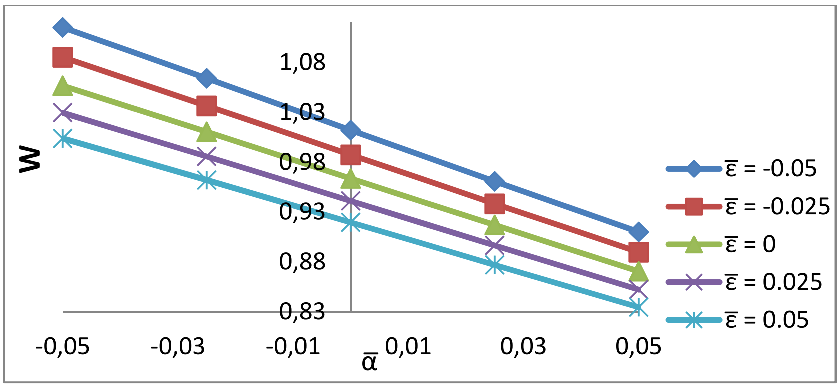

Fig. 12. Variation of Load Carrying capacity with respect to $\bar{\alpha}$ and $\bar{\varepsilon}$

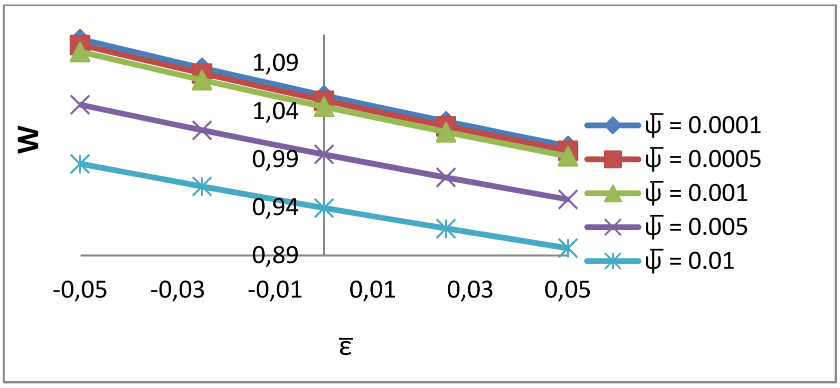

Fig. 13. Variation of Load Carrying capacity with respect to $\bar{\varepsilon}$ and $\bar{\psi}$

The effect of magnetization is presented in fig. 14 - 17 for algebraic form and 18 - 21 for the trigonometrical form of the magnitude of the magnetic field. It is seen from these figures that san increase in the magnetization parameter gives rise to sharply increased load carrying capacity. It is clear that the increase in the load carrying capacity is more in the case of trigonometrical forms of the magnitude. This can also be visualized from equations(10) and (15).

Some of these graphs tend to reveal that the effect of magnetization can go a long way in reducing the adverse effect of porosity and standard deviation in the case of negatively skewed roughness at least when variance [-ve] occurs and this compensation is a little more in the case of the trigonometrical form.

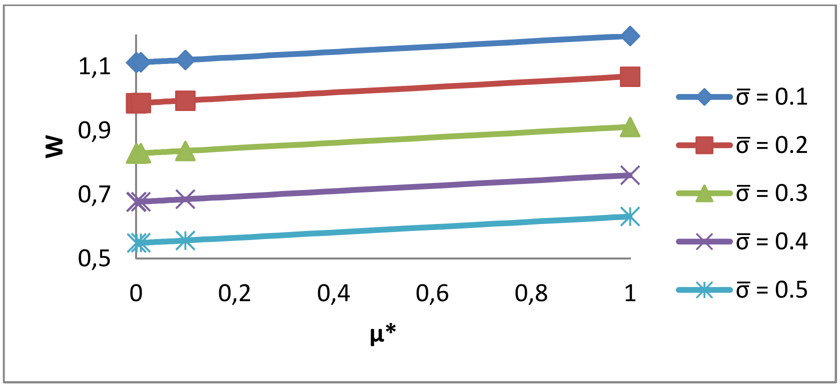

Fig. 14. Variation of Load Carrying capacity with respect to μ^* and $\bar{\sigma}$

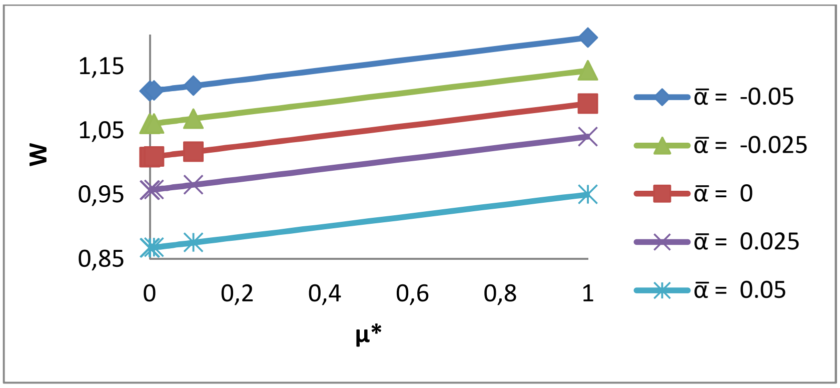

Fig. 15. Variation of Load Carrying capacity with respect to μ and $\bar{\alpha}$*

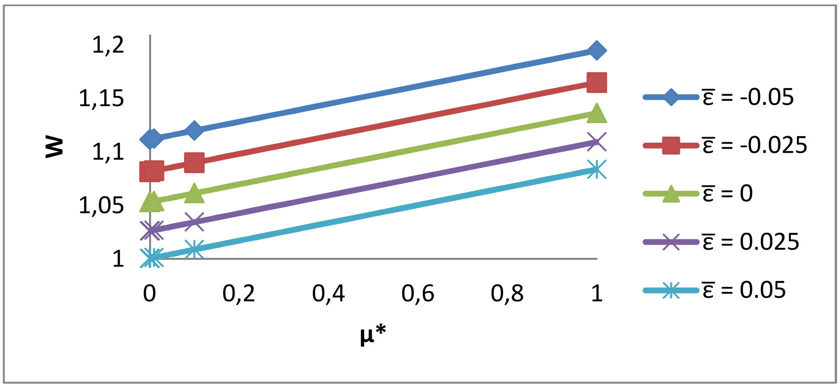

Fig. 16. Variation of Load Carrying capacity with respect to μ and $\bar{\varepsilon}$*

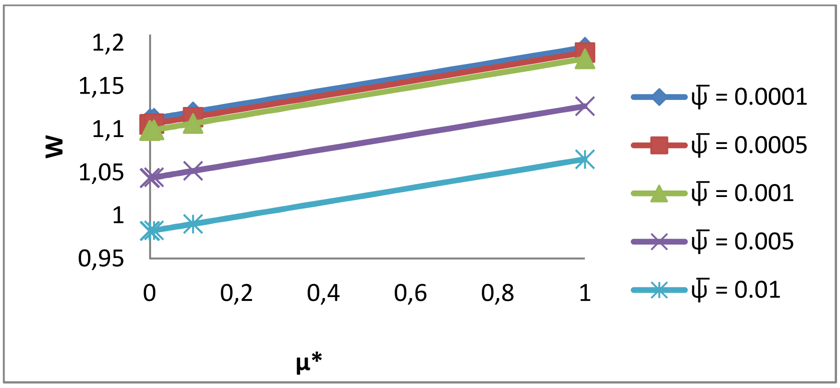

Fig. 17. Variation of Load Carrying capacity with respect to μ and $\bar{\psi}$*

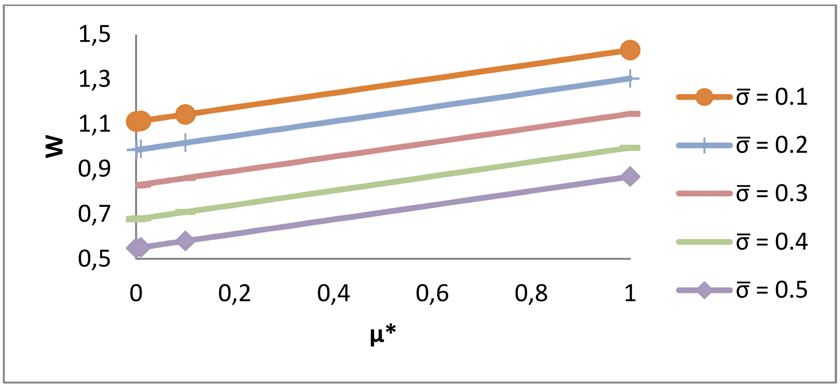

Fig. 18. Variation of Load Carrying capacity with respect to μ^* and $\bar{\sigma}$

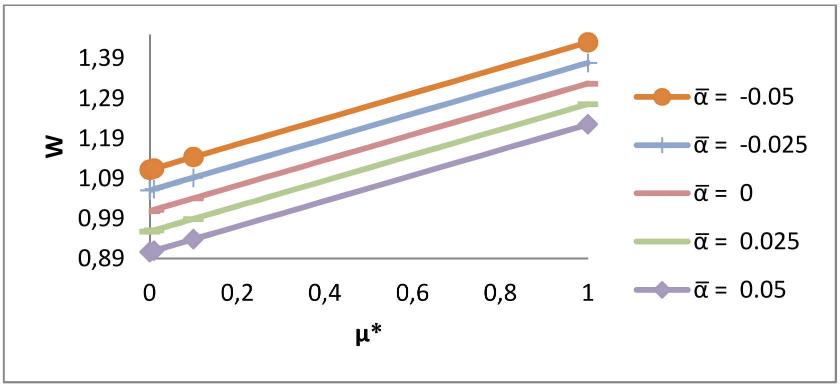

Fig. 19. Variation of Load Carrying capacity with respect to $\mu^*$and $\bar{\alpha}$

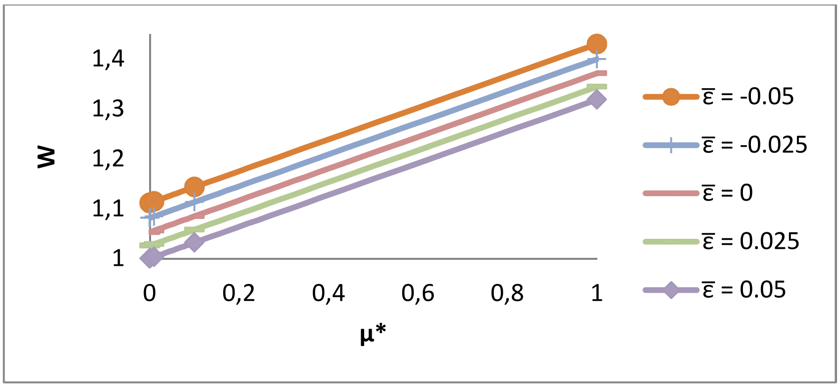

Fig. 20. Variation of Load Carrying capacity with respect to μ^* and $\bar{\varepsilon}$

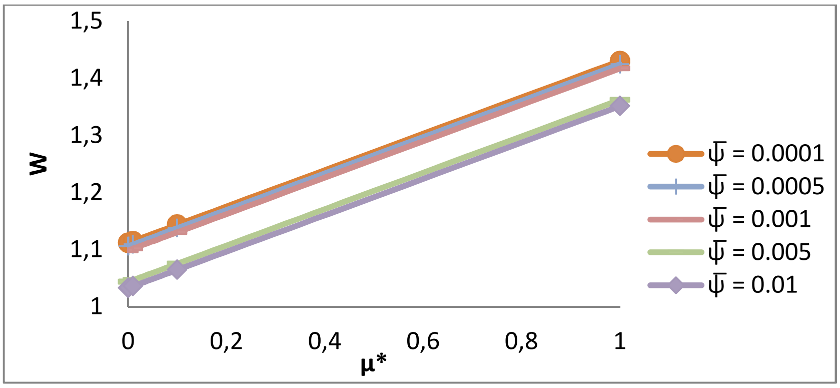

Fig. 21. Variation of Load Carrying capacity with respect to μ and $\bar{\psi}$*

It can be noticed from equations (11) and (16) that the effect of magnetization on the volume flow rate is comparatively more in the case of trigonometrical form of magnitude. This can also be seen from the graphical representations [Fig. 22-25 for algebraic form, Fig. 26-29 for trigonometric form]. It is also found that in the case of trigonometric form the rate of increase in the volume flow rate is more. Further, it is observed from Fig. 25-29 that the effect of porosity on the volume flow rate with respect to magnetization remains insignificant up to the porosity value of 0.001.

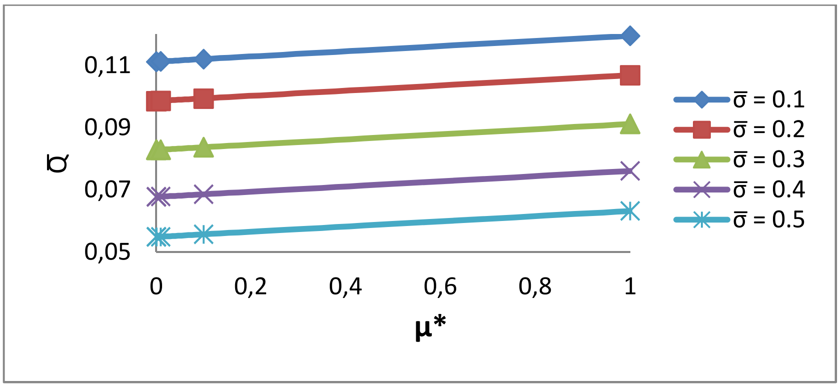

Fig. 22. Variation of Volume flow rate with respect to μ and $\bar{\sigma}$*

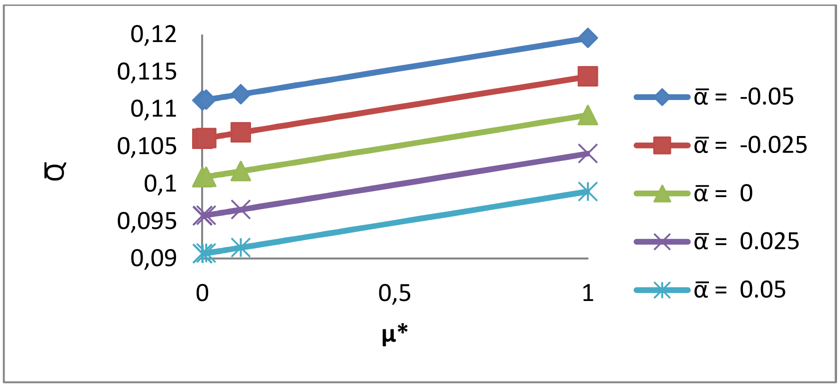

*Fig. 23. Variation of Volume flow rate with respect to μ*and $\bar{\alpha}$*

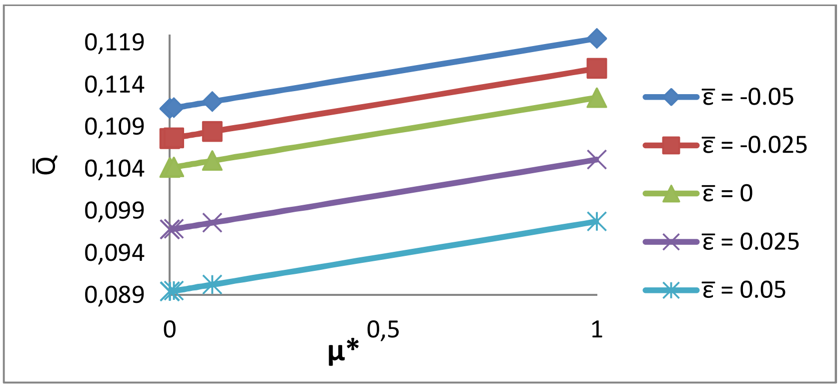

Fig. 24. Variation of Volume flow rate with respect to μ^* and $\bar{\varepsilon}$

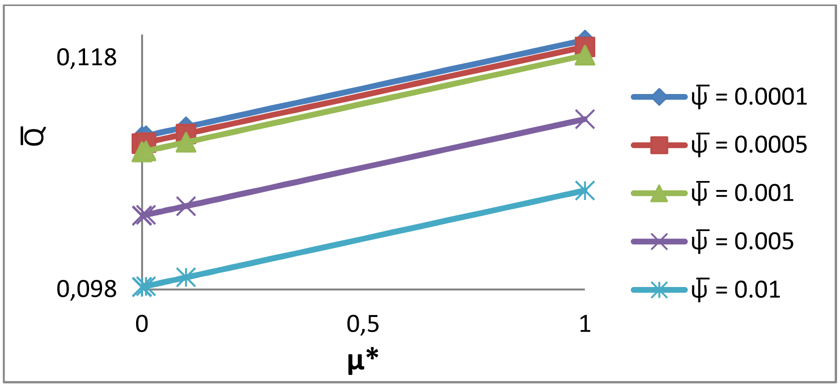

Fig. 25. Variation of Volume flow rate with respect to μ^* and $\bar{\psi}$

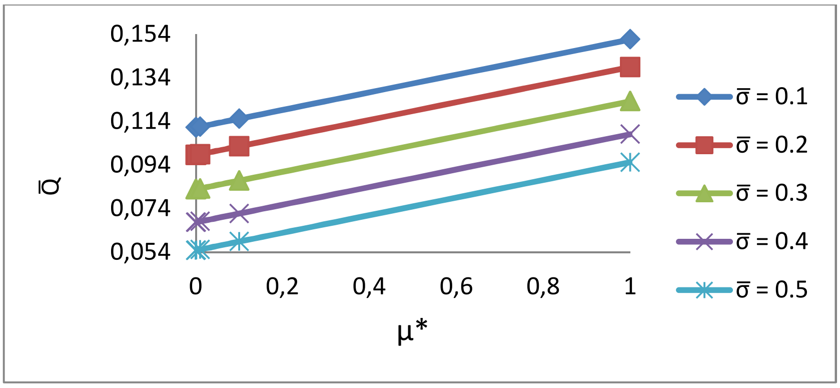

Fig. 26. Variation of Volume flow rate with respect to μ^* and $\bar{\sigma}$

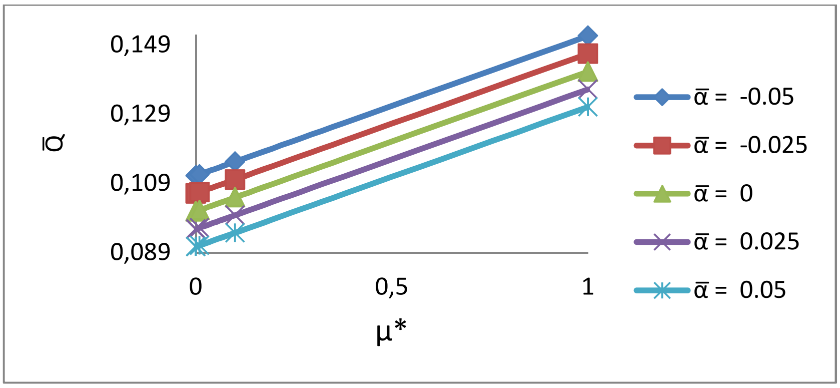

Fig. 27. Variation of Volume flow rate with respect to μ*and $\bar{\alpha}$

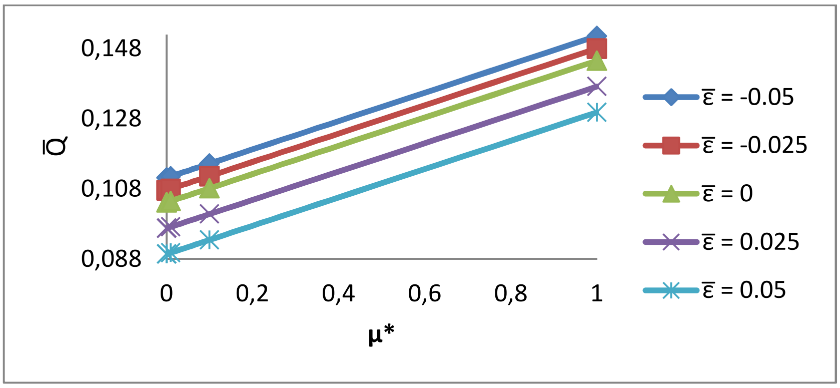

Fig. 28. Variation of Volume flow rate with respect to μ* and $\bar{\varepsilon}$

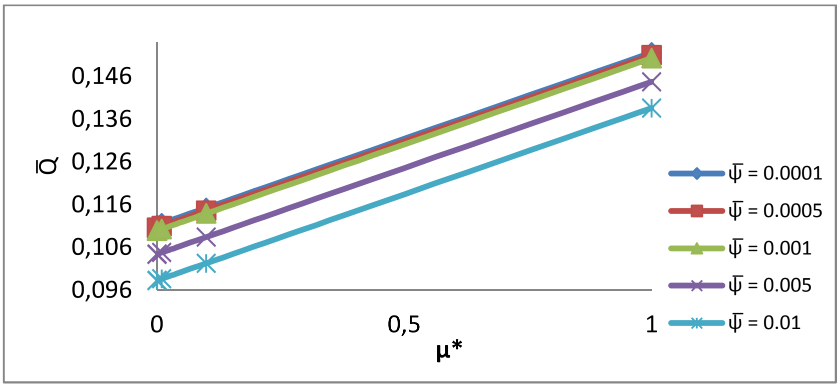

Fig. 29. Variation of Volume flow rate with respect to μ* and $\bar{\psi}$

4 Conclusion

This analysis confirms that the form of the magnitude of the magnetic field provides an additional degree of freedom from design point of view. This investigation makes it clear that the roughness aspects must be considered duly while designing the bearing system, even if the magnetic strength is suitably choosen. It is observed that this type of bearing system supports certain amount of load even when there is no flow unlike the case of conventional lubricants. A close glance at the results reveals that for this type of probability density function the effect of standard deviation is more as compared to the results of some other published works. Lastly, it is noticed that exclusively from roughness point of view, the trigonometric form of the magnitude of the magnetization may be adopted.

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