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Ferrofluid lubrication of an infinitely long rough porous journal bearing

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Abstract

This paper analyzes the performance of a squeeze film in an infinitely long rough journal bearing using the ferrofluid flow model of Jenkins. A random variable with non-zero mean, variance and skewness characterizes the random roughness of the bearing surfaces. The associated stochastically averaged Reynolds type equation is solved with suitable boundary conditions to obtain the expression for pressure distribution resulting in the calculation of load carrying capacity. It is shown that the eccentricity increases the load carrying capacity in spite of the fact that the bearing suffers owing to transverse surface roughness in general. It is observed that the Jenkins material constant decreases the load carrying capacity while the negatively skewed roughness increases the load carrying capacity. The bearing system registers a comparatively enhanced performance in the case of non-uniform magnetic field than in the case of a uniform magnetic field. It is interesting to note that the negative effect of porosity and the Jenkins material constant can be compensated up to some extent in the case of negatively skewed roughness. This compensation becomes more manifest when large negative values of variance are involved.

Keywords: Jenkins model, eccentricity, material constant, load, roughness, porosity

1. Introduction

As the things stand today, the physics of magnetic fluids is among the most promising and rapidly developing parts of the physics of magnetic phenomena. The investigations of (Neuringer-Rosensweig 1964) provided a new impetus to the interest in the magnetic fluid, now undiminishing, which was supported, above all, by a wide variety of their applications in industry, technology and medicine. (Tipei 1982) studied the magnetic fluid lubrication of a short bearing by deriving a Reynolds type equation. Here it was shown that the ferrofluid lubricant improved the performance of the bearing system and bearing stability and stiffness. Also, the magnetic fluid caused reduced wear. Here, of course, the Neuringer-Rosensweig model was used for the flow of the lubricant. (Berkovsky and Vislovich 1983) developed a mathematical model of non-equilibrium thermo mechanics of magnetic fluids as a logical generalization of the well-known Neuringer- Rosensweig model for equilibrium magnetization. (Shukla and Kumar 1987) derived the differential equation for ferrofluid lubrication resorting to Shliomis model (Shliomis 1972). It was established that the Brownian motion of the liquid together with rotation of the magnetic moments with in the particles produced rotational viscosity which supported more load. (Ram and Verma 1999) discussed the performance of a porous inclined slider bearing lubricated with a ferrofluid flowing as per the Jenkins model (Jenkins 1972). (Shah and Bhat 2004) studied ferrofluid squeeze film in a long journal bearing taking different models into consideration. They deduced the results for Neuringer-Rosensweig model from the Jenkins model (Jenkins 1972).

All these above investigations assumed the bearing surfaces to be smooth which in fact is far from being so, especially, after receiving some run in and wear. The random character of the roughness was recognized by (Tzeng and Saibel 1967). They used a stochastic method to describe the random roughness. This method of Tzeng and Saibel was developed and extended further by (Christensen and Tonder 1969a, 1969b and 1970) was employed by (Gupta and Deheri 1996) to study the effect of surface roughness on the squeeze film behavior in a spherical bearing. (Andharia et al. 1997) considered the effect of surface roughness on the hydrodynamic lubrication of slider bearings. Subsequently, Andharia and Patel analyzed the configuration of Andharia, (Gupta and Deheri 2001) in the presence of a magnetic fluid lubricant. Recently, (Patel and Deheri 2011) considered the effect of transverse surface roughness on the performance of a magnetic fluid based parallel plate porous slider bearing taking velocity slip in to account, here the Jenkins model was employed.

An attempt has been made to analyze the performance of an infinitely long rough porous journal bearing lubricated with a ferrofluid adopting Jenkins model.

2. Analyses

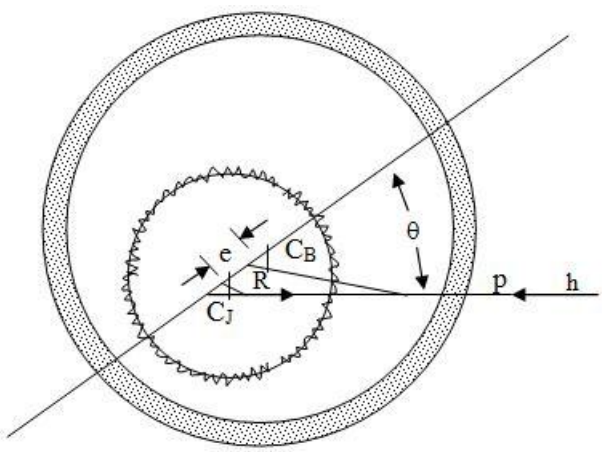

Fig. 1. Configuration of the bearing system.

The bearing shown in Fig. 1 has a journal of radius *R* inside a bearing and the gap between them is filled with a ferrofluid under an external magnetic field of strength *H*. The origin *o* is chosen on the circumference of the journal, the X-axis along its circumference and the Z-axis perpendicular to it. It is considered that it is infinitely long along its axial axis direction, with length *L*. The film thickness *h* is taken as,

$$h = c\left(1 + e\cos\theta\right), \quad \theta = \frac{x}{R} \tag{1}$$

where *c* is the radial clearance, *e* is the eccentricity ratio and θ is the angular coordinate. When the lubricant flows, as per the Jenkins model, and *H* is uniform, the equation governing the film pressure is (Ram and Verma 1999), (Jenkins 1972), (Mauginb 1980) and (Andharia et al. 2001)

$$\frac{d}{dx}\left[\frac{g(h)}{1-\frac{\rho\alpha^{2}\bar{\mu}H}{2\eta}}\frac{dp}{dx}\right]=12\eta\dot{h} \tag{2}$$

where

$$\dot{h} = \frac{dh}{dt}$$

and

$$g(h) = \left\{ h^{3} + 3\alpha h^{2} + 3\left(\alpha^{2} + \sigma^{2}\right)h + 3\sigma^{2}\alpha + \alpha^{3} + \varepsilon + 12\varphi h \right\}$$

Making use of Equation (1) and the dimensionless quantities

$$\bar{h}=\frac{h}{c}\,,\quad \beta=\frac{\rho\alpha^2\bar{\mu}H}{2\eta}\,,\quad P=\frac{c^2p}{\eta R^2\dot{e}}\,,\quad W=\frac{c^2w}{\eta LR^3\dot{e}}\,,\quad \bar{\alpha}=\frac{\alpha}{h}\,,$$

$$\bar{\sigma}=\frac{\sigma}{h}\,,\quad \bar{\varepsilon}=\frac{\varepsilon}{h^3}\,,\psi=\frac{12\varphi h}{h^3}$$

where

$$\dot{e}=\frac{de}{dt}$$

Equation (2) transforms to

$$\frac{d}{d\theta}\left(g\left(\bar{h}\right)\frac{dP}{d\theta}\right)=12\left(1-\beta\right)\cos\theta \tag{3}$$

where

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

Solving Equation (3) under the boundary conditions

$$\frac{dP}{d\theta}=0 \text{ when } \theta=\pi,\quad p\left(0\right)=0$$

one gets the pressure distribution in dimensionless form as

$$P=\ 12\left(1-\beta\right)\int_0^{\theta}\frac{\sin\theta}{g\left(\bar{h}\right)}\,d\theta \tag{4}$$

and the load carrying capacity in non-dimensional form can be expressed as

$$W=12\left(1-\beta\right)\int_0^{2\pi}\frac{\sin^2\theta}{g\left(\bar{h}\right)}\,d\theta \tag{5}$$

When the lubricant flow is as per the Jenkins model with non-uniform *H*, *H* is defined as follows

$$H^2=KR^2\theta\,\left(2\pi-\theta\right) \tag{6}$$

vanishing at $\theta=0,\ 2\pi$, K being a quantity introduced to suit the dimensions of both sides of Equation (6) and the strength of the external field, which is maximum at $\theta=\pi$ like P so that the magnetic pressure augments the film pressure. In this case the Reynolds type equation determining the film pressure is (Ram and Verma 1999; Jenkins 1972; Maugin 1980; Andharia et al. 2001)

$$\frac{d}{dx}\left[\frac{g(h)}{1-\frac{\rho\alpha^{2}\bar{\mu}H}{2\eta}}\frac{d}{dx}\left(p-\frac{1}{2}\mu_{0}\bar{\mu}H^{2}\right)\right]=12\eta\,\dot{h} \tag{7}$$

Using Equations (1) and (6), Equation (7) assumes the form

$$\frac{d}{d\theta}\left[A\frac{d}{d\theta}\left\{P-\mu^{*}\theta(2\pi-\theta)\right\}\right]=12\cos\theta \tag{8}$$

where

$$A=\frac{g(\bar{h})}{1-\beta'\sqrt{\theta(2\pi-\theta)}}\,,\quad \beta'=\frac{\rho\alpha^{2}\bar{\mu}\sqrt{K}R}{2\eta}\,,\quad \mu^{*}=\frac{\mu_{0}\bar{\mu}Kc^{2}}{2\eta\dot{e}}$$

Solving Equation (8) under the boundary conditions discussed before, one obtains the pressure distribution in non-dimensionless form as

$$P=\mu^{*}\theta(2\pi-\theta)+12\int_{0}^{\theta}\frac{\sin\theta}{A}\,d\theta \tag{9}$$

which results in the expression for dimensionless load carrying capacity

$$W=4\pi\mu^{*}+12\int_{0}^{2\pi}\frac{\sin^{2}\theta}{A}\,d\theta \tag{10}$$

3. Results and Discussion

It is clearly observed that equations (4) and (5) present the non-dimensional pressure distribution and load carrying capacity with respect to uniform magnetic field and equations (9) and (10) give the distribution of pressure and load carrying capacity with respect to non-uniform magnetic field. From all these equations it is clear that the load carrying capacity is comparatively greater in the case of non-uniform magnetic field, for a smooth non porous bearing this discussion reduces to the findings of (Shah and Bhat 2004). Further on, for a non-porous smooth bearing with convential lubricant this study gets down to the discussion of (Basu et al. 2005).

For the graphical representation of the results the following fixed values are adopted (Bhat 2003; Prajapati 1995) $\mu^*=0.3$, $\bar{\alpha}=0.05$, $\bar{\varepsilon}=0.05$, $\bar{\sigma}=0.25$, $\psi=0.01$, $e=0.5$, $\beta=0.3$ and $\beta'=0.051$.

It can be seen that Fig. 2-12 deal with uniform magnetic field while Fig. 13-29 deal with non-uniform magnetic field.

The variation of load carrying capacity presented in Fig. 2-5 indicates that the load carrying capacity decreases due to Jenkins material constant. However, increasing values of standard deviation and porosity cause reduced load carrying capacity, while the increasing values of the eccentricity induce an increase in the load carrying capacity. Furthermore, the negatively skewed roughness increases the load carrying capacity while the load carrying capacity decreases due to positively skewed roughness.

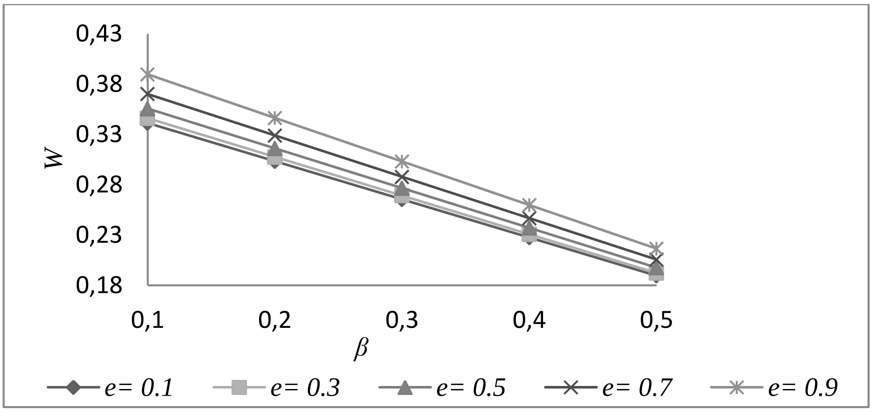

Fig. 2. Variation of load carrying capacity with respect to β and e.

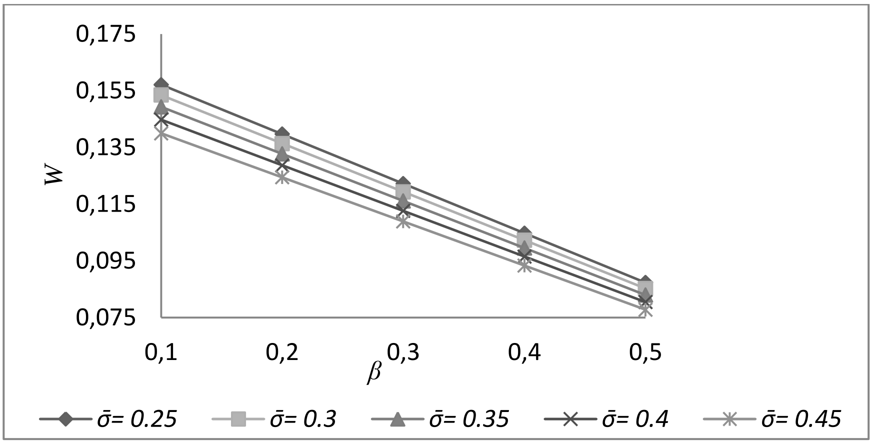

Fig. 3. Variation of load carrying capacity with respect to β and $\bar{\sigma}$.

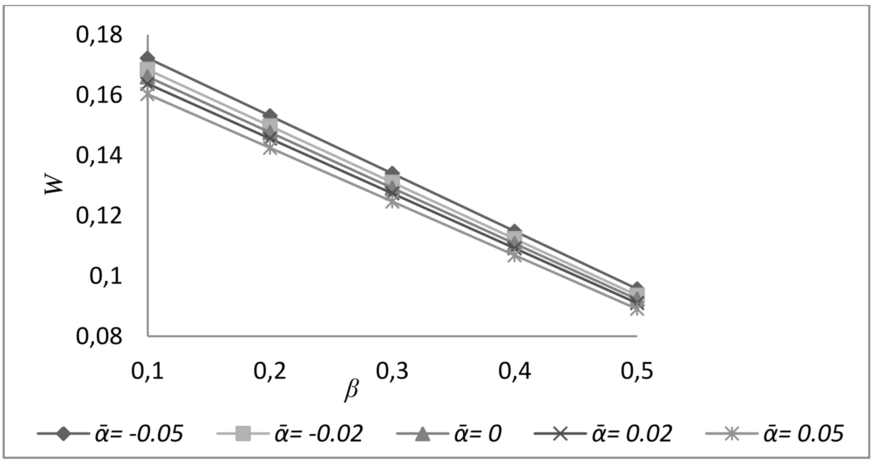

Fig. 4. Variation of load carrying capacity with respect to β and $\bar{\alpha}$.

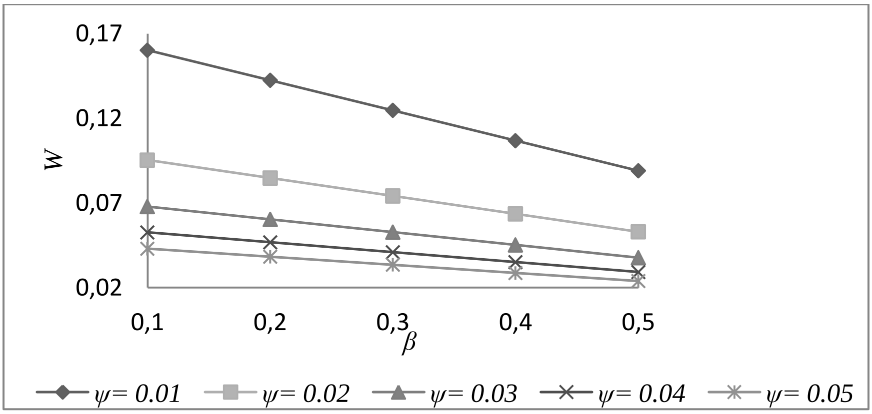

Fig. 5. Variation of load carrying capacity with respect to β and ψ.

The effect of eccentricity on the load carrying capacity shown in Fig. 6-8, makes it clear that it increases the load carrying capacity.

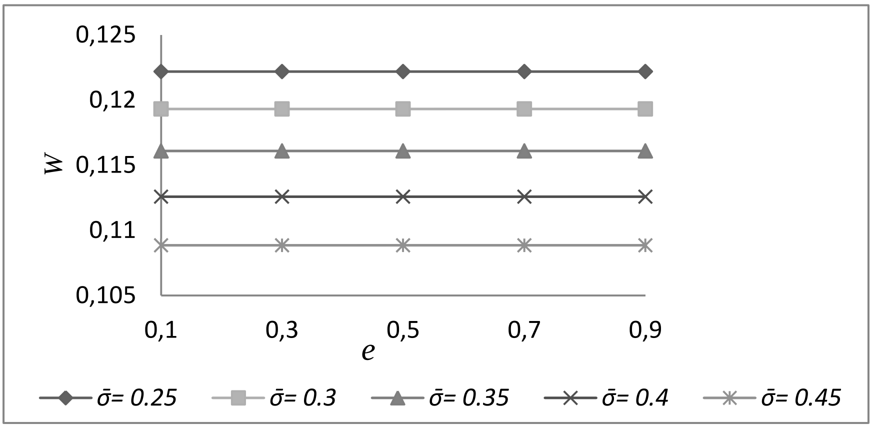

Fig. 6. Variation of load carrying capacity with respect to e and $\bar{\sigma}$.

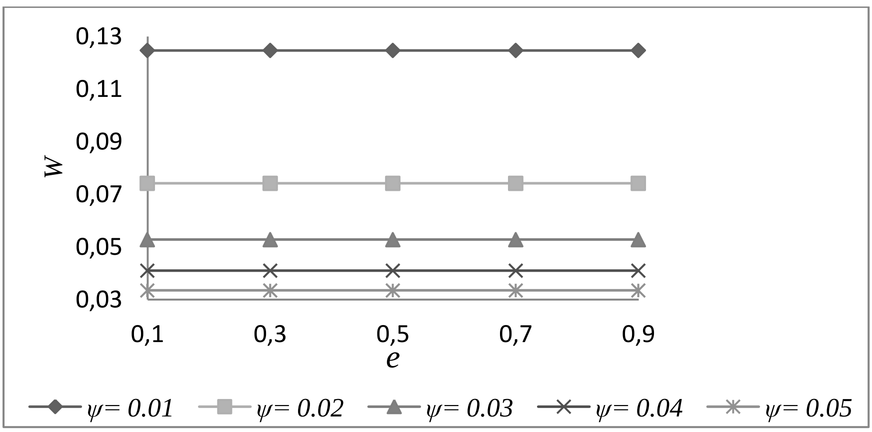

Fig. 7. Variation of load carrying capacity with respect to e and ψ.

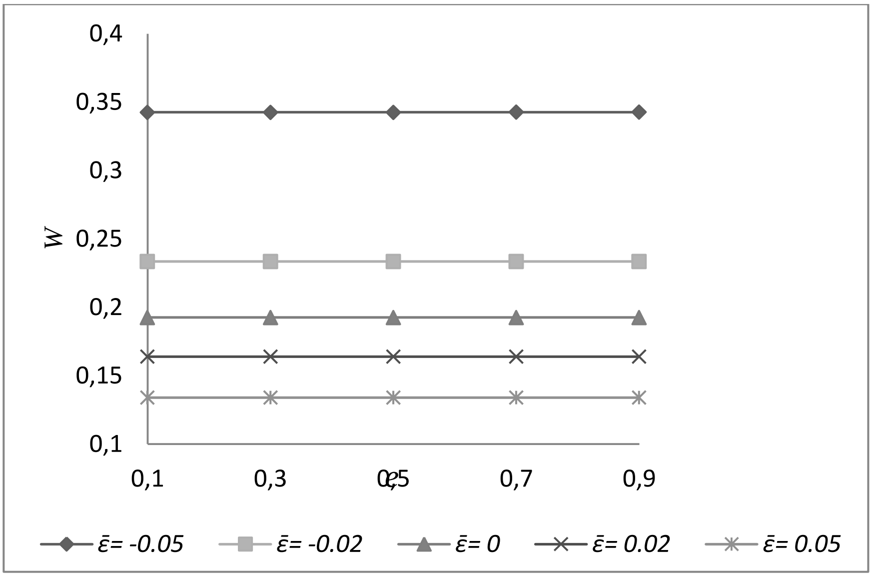

Fig. 8. Variation of load carrying capacity with respect to e and $\bar{\varepsilon}$.

The effect of standard deviation displayed in Fig. 9-10 suggests that the standard deviation has a considerable adverse effect on the performance of the bearing system in the sense that it decreases the load carrying capacity. Also, the decrease is greater in the case of variance.

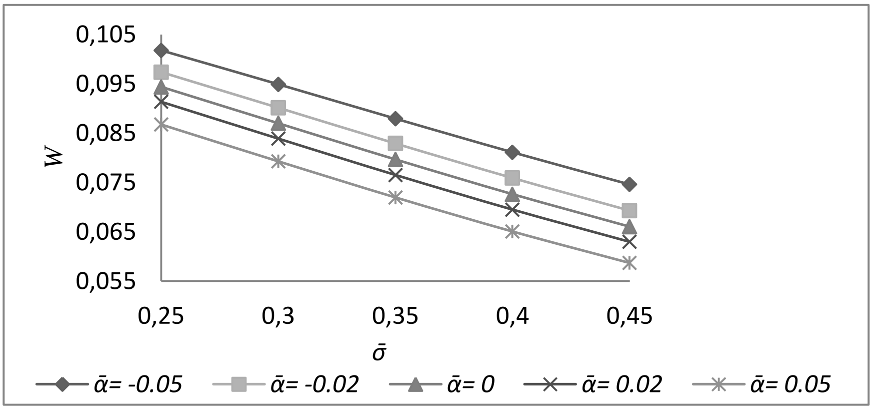

Fig. 9. Variation of load carrying capacity with respect to $\bar{\sigma}$ and $\bar{\alpha}$.

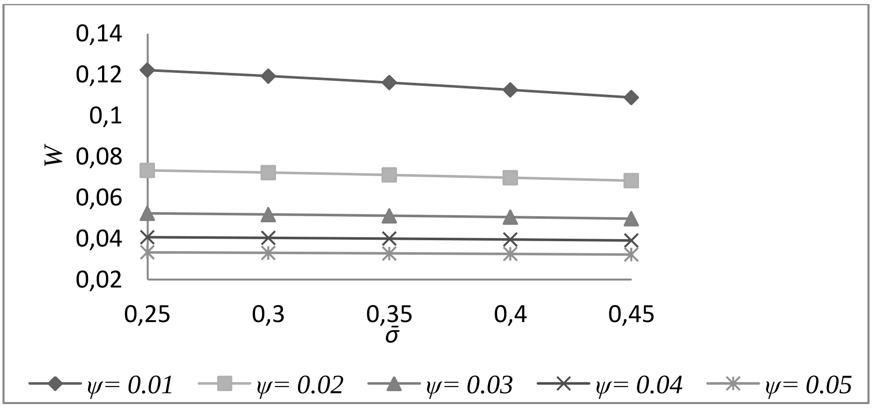

Fig. 10. Variation of load carrying capacity with respect to $\bar{\sigma}$ and ψ.

The effect of variance on the load carrying capacity is depicted in Fig. 11. It becomes clear that variance (-ve) increases the load carrying capacity while variance (+ve) decreases the load carrying capacity, thereby, following the path of skewness.

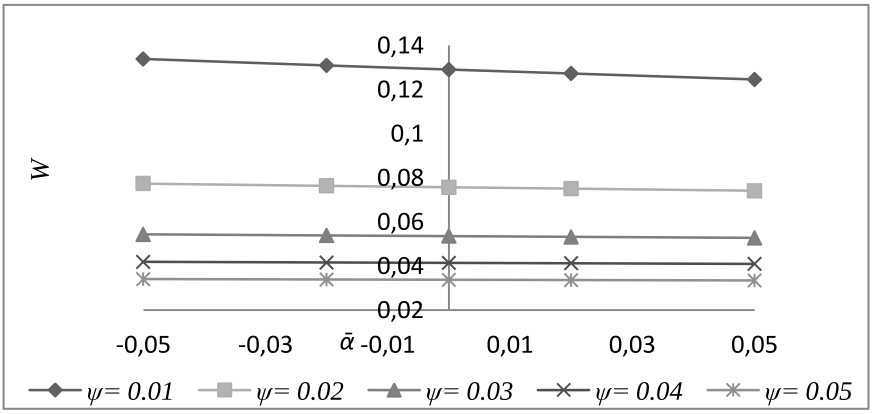

Fig. 11. Variation of load carrying capacity with respect to $\bar{\alpha}$ and ψ.

The effect of porosity on the load carrying capacity displayed in Fig. 12 suggests that the effect of porosity is negligible when porosity is greater than or equal to 0.03.

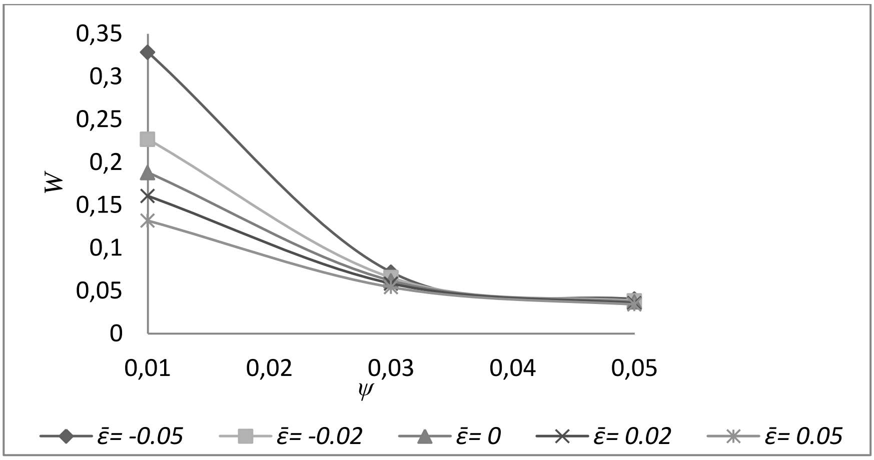

Fig. 12. Variation of load carrying capacity with respect to ψ and $\bar{\varepsilon}$.

The variation of load carrying capacity with respect to magnetization parameter displayed in Fig. 13-17 indicates that the magnetization increases the load carrying capacity. However, the increasing values of standard deviation, positively skewed roughness, Jenkins material constant and porosity cause decreased load carrying capacity while the increasing values of eccentricity ratio induce an increase in the load carrying capacity.

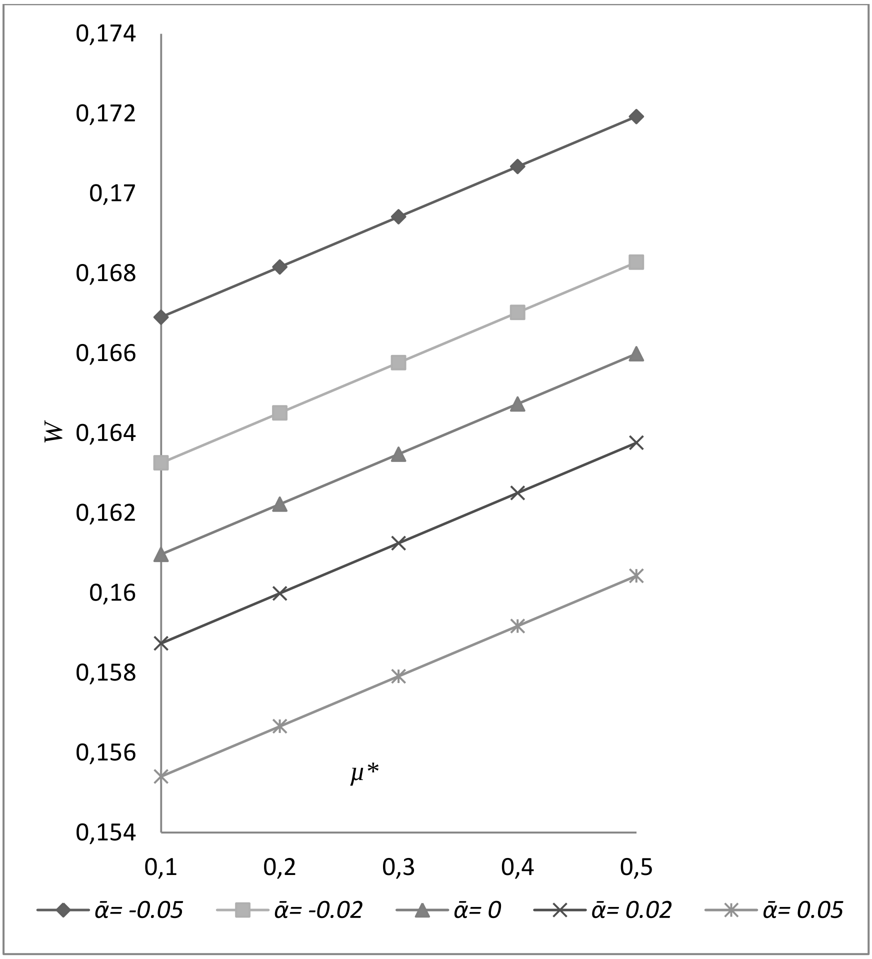

Fig. 13. Variation of load carrying capacity with respect to $\mu*$ and $\bar{\alpha}$.

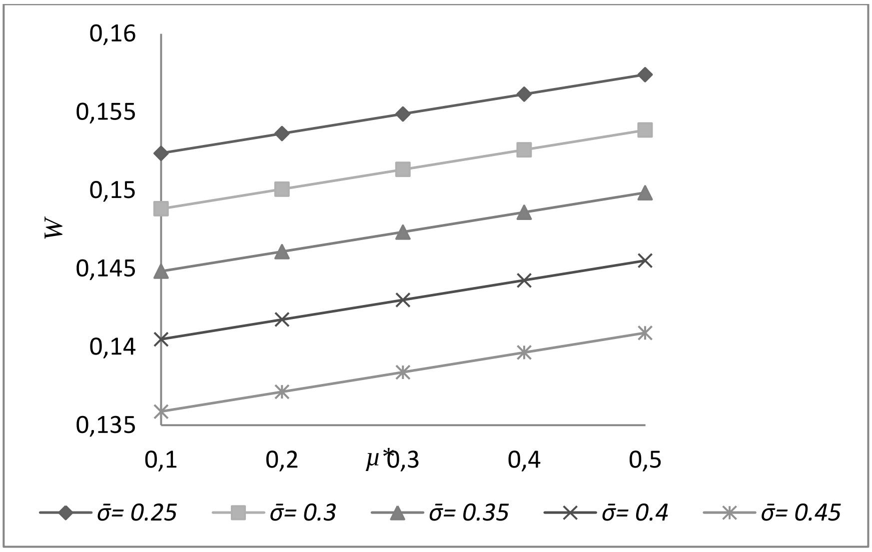

Fig. 14. Variation of load carrying capacity with respect to $\mu*$ and $\bar{\sigma}$.

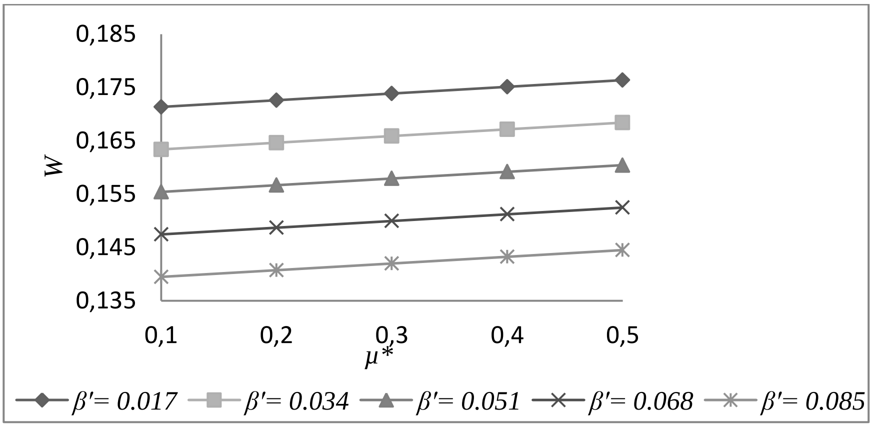

Fig. 15. Variation of load carrying capacity with respect to $\mu*$ and β'.

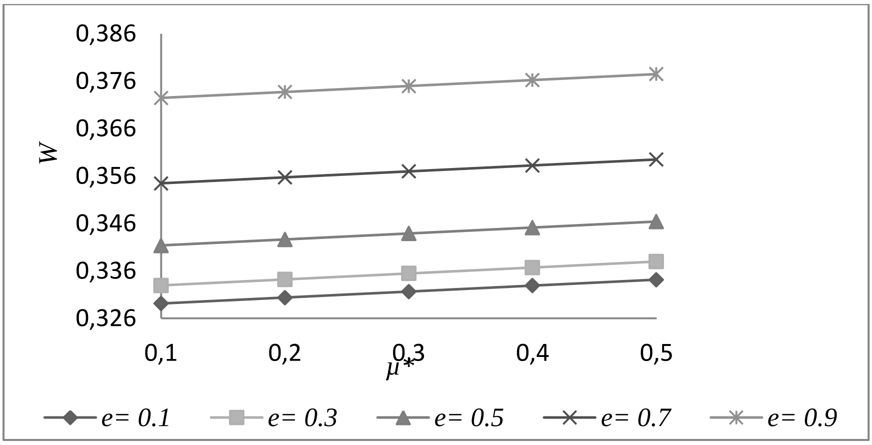

Fig. 16. Variation of load carrying capacity with respect to $\mu*$ and e

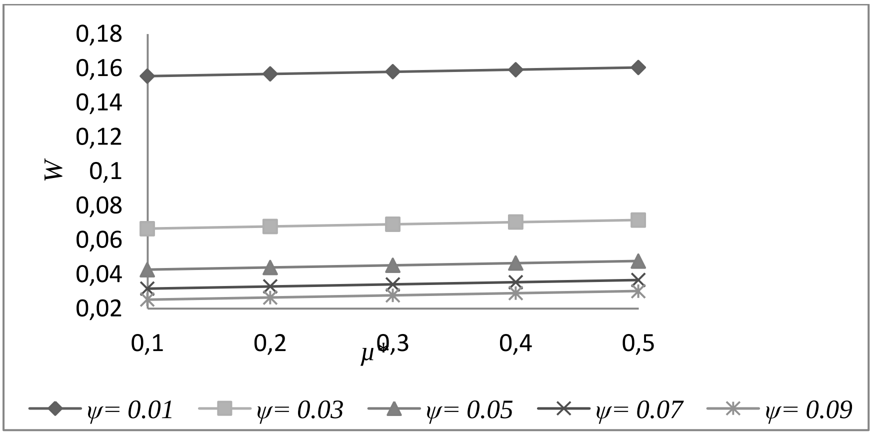

Fig. 17. Variation of load carrying capacity with respect to $\mu*$ and ψ.

The effect of Jenkins material constant on the distribution of load carrying capacity is shown in Fig. 18-21 which makes it clear that it decreases the load carrying capacity sharply. Further, initial effect of porosity is not that sharp.

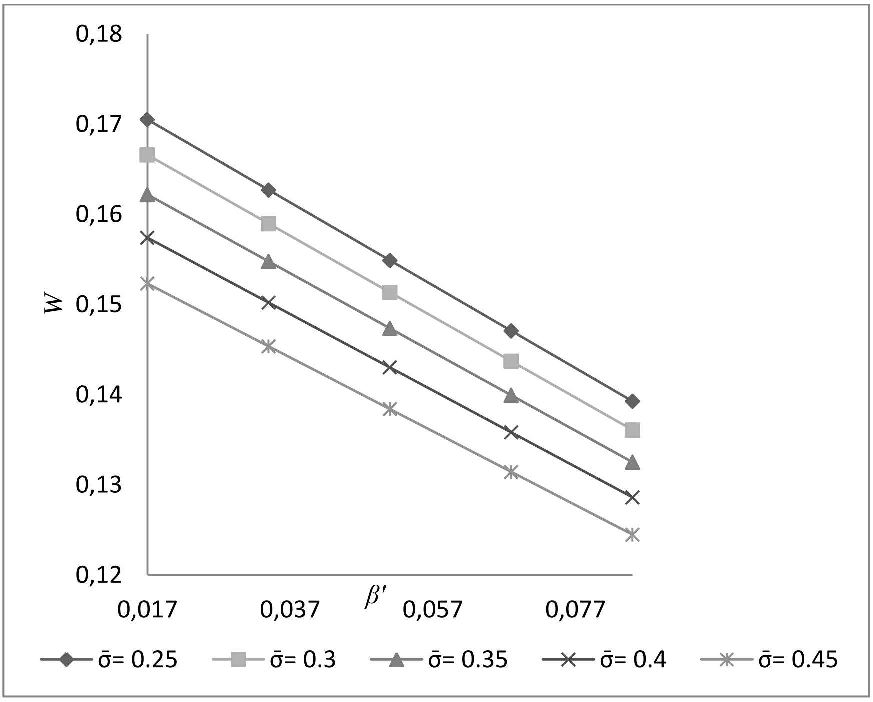

Fig. 18. Variation of load carrying capacity with respect to β' and $\bar{\sigma}$.

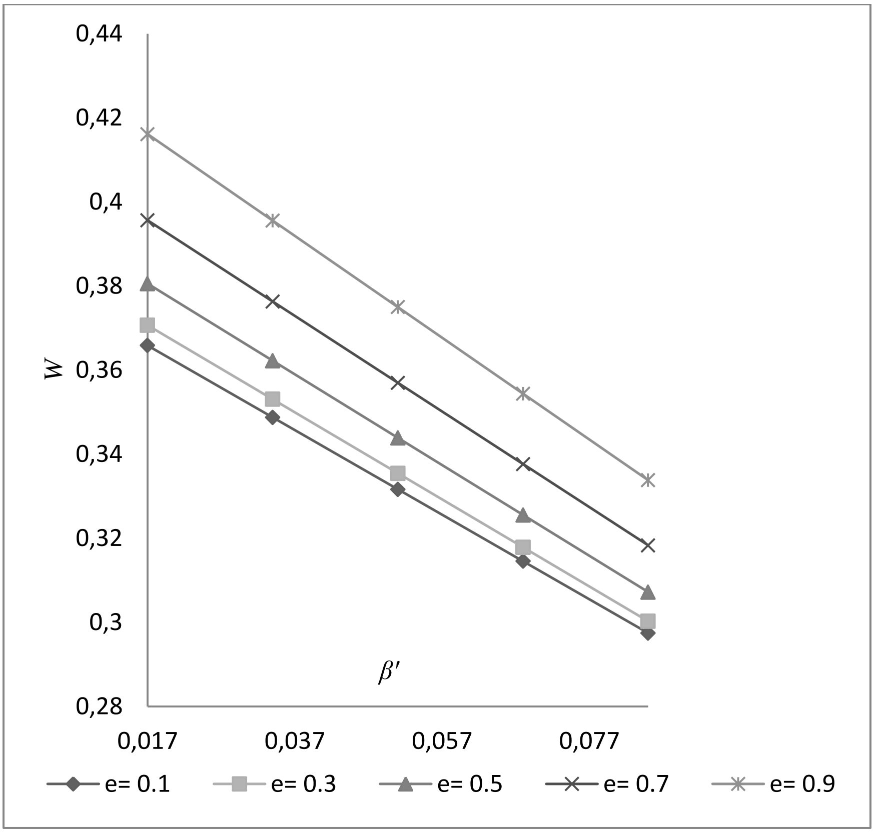

Fig. 19. Variation of load carrying capacity with respect to β' and e.

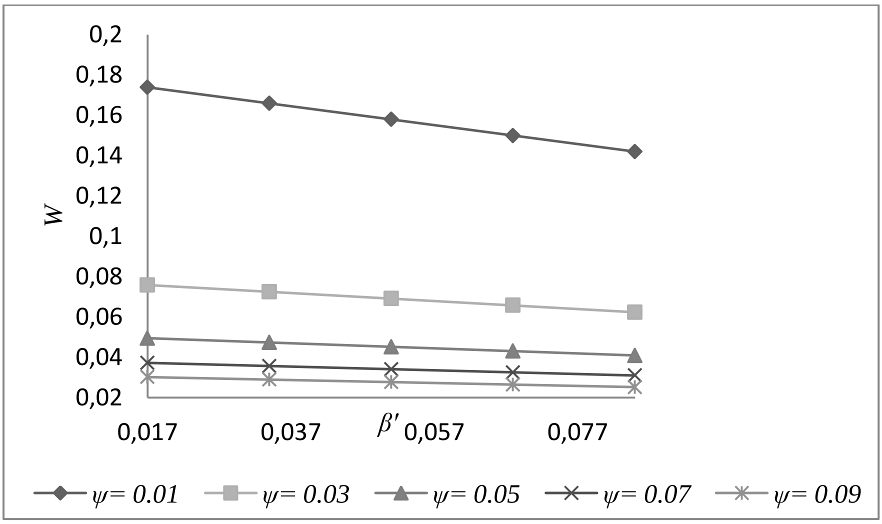

Fig. 20. Variation of load carrying capacity with respect to β' and ψ.

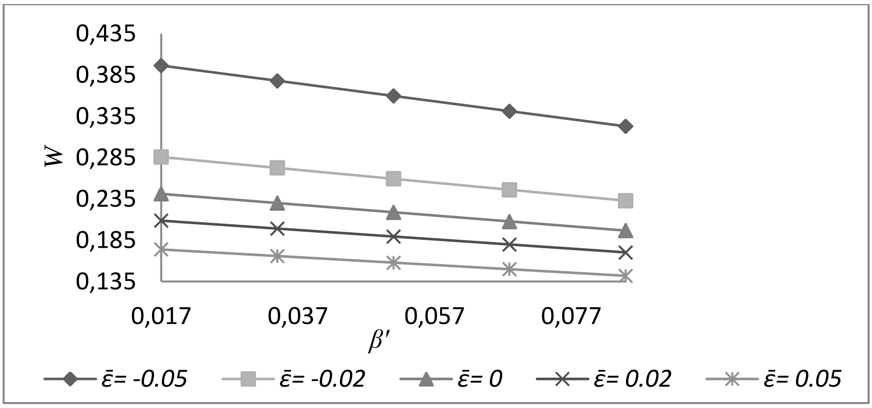

Fig. 21. Variation of load carrying capacity with respect to β' and $\bar{\varepsilon}$.

The effect of standard deviation presented in Fig. 22-24 suggests that the standard deviation adversely affects the performance of the bearing system in the sense that it decreases the load carrying capacity. Besides, the rate of decrease is higher in the case of eccentricity.

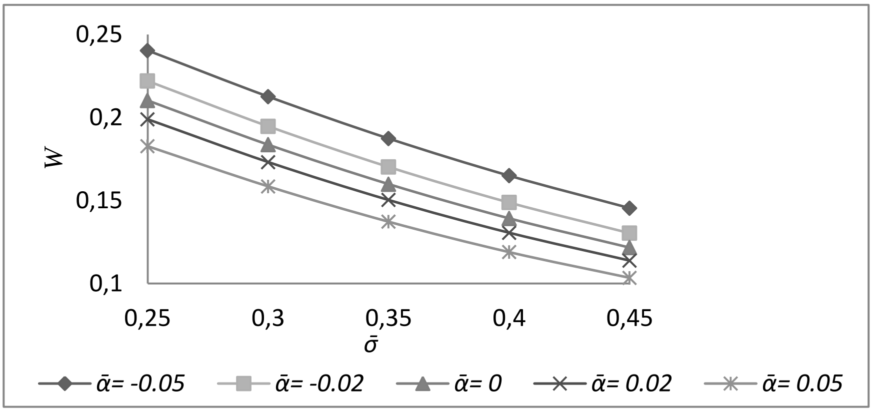

Fig. 22. Variation of load carrying capacity with respect to $\bar{\sigma}$ and $\bar{\alpha}$.

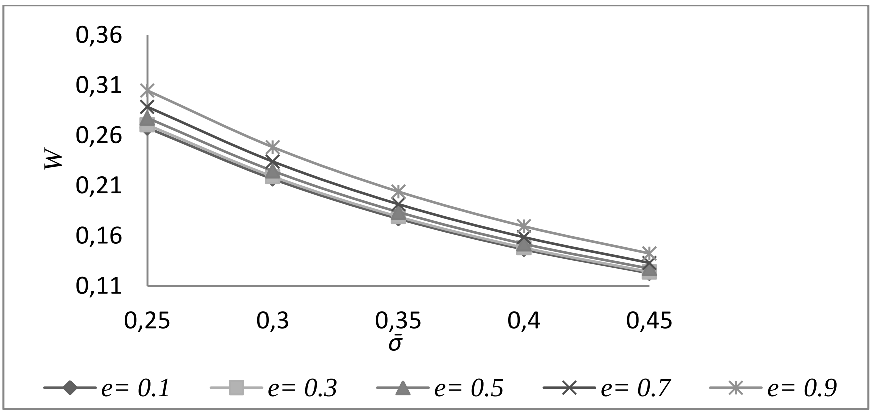

Fig. 23. Variation of load carrying capacity with respect to $\bar{\sigma}$ and e.

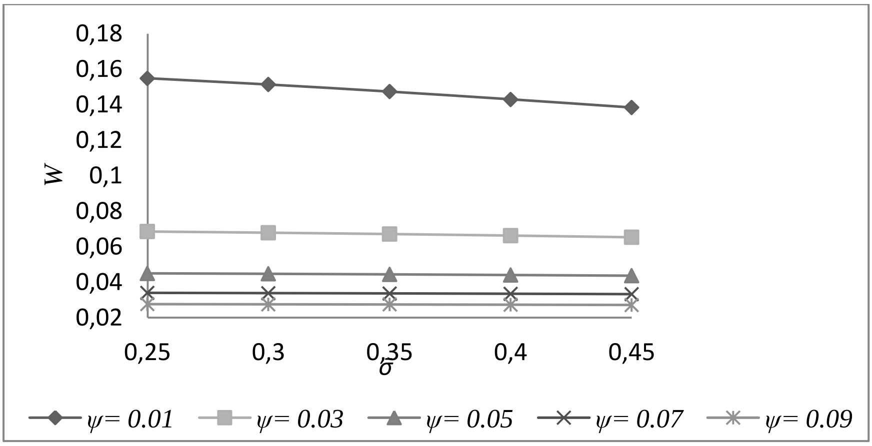

Fig. 24. Variation of load carrying capacity with respect to $\bar{\sigma}$ and ψ.

The effect of variance on distribution of load carrying capacity is depicted in Fig. 25-27. It becomes evident that variance (-ve) increases the load carrying capacity while variance (+ve) decreases the load carrying capacity.

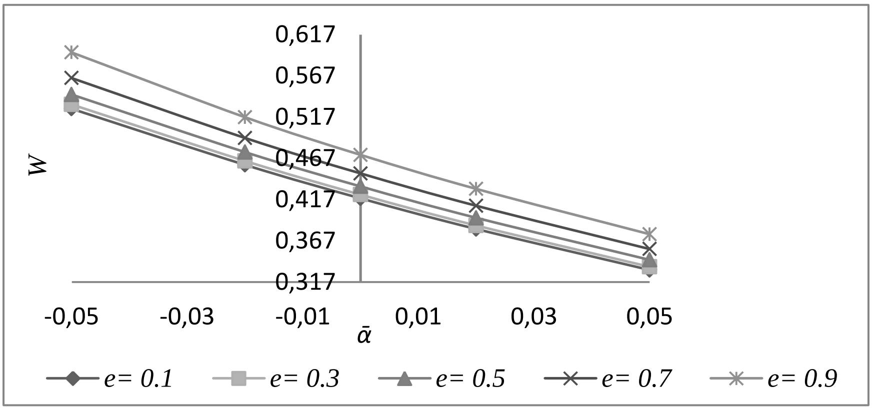

Fig. 25. Variation of load carrying capacity with respect to $\bar{\alpha}$ and e.

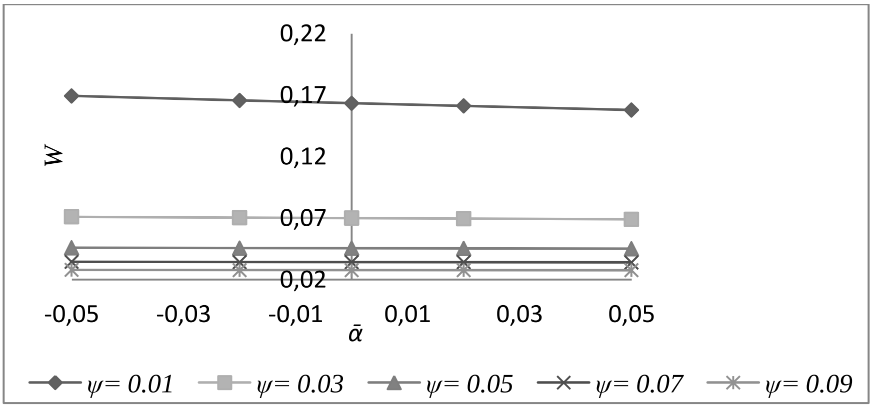

Fig. 26. Variation of load carrying capacity with respect to $\bar{\alpha}$ and ψ.

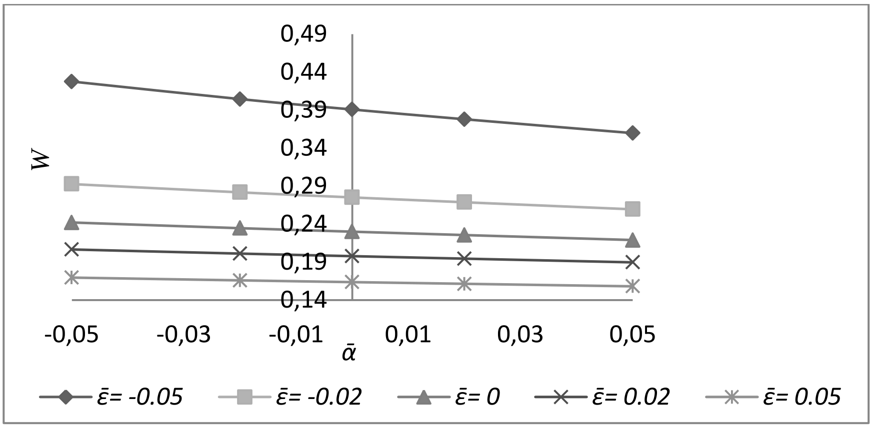

Fig. 27. Variation of load carrying capacity with respect to $\bar{\alpha}$ and $\bar{\varepsilon}$.

The effect of porosity on the distribution of the load carrying capacity can be seen in Fig. 28. It is manifest that porosity decreases load carrying capacity. However, the effect of skewness on the porosity is negligible beyond porosity value 0.03. It is observed that negatively skewed roughness increases the load carrying capacity while the load carrying capacity decreases owing to positively skewed roughness, thus, following the path of variance.

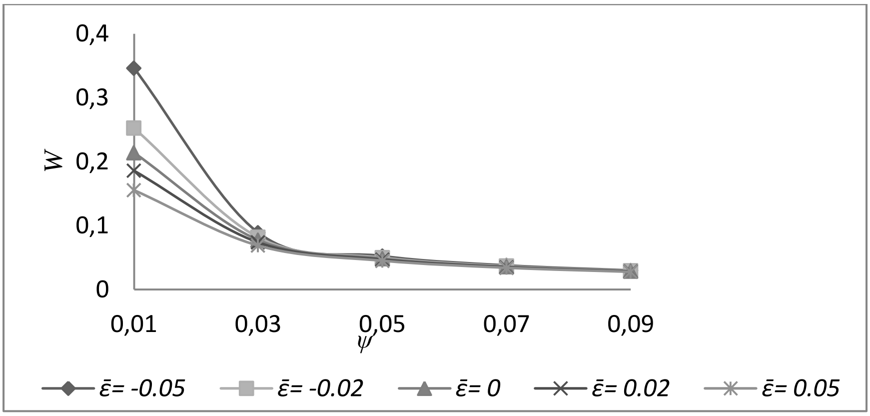

Fig. 28. Variation of load carrying capacity with respect to ψ and $\bar{\varepsilon}$.

The effect of eccentricity on the load carrying capacity is displayed in Fig. 29. It is found that the load carrying capacity increases negligibly with the increasing values of skewness.

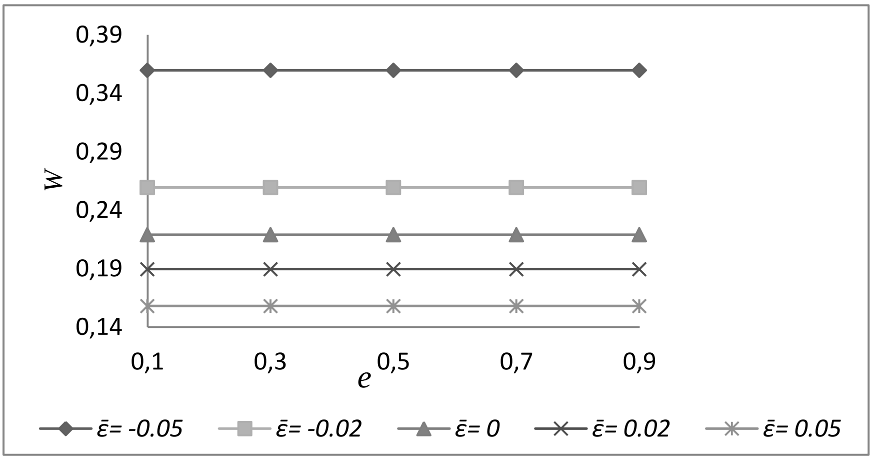

Fig. 29. Variation of load carrying capacity with respect to e and $\bar{\varepsilon}$.

It is found that the effect of negatively skewed roughness is more sharp in the case of non-uniform magnetic field rather than uniform magnetic field. However, the reverse is true in the case of variance. A comparison of the present investigation with the study of (Shah and Bhat, 2004) reveals that the performance of the bearing system is relatively better here in spite of the fact that transverse surface roughness adversely affects the bearing system. Further, the effect of β' is more pronounced here. Besides, the effect of eccentricity is equally sharp.

4. Conclusions

The negative effect of standard deviation, porosity and Jenkins material constants can be compensated up to some extent by the positive effect of magnetization in the case of negatively skewed roughness especially when variance is involved. Furthermore, the bearing can support a load even in the absence of flow. Looking to the overall scenario, the case of non-uniform magnetic field presents a better picture with regards to the performance.

Acknowledgements

The authors acknowledge with thanks the fruitful comments and suggestions of the Reviewers/ Editors.

c	Radial clearance
e	Eccentricity ratio
h	Fluid film thickness at any point
p	Lubricant pressure
w	Load carrying capacity
C_B	Bearing centre
C_J	Journal centre
H	strength of the magnetic field
L	Length of the bearing
P	Dimensionless pressure
W	Dimensionless load carrying capacity
η	Fluid viscosity
ρ	Fluid density
β, β'	Jenkins material constant
σ	Standard deviation
α	Variance
ε	Skewness
ψ	Porosity
$\bar{\sigma}$	Dimensionless standard deviation
$\bar{\alpha}$	Dimensionless variance
$\bar{\varepsilon}$	Dimensionless skewness
μ_0	The permeability of the free space
μ^*	Magnetization parameter in non-dimensional form
$\bar{\mu}$	Magnetic susceptibility

Table 1. Nomenclature.

Извод

Подмазивање бескарајно дуге храпаве порозне површине носећег лежаја ферофлуидом

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Резиме

Овај рад анализира перформансе подмазивача на бесконачно дугом храпавом носећем лежају применом Џенкинсовог модела протока ферофлуида. Насумичну храпавост носећих површина карактерише случајна променљива са математичким очекивањем различитим од нуле, варијанса и закошеност. Повезана стохастички усредњена Рејнолдсова једначина решена је применом одговарајућих граничних услова како би се добио израз за расподелу притисака који је добијен из рачунања носивости. Показали смо да ексцентричност повећава капацитет носивости упркос чињеници да носеће површине трпе због трансверзалне храпавости површине. Уочили смо да Џенкинсова материјална константа смањује носивост, док негативна закошеност повећава носивост. Перформансе система носећег лежаја су побољшане у случају променљивог магнетног поља у односу на стално магнетно поље. Занимљиво је напоменути да негативни ефекти порозности и Џенкинсове константе могу бити донекле умањени у случају негативно закошене храпавости. Ово умањење постаје очигледније када су укључене велике негативне вредности варијансе.

Кључне речи: Џенкинсов модел, ексцентричност, материјална константа, капацитет, храпавост, порозност

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