Chapter 1

Introduction

Contents

1.1   Motivation and Brief Review of Literature

We are motivated for the present work because lubrication theory of various bearing design systems has many applications in real life. For example, it is useful in mechanism like machine tools, gears, rolling elements, hydraulic systems, engines, clutch plates, skeletal joints in human body, and so on. Many researchers have tried to study such problems from different viewpoints as follows.

Moore [1] gave excellent review on squeeze films. Wu [2] in an innovative analysis, dealt with the case of squeeze film behaviour for porous annular disks. It is concluded that because fluid can flow through the porous material as well as through the space between the bounding surfaces, the performance of a porous walled squeeze film can differ substantially from that of a solid walled squeeze film. Wu [3] studied squeeze film performance of porous rectangular plates with slip velocity and concluded that the presence of the slip velocity reduces the load carrying capacity and the response time. Later [4] extended the above analysis of [2] by introducing the effect of velocity slip to porous walled squeeze film with porous matrix attached to the upper plate. They found that the load carrying capacity decreases due to the effect of porosity and slip. Prakash and Vij [5] investigated a porous inclined slider bearing and found that porosity caused decrease in the load capacity and friction, while it increases the coefficient of friction. Prakash and Vij [6] analyzed lower porous plate squeeze film bearing of different shapes (annular, circular, elliptic, rectangular and cone) using Morgan-Cameron approximation. The effects of the shape of plate and porosity on the bearing performance are calculated. Prakash and Vij [7] analyzed squeeze film between two rotating annular disks, one with porous facing, with the effect of the slip velocity at the porous surface. The analytical solution of the problem is obtained. It is concluded that effect of the slip, reduces the load carrying capacity and response

time as compare to no slip analysis. Bhat and Hingu [8] theoretically analyzed hydromagnetic squeeze film between porous rectangular plates. The upper surface having two layered porous facing with different permeabilities. The uniform transverse magnetic field is used. Results are presented for pressure distribution, load carrying capacity and film thickness as functions of time. The results show that the modifications of the action of the squeeze film due to the applied magnetic field is more significant than that due to the non-homogeneity of the porous housing. Gupta and Bhat [9] found that the load capacity and friction could be increased by using a transverse magnetic field using conducting lubricant. Shukla *et. al.* [10] derived generalized form of Reynolds equation with slip at bearing surfaces with the effects of variations of viscosity in the film and slip at the bearing surfaces. Various specific cases have been deduced and the concept of multiple layer lubrication is introduced. It is concluded that the higher lubrication viscosity near the bearing surface is beneficial in reducing the coefficient of friction but the effect of slip is unfavourable. Gupta *et. al*. [11] analyzed squeeze film behaviour between rotating annular plates when the curved upper plate with a uniform porous facing approached normally to impermeable flat lower plate. The results show that the load carrying capacity decreased when the speed of the rotation of the upper plate increased up to certain extent. Verma [12] analyzed double layer porous journal bearing using short bearing approximation considering curvature of the bearing. Expressions for pressure distribution, load carrying capacity, coefficient of friction and the attitude angle are derived. It is shown that the bearing characteristics are improved due to low permeability of the inner porous layer. Bujurke *et. al.* [13] studied theoretically porous slider bearing with couple stress fluid where the lower surface is covered by a thin porous material and the upper one is having arbitrary shape which moves in its own plane with constant velocity. Analytical expressions are obtained for load carrying capacity, frictional

force and the center of pressure. The results show that load carrying capacity increases whereas coefficient of friction decreases. Various special geometries, like step bearings and inclined slider bearings are also discussed. Bounds on flow rate, frictional coefficient, center of pressure and time height relation are obtained and compared with classical case. Elsharkawy *et. al.* [14] obtained closed form analytical solutions for three different types of squeeze film porous bearings. It is shown that with the increase in permeability parameter, both the pressure profiles and the load carrying capacity decreases in the case of pure squeeze motion. The results also show that for dimensionless permeability parameters less than 0.001, the effect of the porous layer on the hydrodynamic lubrication of squeeze film porous bearings can be neglected. Das [15] studied slider bearings lubricated with couple-stress fluids in the presence of a uniform magnetic field. An expression for a modified Reynolds equation is derived to find pressure gradient in terms of inlet-outlet (IO) film height ratio. From the results it is observed that load carrying capacity and IO film ratio depend on the couple-stress, magnetic parameters and the shape of bearings. Bujurke and Naduvinamani [16] studied theoretically squeeze film lubrication between porous rectangular plates under the consideration of anisotropic permeability and surface roughness. It is found that anisotropic permeability has more effect on centre of the load carrying capacity than the roughness parameter. Walicka and Walicki [17] analyzed micropolar fluid lubricated curvilinear hydrostatic thrust bearing under the presence a cross magnetic field. The formula for pressure distribution is obtained and discussed. Yin and Kumar [18] studied the lubrication flow between a cavity and a flexible wall. Reynolds equation for the fluid is coupled to a model for the wall which is backed by a series of springs and/or held by a uniform tension force. The resulting ordinary nonlinear differential equations are solved to obtain pressure profiles and wall positions. It is observed that when the wall modulus or tension is large relative

to viscous forces, the wall hardly deforms and both a pressure mountain and valley are observed due to the gap change produced by the cavity topography. Again, when the wall modulus and tension are small relative to viscous forces, the wall easily deforms and assumes a shape similar to that of the cavity. The pressure profiles are also dramatically altered and in some cases show only a valley without a mountain. Cavity shape is found to have a significant influence on both the pressure profiles and the wall deformation. The results suggest that surface topography may significantly modify the elastohydrodynamic interactions that arise in lubrication flows near deformable solid boundaries. Al-Fadhalah and Elsharkawy [19] analyzed numerically the effect of non-Newtonian lubrication on the separation flow of a fully flooded sphere from a flat under the constant applied load. Different non-Newtonian fluid models are utilized to account for the microstructure and rheology of additives suspended in the film lubricant. The equation of motion of the sphere is used to examine the effect of the sphere inertia on accelerating the separation process as the film viscous force decreases. Compared to Newtonian fluid, the results show that there is a delay on the separation time for large non-Newtonian parameters. Gao *et. al.* [20] analyzed numerically plain journal bearing with lubrication by water. Considering the differences between the physical properties of the water and of the oil, the effects of eccentricity ratio on pressure distribution of water film are analyzed by CFD. Based on the analysis of different dimensions with different rotational speeds, a reference is produced for selecting the initial diameter dimension which is used to design an efficient water lubricated plain bearing under the given load and rotational speed. Kashinath and Nagangouda [21] analyzed MHD effect on porous composite slider bearing lubricated with couple-stress fluids. A modified Reynolds equation is derived. The closed forms of expressions are obtained for the dimensionless fluid film pressure, load carrying capacity, frictional force and coefficient of friction. The results

shows that when a magnetic field is applied, each particle experience force which causes the colloidal homogeneous suspension to move en masse significant MHD effects causes the fluid pressure, load carrying capacity, frictional force and coefficient friction.

In recent years, many theoretical and experimental inventions are made on the improvement of the bearing design systems as well as lubricating substances in order to improve the efficiency of the bearing performances. One of the major revolutions in the direction of lubricating substances is an invention of ferrofluids (FFs) as lubricant. Ferrofluids (FFs) or Magnetic fluids (MFs) [22] are stable colloidal suspensions containing fine ferromagnetic particles dispersing in a liquid, called carrier liquid, in which a surfactant is added to generate a coating layer preventing the flocculation of the particles. When an external magnetic field $\mathbf{H}$ is applied, FFs experience magnetic body forces $(\mathbf{M} \bullet \nabla)\mathbf{H}$ which depend upon the magnetization vector $\mathbf{M}$ of ferromagnetic particles. Owing to these features, FFs are also useful in many applications [23-26] like in sensors, sealing devices, filtering apparatus, elastic damper, etc.

Tipei [27] analyzed the general momentum equations under the assumption of FFs as Newtonian fluids. The velocity and pressure fields for thin ferrofluid (FF) films are then obtained. The short bearing case is studied. It is shown that the effect of magnetic particles increases load carrying capacity under the values of applied magnetic fields as 10^5-10^6 *A/m*. Also, it is shown that FF lubricant improves the bearing stability and stiffness. Agrawal [28] studied the effects of Magnetic fluid (MF) on a porous inclined slider bearing and shown that the magnetization of the magnetic particles in the lubricant increases load carrying capacity without affecting the friction on the moving slider. Verma [29] studied effects of MF on squeeze film bearing design system under an externally applied magnetic field oblique to the lower surface with which is composed of three thin layers with different porosities. Explicit solutions for

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velocity, pressure, load carrying capacity and response time are obtained. It is found that upper plate takes longer time to come down in this case as compared to conventional lubricant based squeeze film. Chi *et. al.* [30] studied new type of FF lubricated journal bearing consisting of three pads. One of them is a deformable elastic pad. The theoretical analysis and experimental investigation show that the performance of the bearing is better than that of ordinary bearings. Moreover, the bearing operated without leakage and any feed system. Kumar *et. al.* [31] studied squeeze film for spherical and conical bearings using FF as lubricant with the effects of rotation of particles and constant magnetic field in transverse direction and numerically studied various bearing characteristics. Bhat and Deheri [32] discussed about curved porous circular disks squeeze film with the effect of MF and shown that pressure, load carrying capacity and response time increases with the increase of magnetization. Prajapati [33] analyzed various designed bearings like circular, annular, elliptic, conical, etc. It is shown that with the increase of magnetization parameter $\sim$ *, the load carrying capacity increases. Thus, concluded the superiority performance of the bearings with MF as lubricant. It is also concluded that the bearing with MF can support a load even when there is no flow. Ram and Verma [34] studied FF lubricated porous inclined slider bearing and shown the better performance as compared to conventional lubricant. Shah *et. al.* [35] theoretically studied MF based squeeze film behaviour between rotating porous annular curved plates in presence of external magnetic field oblique to the lower plate. It is shown that the increase of pressure and load carrying capacity depended only on the magnetization parameter. However, the increase in response time depended on magnetization, fluid inertia and speed of rotation of the plates. Again, in [36], Shah and Bhat studied squeeze film in a long journal bearing using FF as lubricant and found that load carrying capacity and response time increased with the increasing values of the eccentricity ratio. Patel

and Deheri [37] discussed about MF based squeeze film between porous conical plates and found that negative effect induced by the porosity can be neutralized by the positive effect caused by the magnetization parameter. Ahmad and Singh [38] discussed MF based porous pivoted slider bearings with slip velocity to study the effect of parameters like load carrying capacity and centre of pressure. It is shown that load carrying capacity increases as the magnetic parameter increases, whereas it decreases as the slip parameter and permeability parameter increases. Also, it is shown that centre of pressure increases with the increase of magnetic parameter, slip parameter and permeability parameter. Andharia and Deheri [39] studied longitudinal roughness effect on MF based squeeze film between conical plates. It is shown that the performance of the bearing gets enhanced due to negative skewed roughness. Also, it is shown that the standard deviation increases the load carrying capacity which is unlike the case of transverse surface roughness. Again, Andharia and Deheri [40] studied MF based squeeze film for truncated conical plates with the effect of longitudinal roughness and found that load carrying capacity can be increased with magnetization as well as negatively skewed roughness. The pressure and response time also found to increase with magnetization. Huang *et. al.* [41] studied FF lubrication with external magnetic field experimentally. The results indicate that FF has a good friction- reduction performance in the presence of the external magnetic field. Shah and Patel [42] discussed impact of various porous structures on curved porous circular plates squeeze film using FF as lubricant and found that globular sphere model have more impact on increase of load carrying capacity as compare to capillary fissures model. Lin *et. al.* [43] studied squeeze film characteristics for conical plates with the effect of fluid inertia and FF, and shown the better performance of the system as compared to non-inertia non-magnetic case. In [44], Lin *et. al.* studied squeeze film characteristics of parallel circular disks with the effects of FF and

non-Newtonian couple stresses using transverse magnetic field. With these effects, it is shown that higher load carrying capacity and lengthens approaching time obtained. Hsu *et. al.* in [45] studied combined effects of magnetic field and surface roughness on FF lubricated long journal bearing. It is shown that film pressure and load carrying capacity can be enhanced under the effect of transverse roughness, while attitude angle and friction coefficient is reduced. The longitudinal roughness has the opposite effect. Shah and Patel [46] discussed effects of various and arbitrary porous structure in the study of squeeze step bearing lubricated with MF using variable magnetic field. It is concluded that the load carrying capacity increases with the increase of length of the first step as well as with the increase of magnetic field strength. The magnetic field strength which gives better results is of the order of 10^4.

1.2 Investigated Problems of the Thesis

Chapter 2 deals with the physico-mathematical background necessary to understand the subsequent Chapters.

Chapter 3 proposes mathematical modeling and analysis of FF lubricated newly designed slider bearing having convex pad stator with two porous layers attached to the slider. The problem considers the effect of slip velocity at the film-porous interface. The squeeze velocity $V = -\dot{h}$ appears when the upper impermeable plate approach to lower one is also considered here for study.

The magnetic field strength used as

$$H^2 = K\, x(A - x),$$

which is oblique to the lower plate. Here, K is chosen to suit the dimensions of both sides and A is the length of the slider bearing.

From the resulting Reynolds equation of the above model, expressions for dimensionless form of pressure and load carrying capacity are obtained. The expression for the dimensionless load carrying capacity is then solved numerically to examine its possible effect on the designed bearing system.

From the results and discussion it is concluded that

(1) When $k_1 > k_2$, dimensionless load carrying capacity increases about 6.35 % for both

   $\dot{h} = 0$ and $\dot{h} \neq 0$ as compared to $k_1 < k_2$.

(2) The dimensionless load carrying capacity increases about 113% for both $\dot{h} = 0$ and $\dot{h} \neq 0$

   when $k_1 = k_2 = 0.0001$ as compared to $k_1 = k_2 = 0.01$.

where k_1 and k_2 represents the permeabilities of the upper and lower porous layers, respectively.

Chapter 4 discusses a FF lubricated squeeze film bearing design system formed by upper spherical surface and a flat porous plate considering variable magnetic field

$$H^2 = \frac{K r^2 (a-r)}{a},$$

which is oblique to the lower plate. Here, K is chosen to suit the dimensions of both sides, r is the radial coordinate and a is the radius of the sphere.

It is noted here that porous plate is considered because of its advantageous property of self-lubrication and no need of exterior lubricant supply. The analytical model, known as Reynolds equation, is derived using equation of continuity in film as well as porous region and

equations from ferrohydrodynamics theory. The above model also considers the validity of Darcy's law in the porous region.

The following conclusions are made from results and discussion.

(1) $\bar{p}$ is maximum nearer to $R = 0.1$

(2) $\bar{p}$ is maximum and constant, when $2.92 \times 10^{-6} \leq \bar{w}_r \leq 2.92 \times 10^{-3}$

(3) $\bar{p}$ is maximum and constant, when $0 < \bar{H}_0 < 0.01$

(4) Better load carrying capacity can be obtained, when $0.005 \leq \bar{h}_m \leq 0.009$,

$0.00001 \leq \bar{H}_0 \leq 0.01$ and $2.92 \times 10^{-6} \leq \bar{w}_r \leq 2.92 \times 10^{-3}$

(5) $\bar{t}$ is maximum for $\bar{h}_m = 0.001$, $\bar{H}_0 = 0.00001$ and $w_r^* = 10^{-6} - 10^{-3}$

(6) $\bar{t}$ has almost constant behaviour for $0.003 \leq \bar{h}_m \leq 0.009$

where

$\bar{p}$ dimensionless pressure distribution

R dimensionless radial coordinate

$\bar{w}_r$ dimensionless radial permeability parameter of the porous region

$\bar{H}_0$ dimensionless thickness of the porous layer

$\bar{h}_m$ dimensionless minimum film thickness

w_r^* dimensionless radial permeability parameter of the porous region

$\bar{t}$ dimensionless response time.

It should be noted here that, when porous layer is inserted then the pressure of the

porous medium provides a path for the fluid to come out easily from the bearing to the environment, which varies with permeability. Thus, the presence of the porous material decreases the resistance to flow in r-direction and as a consequence the load carrying capacity is reduced.

In our case, the loss in dimensionless load carrying capacity $\overline{W}$ due to effect of porosity is almost zero because of using FF as lubricant (which is controlled by oblique and variable magnetic field) for smaller values of $\overline{H}_0$ and $\overline{w}_r$. Moreover, because of porosity effect, self-lubrication property is an added advantage.

Chapter 5 deals with the variations in dimensionless load carrying capacity $\overline{W}$ for porous infinitely long rectangular plates squeeze film-bearing as a function of magnetization parameter ~* for different values of permeability parameter Œ. It is observed from the results that $\overline{W}$ only moderately increase as ~* increases. But with the decrease of Œ, $\overline{W}$ increases significantly. The better performance of $\overline{W}$ is obtained when $0.0001 \leq Œ \leq 0.01$.

Dimensions of the width of infinitely long rectangular plates bearing along x-axis is $-b/2 \leq x \leq b/2$, while along y-axis is $-a/2 \leq y \leq a/2$.

Moreover, the oblique variable magnetic field with strength

$$H^2 = K\left(\frac{b}{2} - x\right)\left(\frac{b}{2} + x\right)$$

is considered with respect to x-axis. Here, K is chosen to suit the dimensions of both sides.

When $a > b$ considered, that is width of the rectangular plates is smaller along x-axis than y-axis, then the load carrying capacity is significantly less as compared to $a < b$. The dimensionless load carrying capacity $\overline{W}$ increases up to 300% when $a < b$. This is because of FF,

in the presence of magnetic field (here magnetic field is taken along x-axis) generates spikes and greater the generation of spikes, which may lead to better load carrying capacity. Thus, it is suggested to consider the direction of the oblique variable magnetic field along the longer width of the bearing design.

Chapter 6 deals with variations of dimensionless load carrying capacity $\bar{W}$ for porous truncated cone squeeze film-bearing considering

$$\bar{W} = -\frac{Wh^3}{\mathsf{y}\,\dot{h}f^2(a^2-b^2)^2\cosec^4\check{\mathsf{S}}},$$

where

W load carrying capacity

h film thickness

a upper radius of the truncated cone

b lower radius of the truncated cone

$\dot{h}$ dh/dt, squeeze velocity

S semi-vertical angle (radian)

y fluid viscosity.

It is observed that porous truncated cone does not support load when dimensionless magnetization parameter $\sim* = 0$ and dimensionless permeability parameter $Œ = 0.0001$, that is when there is no use of FF as lubricant. But when FF is used as lubricant, then it supports load

and this effect is more evident as $\sim{}^{*}$ increases. Moreover, the reverse trend of $\bar{W}$ is observed with respect to Œ.

1.3   Scope of the Present Work

The scope of the present work lies in-depth study of the following:

1. Study of different components of bearings

2. Study of various characteristics of the bearings

3. Study of surface topology of the bearings

4. Study of physical and chemical properties of the whole system

5. Study of mathematical modeling of the whole system

etc.

The above points shows the ample evidence of the relevance of the present research to various branches of engineering and science; in particular, mechanical engineering, chemical engineering, civil engineering, material science, physics, chemistry, and of course mathematics, etc.

1.4   References

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