EFFECT OF ROTATION OF MAGNETIC PARTICLES ON A FERROFLUID SQUEEZE FILM BETWEEN POROUS CURVED ANNULAR PLATES AND SURFACE ROUGHNESS EFFECT
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An attempt has been made to discuss the effect of rotation of magnetic particles on the ferrofluid based squeeze film performance between two porous rough annular plates when the upper plate approaches the lower one normally. The Reynolds type equation is stochastically averaged with respect to the random roughness parameter characterizing the random roughness. Expression for pressure distribution is obtained by solving the associated stochastically averaged Reynolds type equation. Further, this leads to the calculation of load carrying capacity of the bearing. The load carrying capacity is observed to be increasing when the volume concentration of the magnetic particles or the curvature of the upper plate is increased. Although, the effect of porosity and standard deviation associated with roughness is adverse, this article presents some measures to overcome this adverse effect in the case of negatively skewed roughness by the positive effect of the magnetization suitably choosing the curvature parameter.

7.1 INTRODUCTION

Moore [1965] gave an account of the development of squeeze films from the days of original Reynolds-Stefan equation. Fundamental equations incorporating the effects of inertia, variable viscosity, non-Newtonian fluids, surface tension, dynamic loading and surface wear were presented. The study of squeeze film behavior between flat annular plates is a classical (Khonsari and Booser [2001], Wu [1970, 1971]) one. It is well known that vibrations in jet engines can be absorbed using annular squeeze films between engine bearing and their supports. However, owing to elastic, thermal and uneven wear effects, the plates
encountered in practice are not actually flat. With this point of view Shah and Bhat [2005] considered ferrofluid squeeze film between curved annular plates including rotation of magnetic particles in the case of an exponentially curved upper plate. Here, the ferrofluid lubricant was under a constant transverse magnetic field while the flow was based on Shliomis model [1972].

Recently, various investigations have been made using a ferrofluid as the lubricant owing to its advantages such as long life, silent operation and reduced wear. Even with an appropriate magnetic field the ferrofluid lubricant can prevent leakages. It can also be fixed at the desired friction zone by applying an external magnetic field.

In general, the magnetic fluid can outperform non-magnetic lubricants in lubricating magnetic pairs owing to the magnetic attraction that leads to an effective adhesion of the magnetic lubricant on to the friction surface.

Kaiser and Miskolczy [1970] prepared stable colloidal dispersions of sub domain size magnetic particles that retained their liquid characteristics in the presence of a magnetic field.

Phan-Thien [1982] derived an averaged Reynolds equation using the two-space homogenization method and applied this equation to squeeze film bearings with a sinusoidal or an isotropic surface roughness.

the work of Bhat and Deheri [1991 a] to include the curvature of the
upper disk and rotation of both discs.

Deheri et al. [2011] extended the analysis of Gupta and Vora
[1980] by taking a ferrofluid lubricant. From this investigation it was
established that magnetization of the fluid increased the load carrying
capacity of the bearing studied. In these investigations Neuringer-
Rosensweig model was used for the ferrofluid lubricant under a
variable/magnetic field. The Neuringer-Rosensweig model failed to give
any contribution to the flow field when a constant magnetic field was
used unlike, the case of Shliomis [1972] which was resorted to by Sinha
et al. [1993] and by Shukla and Kumar [1987].

The bearing surfaces develop roughness particularly, after
receiving some run in and wear. The random character of the roughness
was recognized by Christensen and Tonder [1969 a, 1969 b, 1970] who
used a stochastic method to characterize the random roughness.
Subsequently, the method developed by Christensen and Tonder [1969 a,
1969 b, 1970] was adopted in a number of investigations (Ting [1975],
Chikazumi et al. [1987], Prajapati [1991, 1992], Guha [1993], Gupta and
Deheri [1996], Andharia et al. [1999]). It was conclusively established
that the surface roughness induced a significant effect on the performance
of the bearing system in general, while the transverse surface roughness
turned in an adverse effect in particular.

Patel and Deheri [2004] considered the magnetic fluid based
squeeze film behavior between annular plates and analyzed the effect of
transverse surface roughness. Vadher et al. [2008] analyzed the performance of a hydromagnetic squeeze film between two conducting rough porous annular plates. Deheri and Abhangi [2008] observed the squeeze film behavior in curved rough circular plates under the presence of a magnetic fluid lubricant. The above three studies proved that the negative effect of transverse roughness can be reduced by the positive effect of magnetization. Therefore, it was deemed appropriate to analyze the behavior of a curved squeeze film between two transversely rough annular plates with a ferrofluid lubricant under a constant transverse magnetic field making use of the Shliomis model.

7.2 ANALYSIS

![Figure 1 Configuration of the bearing System](image)

The bearing consists of two annular plates each of inside radius $b$ and outside radius $a$ ($a > b$). The geometry and configuration of the problem is displayed in Fig.1. The film thickness $h$ is taken as in Murti [1975], which is
\[ h = h_0 e^{-\beta r^2} \quad b \leq r \leq a \quad (7.1) \]

where \( r \) is the radial coordinate, \( h_0 \) is the central film thickness and \( \beta \) is the curvature of the upper plate. The upper plate approaches the lower one with a constant normal velocity

\[ \dot{h}_0 = \frac{dh_0}{dt} \]

With the usual assumptions of hydromagnetic lubrication, the film pressure \( p \) can be determined from the Reynolds type equation (Shah and Bhat [2005], Andharia et al. [2001], Ting [1975]) as

\[ \frac{1}{r} \frac{d}{dr} \left( G(h) \frac{dp}{dr} \right) = 12 \eta_0 \left( 1 + \frac{5}{2} \phi \right) (1 + \tau) h_0 \quad (7.2) \]

where

\[ G(h) = h^3 + 3a h^2 + 3 \left( \alpha^2 + \sigma^2 \right) h + 3a^2 \alpha + \alpha^3 + \epsilon + 12 \phi H \]

and \( \eta_0, \phi \) and \( \tau \) are the viscosity of the liquid, volume concentration of the magnetic particles and the rotational viscosity parameter respectively.

With the introduction of the dimensionless quantities

\[ \bar{h} = \frac{h}{h_0}, \quad \bar{\alpha} = \frac{\alpha}{h_0}, \quad \bar{\sigma} = \frac{\sigma}{h_0}, \quad \bar{\epsilon} = \frac{\epsilon}{h_0^3}, \quad \bar{\omega} = \frac{\phi H}{h_0^3}, \quad \bar{R} = \frac{r}{h_0}, \quad \bar{\beta} = \frac{\beta b^2}{\eta_0 h_0^2}, \quad \bar{P} = \frac{-h_0^3 \bar{p}}{\eta_0 b^2 h_0} \]

\[ \bar{W} = \frac{-h_0^3 \bar{w}}{2\pi \eta_0 b^4 h_0} \]
Equation (7.2) transforms to

\[ \frac{1}{R} \frac{d}{dR} \left( e^{-3 \beta R^2} + 3 \alpha e^{-2 \beta R^2} + 3 \left( \alpha^2 + \sigma^2 \right) e^{-\beta R^2} + \left( 3 \sigma^2 \alpha + \alpha^3 + \epsilon + 12 \psi \right) + a^2 \right) \frac{dP}{dR} \]

\[ = -12 \left( 1 + \frac{5}{2} \varphi \right) (1 + \tau) \]  

(7.3)

in view of Equation (7.1).

Solving Equation (7.3) under the boundary conditions

\[ P(1) = P(k) = 0, \]

where \( k = \frac{a}{b} \), one obtains the expression for dimensionless pressure \( P \) as

\[ P = N \int_{1}^{R} \frac{G(R)}{R} dR - \frac{1 + \frac{5}{2} \varphi (1 + \tau)}{\beta} \left( G(R) - G(1) \right) \]

(7.4)

where

\[ N = \frac{1 + \frac{5}{2} \varphi (1 + \tau) (G(k) - G(l))}{\frac{k}{\beta} \int_{1}^{R} G(R) dR} \]

and

\[ G(R) = e^{3 \beta R^2} + 3 \alpha e^{2 \beta R^2} + 3 \left( \alpha^2 + \sigma^2 \right) e^{\beta R^2} + \left( 3 \sigma^2 \alpha + \alpha^3 + \epsilon + 12 \psi \right) \]

Now, the load carrying capacity \( w \) of the bearing can be expressed in non-dimensional form as
\[ W = \frac{k}{R} \frac{dP}{dR} = -\frac{1}{2} R^2 \frac{dP}{dR} \]

\[ = -\frac{1}{12 \bar{\beta}^2} \left[ N\bar{\beta} (G(k) - G(1)) - 2 \left( 1 + \frac{5}{2} \varphi \right) \left( 1 + \tau \right) (A - B) \right] \] (7.5)

where

\[ A = \left( \frac{3}{4} k^2 - 1 \right) e^{\frac{3}{4} k^2} + 3\bar{\alpha} \left( \frac{2}{4} k^2 - 1 \right) e^{\frac{3}{4} k^2} + \left( \frac{3}{2} \bar{\alpha}^2 + \bar{\sigma}^2 \right) \left( \frac{1}{4} k^2 - 1 \right) e^{\frac{3}{4} k^2} + \left( 3\bar{\alpha}^2 + \bar{\sigma}^2 + \bar{\epsilon} + 12 \varphi \right) \]

and

\[ B = \left( \frac{3}{4} \bar{\beta}^2 - 1 \right) e^{\frac{3}{4} \bar{\beta}^2} + 3\bar{\alpha} \left( \frac{2}{4} \bar{\beta}^2 - 1 \right) e^{\frac{3}{4} \bar{\beta}^2} + \left( \bar{\alpha}^2 + \bar{\sigma}^2 \right) \left( \frac{1}{4} \bar{\beta}^2 - 1 \right) e^{\frac{3}{4} \bar{\beta}^2} + \left( 3\bar{\alpha}^2 + \bar{\sigma}^2 + \bar{\epsilon} + 12 \varphi \right) \]

7.3 RESULTS AND DISCUSSION

It is clearly seen that Equation (7.4) presents the expression for the dimensionless pressure distribution while the non dimensional load carrying capacity is determined from Equation (7.5). The squeeze film performance between flat rough surfaces can be obtained by letting \( \bar{\beta} \) tending to zero.

Further, setting roughness parameters to be zero this study transforms to the ferrofluid based squeeze film in annular plates studied by Bhat and Deheri [1991a] in the absence of rotation of magnetic particles. It can be seen that the current investigation reduces to the discussion of Shah and Bhat [2005] in the absence of porosity and roughness.

A comparison of this paper with that of Shah and Bhat [2005] indicates that the situation is little bit improved here in spite of the
adverse effect of porosity and standard deviation associated with roughness.

The variation of non dimensional load carrying capacity with respect to the rotational viscosity parameter ($\tau$) presented in Figures 2-7 makes it clear that the load carrying capacity increases sharply due to the magnetization.

Fig. 2 Variation of load carrying capacity with respect to $\tau$ and $\alpha$

Fig. 3 Variation of load carrying capacity with respect to $\tau$ and $\epsilon$
Fig. 4 Variation of load carrying capacity with respect to $\tau$ and $\beta$

Fig. 5 Variation of load carrying capacity with respect to $\tau$ and $\phi$
Fig. 6 Variation of load carrying capacity with respect to $\tau$ and $\sigma^2$

Fig. 7 Variation of load carrying capacity with respect to $\tau$ and $\psi$

The effect of variance on the load carrying capacity is displayed in Figures 8-12. It is clearly seen that variance (+ve) increases the load carrying capacity while variance (-ve) decreases the load carrying
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capacity. It is interesting to note that this is unlike the case when there is no rotation of the magnetic particles as discussed in Vadher et al. [2008].

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

Fig. 9 Variation of load carrying capacity with respect to $\bar{a}$ and $\bar{\beta}$
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Fig. 10 Variation of load carrying capacity with respect to $\tilde{\alpha}$ and $\varphi$

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

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The effect of standard deviation depicted in Figures 13-16 indicates that the load carrying capacity decreases sharply with increasing values of standard deviation.
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Fig. 14 Variation of load carrying capacity with respect to $\sigma$ and $\bar{\beta}$

Fig. 15 Variation of load carrying capacity with respect to $\sigma$ and $\varphi$
Fig. 16 Variation of load carrying capacity with respect to $\sigma$ and $\psi$

Figures 17-19 establish that the trends of the load carrying capacity with respect to skewness are opposite to that of the variance. In fact, negatively skewed roughness increases the load carrying capacity significantly.

Fig. 17 Variation of load carrying capacity with respect to $\varepsilon$ and $\bar{\beta}$
The effect of rotation of magnetic particles on a ferrofluid squeeze film between porous curved annular plates and surface roughness effect is investigated. The load carrying capacity decreases with increasing porosity, as shown in Figures 20-21. The figures illustrate the variation of load carrying capacity with respect to eccentricity (ε) and porosity (φ), with specific values of φ: 0.15, 0.25, 0.35, 0.45, and 0.55. Similarly, Figures 20-21 show the variation with respect to eccentricity (ε) and Ψ, with specific values of Ψ: 0.01, 0.015, 0.02, 0.025, and 0.03.

The fact that porosity decreases the load carrying capacity can be seen from Figures 20-21.
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Fig. 20 Variation of load carrying capacity with respect to $\psi$ and $\beta$

![Graph showing variation of load carrying capacity with respect to $\psi$ and $\beta$]

Fig. 21 Variation of load carrying capacity with respect to $\psi$ and $\varphi$

Lastly, it is manifest from Figure 22 that the combined effect of volume concentration of the magnetic particles and the curvature of the upper plate is significantly positive in the sense that the load carrying capacity rises sharply.
The load carrying capacity is observed to be increased when the volume concentration of the magnetic particles or the curvature of the upper plate is increased. Indeed, the upper plate's curvature parameter plays a significant role in augmenting the performance of the bearing system. Further, equally significant is the positive contribution of the volume concentration of the magnetic particles. Some of the figures presented here reveal that the negative effect of porosity can be reduced considerably by the positive effect of ferrofluid lubrication; here of course, the rotation of magnetic particles may play an important role.

7.4 CONCLUSION

Although, the effect of porosity and standard deviation associated with roughness is adverse, this article presents some measures to overcome this adverse effect in the case of negatively skewed roughness by the positive effect of the magnetization, suitably choosing the
curvature parameter. This investigation makes it mandatory that the roughness must be given due consideration while designing the bearing system even if, the rotation of magnetic particles are involved in the ferrofluid lubrication. A constant magnetic field fails to enhance the bearing performance characteristics in the Neuringer-Rosensweig model but it does so in the case of Shliomis model, in which rotation of magnetic particles and their moments are included. The load carrying capacity of the annular ferrofluid based squeeze film can be made optimal by choosing appropriately the upper plate's curvature parameter, in the case of negatively skewed roughness.
General Conclusion:

Most of the problems considered in this dissertation are related to slider bearings or parallel plate squeeze film bearing. The porous bearings have become very popular because of, amongst several advantages they offer, one which is most important is that of self lubrication.

The use of Morgan-Cameron approximation in the mathematical analysis has considerable, simplified derivations for understanding the performance of a porous bearing. vis-à-vis the performance of equivalent non porous bearing. Although, the existence of tangential slip velocity at the lubricant film porous matrix interface is experimentally confirmed, most of the analyses consider no slip condition. It has been investigated that the tangential velocity slip significantly affects the bearing performance. Due to various reasons like wearing out of the surfaces due to contaminations of the lubricant, long run in time etc. the bearing surfaces develop roughness which affects the bearing performance severely, particularly, when the roughness becomes of the order of the lubricant film thickness. Use of electromagnetic fields for improving the bearing performance by extra electromagnetic pumping of the lubricant into the clearance space has been well recognized. In fact, the use of magnetic fluid as a lubricant modifies and improves the performance of bearing system and additional advantages of this lies in the fact that the bearing may support a load even when there is no flow.
The analysis of bearings working with magnetic lubricants has invited good attention. Besides, increasing the load carrying capacity the magnetic lubricant has an important property that the application of magnetic field keeps the magnetic lubricant adhered to the bearing surfaces. The magnetic lubrication offers some scopes for minimizing the roughness induced adverse effects.
Future Scope:

The analysis found in this dissertation suggests the investigation of bearing performance in various other directions.

❖ Longitudinally rough magnetic fluid based inclined slider bearing can be subjected to investigation by considering the Jenkins model taking the velocity slip into account.

❖ Longitudinally rough ferrofluid based parallel plate slider bearing can be examined by taking Shliomis model and considering the slip velocity.

❖ Jenkins model based ferrofluid squeeze film in longitudinally rough journal bearings can be investigated.

❖ Effect of longitudinal surface roughness on the performance of a porous annular squeeze film can be a matter of investigation in view of slip velocity effect.