Chapter 1

Introduction

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1.1 Motivation and Development of Theory of Lubrication

The motivation of the present work has come from the various applications of lubrication theory to various fields of real life. Bearing design systems always have an attraction for researchers because of its appearance in various fields, for example

1. In industries it is useful in mechanism like machine tools, gears, rolling elements, hydraulic system, engines, clutch plates, etc.
2. In human body similar type of system observed in skeletal joints.

Many researchers have tried to analyze various bearing design systems from different viewpoints. Referring from year 1970, Wu [108] in an innovative analysis, dealt with the case of squeeze film behaviour for porous annular disks in which he showed that owing to the fact that 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. Also, Wu [109] extended the analysis of [108] by inserting the effect of rotation of the disks. Ting [97] simplified the analysis of [109] considering the rotation of only lower disk. Later [96] extended the above analysis [108] by introducing the effect of velocity slip to porous walled squeeze film with porous matrix appeared in the above plate. They found that the load capacity decreases due to the effect of porosity and slip. Prakash and Vij in [67] investigated a porous inclined slider bearing without the effect of magnetic fluid and found that porosity caused decrease in the load capacity and friction, while it increased the coefficient of friction. Also, in [67] they have made use of well know Morgan-Cameron approximation to analyze the problem. Murti in [54] discuss about the squeeze film behaviour in porous circular disks. Kulkarni *et al.* in [38] derived new lubrication equation for porous bearings, considering non-isotropic permeability as well as non-adherence of the lubricant at the porous interface. Gupta and Sinha [26] extended the analysis of [108] by considering the effect of current. Subsequently, Bhat and Patel in [9] presented in analysis of the problem of [97] by including the effect of an axial current. Again, Wu in [107] presented review of porous squeeze films. Gupta and Bhat in [25] found that the load capacity and friction could be increased by using a transverse magnetic field on the bearing and a conducting lubricant. Prakash *et. al.* in [66] studied about surface roughness effects in hydrodynamic porous bearings. Where they have considered different roughness patterns and shown that surface roughness considerably influence on the operating characteristic of porous bearings. In 1983 Safar [75] studied about the effect of centrifugal forces on hydrostatic misaligned thrust bearings. The results show that centrifugal forces reduce considerably the load capacity, the friction torque and increase the lubricant flow rate. Verma in [102] studied about double layer porous journal bearing using short bearing approximation, where curvature of the bearing also taken under consideration. The results show that the bearing characteristics are improved due to low permeability of the inner porous layer. In [21] Davis *et. al.* studied about elastohydrodynamic collision of two spheres, and discussed about the rational criteria for predicting whether a solid particle will stick or rebound subsequent to impact during filtration or coagulation when viscous forces are important. In [11] Bujurke *et. al.* studied about the sphere plate model using couple stress fluid with special reference to synovial joints. They have shown that, the influence of elasticity increases load carrying capacity and decrease the coefficient of friction, which result in the efficient lubrication and proper functioning of synovial joints. Elsharkawy *et. al.* in [22] studied about closed form analytical solutions for three different types of squeeze film porous bearings. The results show that as the permeability parameter increases, both the pressure profiles and the load carrying capacity of the bearing decrease in the case of pure squeeze motion. Also, the 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. Lin *et. al.* in [41] derived two coupled equations for porous squeeze film phenomenon using the Brinkman model. The results are compared with slip flow model and Darcy's model. In [58] Naduvinamani *et. al.* discussed squeeze film lubrication of porous journal bearings problem using couple stress fluid. The results show that effect of couple stress reduces the velocity of the journal centre and increase the minimum permissible height of the squeeze film. Bayada *et. al.* in 2005 [6] given new models in micropolar fluid and their application to lubrication. In 2006 [20], Chu *et. al.* presented study on elastohydrodynamic lubrication of circular contacts at pure squeeze motion with non- Newtonian lubricants. The results show that for larger flow index there was larger the film thickness and smaller the maximum central pressure. Jaffar in [32] studied about numerical solution of elastohydrodynamic lubrication problem of a rigid cylinder and an elastic layer bounded to a rigid foundation. The results were investigated for the influences of the layer thickness, the layer compressibility and central squeeze film velocity

With the advent of Magnetic Fluids (MFs) or Ferrofluids (FFs) (defined below) in 1965 by R. E. Rosensweig [74], many applications in various fields like in sensors, sealing devices, filtering apparatus, elastic damper, spindle motor, etc.[5, 17, 23, 42, 45, 64, 70, 110] are found due to distinguish features of MFs.

MFs or FFs 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 depends upon the magnetization vector $\mathbf{M}$ of ferromagnetic particles.

As mentioned above, many researchers have tried to find its applications in various fields [5, 17, 23, 42, 45, 64, 70, 110]. The application of FF as lubricant is one of them. The following are some references in this regard:

Walker *et. al.* in 1979 [105] studied thrust bearings in which the lubricant is FF confined by an applied magnetic field to the gap between two plates, one fixed and one mounted on the rotating shaft carrying an axial load. Various geometries of the plates are considered, for example cones, paraboloids and frustrums. The results indicate that paraboloid and frustrums are suitable, but cones are not. Moreover, the results show that large changes an axial load produce relatively small changes in gap width. Tipei in [98] discussed about theory of lubrication with FF and applied it short bearings. It was shown in this paper that ferromagnetic lubricant may improve substantially the performance of bearing operating under low loads and/or at low speed. Miyake *et. al*. in [50] developed FF lubricated an experimental thrust bearing which is used in clean circumstances, such as in vacuum and in a clean room. Agrawal [1] studied effects of FF on a porous inclined slider bearing and found that the magnetization of the magnetic particles in the lubricant increases load capacity without affecting the friction on the moving slider. Chang *et. al.* 1987 [15] studied about two types of four-pad step-pocket journal bearings lubricated with FF. The results show the better performance of the bearings as compared to ordinary fluid. Chi *et. al.* in [18] discusses about new type of FF lubricated journal bearing. Chandra *et. al*. in [14] studied FF lubricated journal bearings by considering cavitation boundary conditions and shown that there is a significant quantitative enhancement of bearing characteristics. Sinha *et. al.* in [95] discusses about FF lubricated cylindrical rollers with cavitation. Verma *et. al.* in [71] studied FF lubrication of porous inclined slider bearing. Osman *et. al.* in 2001 [61] studied about static and dynamic characteristics of magnetized journal bearings lubricated with FF. Finite difference procedure was adopted to calculate pressure distributions. Uhlmann *et. al.* in [99] discusses about some applications of FFs in tribotechnical systems. Chao *et. al.* in [16] calculated rotordynamic coefficients of FF lubricated and herringbone-grooved journal bearing via finite difference analysis. Ochoński in [59] studied experimentally slider bearings lubricated with MFs. Nada *et. al.* in 2007 [56] studied about static performance of finite hydrodynamic journal bearings lubricated by MFs with couple stresses. Patel *et. al.* in [62] discussed about MF based squeeze film between porous elliptical plates. In [2] Ahmad *et. al.* studied about MF lubricated porous pivoted slider bearing with slip velocity. Kuzhir [39] studied on FF lubricated journal bearings with free boundary of lubricant film using perturbation technique. In [52], Montazeri discussed numerically hydrodynamic journal bearings lubricated with FF. The results show that as compared to conventional lubricant, FF as lubricant improves the hydrodynamic characteristic of journal bearings and provides a higher load capacity and a reduced friction coefficient. Kao *et. al.* studied about the performance prediction of a small-sized herringbone- grooved bearing with FF lubrication considering cavitations using finite difference analysis in [36]. Urreta *et. al.* in [100] discuss about the hydrodynamic bearing lubricated with MF. Miszczak *et. al.* in [49] presented experimental research regarding concentration of magnetic particles Fe_3O_4 in FF for slide journal bearing lubrication. Huang *et. al.* studied about FF lubrication with external magnetic field in [30]. Lin in [40] derived FF lubrication equation of cylindrical squeeze films with convective fluid inertia forces and application to circular disks. Guha in 2012 [24] studied on the steady state performance of hydrodynamic flexible journal bearings of finite width lubricated by FF with micropolor effect. Singh *et. al.* in [94] studied about curved slider bearing with FFs as lubricant. Hsu *et. al.* in [29] discussed about combined effects of magnetic field and surface roughness on long journal bearing lubricated with FF. Shah *et. al.* in [77, 79-84, 86, 88-92] studied about FF lubricated various designed bearings like porous slider bearings of different shapes, long journal bearing, axially undefined journal bearing, squeeze film bearings with the inclusion of effects of slip velocity at the porous boundary and anisotropic permeability of the porous matrix attached to the impermeable plate.

All of above researchers investigated the bearing design systems from different viewpoints, for example, some have studied without use of FF and some with FF. The researchers who have studied the bearing design systems with FF either experimentally or theoretically. The theoretical development everywhere leads to different mathematical model because of considering various effects and types of FF. In the present thesis, various bearing design systems are considered with different effects as porosity, permeability, slip velocity, squeeze velocity, etc. The following section gives brief outline of the investigated problems.

1.2 Investigated Problems of the Thesis

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

Chapter 3 discuss the problem on double porous layer (or matrix or region) slider bearing for computation of various bearing characteristics like load carrying capacity, friction, coefficient of friction and center of pressures as the problem was not discussed earlier with the use of MF. The porous layer in the bearing is considered because of its advantageous property of self lubrication. With this motivation the study of behaviour of an inclined slider bearing with the porous matrix attached to both the plates or surfaces or discs (that is upper and lower) is proposed here with a water based FF lubricant under a magnetic field strength H oblique to the lower surface as

$$H^2 = Kx\,(A - x), \qquad \ldots (1.1)$$

where K being a quantity chosen to suit the dimensions of both sides, A is the length of the slider bearing, and x represents coordinate direction.

Also, effects of slip velocity and anisotropic permeability at both the porous plates, as well as squeeze velocity when the upper plate approaches to lower one are included.

The following observations were made:

1. Because of having the self lubrication property of the porous plate bearings, it is suggested to have both the porous plate for better self lubrication.
2. Better load capacity is obtained when the thickness of l_1 and l_2 are small.
3. Small thickness of l_2 has more influence on better load capacity when $l_1 = 0$ and $\varphi_x = 0.00001$, $\psi_x = 0.001$.

4. Small thickness of l_1 has more influence on better load capacity when $l_2 = 0$ and $\varphi_x = 0.001$, $\psi_x = 0.00001$.

where φ_x and ψ_x are permeabilities of lower and upper porous regions in the x-direction respectively, l_1 and l_2 are width of upper and lower porous regions respectively.

Chapter 4 deals with double porous layer squeeze film bearing of various shapes to study load carrying capacity. The purpose of the present study is to analyse and compare newly designed squeeze film bearing of different shapes, which formed when a upper porous plate approach to a lower porous plate considering the effects of porosity, slip velocity, anisotropic permeability and rotation at both the ends. Moreover, the study also includes the effects of variable porous thickness. The porous matrix is attached because of its advantageous property of self lubrication. The lubricant used here is water based FF which is controlled by oblique and variable magnetic field strength as

$$H^2 = \frac{Kr^2(a-r)}{a}, \qquad \dots (1.2)$$

where K being a quantity chosen to suit the dimensions of both sides, a is the radius of each circular plates (lower and upper) in squeeze bearing, and r is radial coordinate.

Expressions for pressure and load carrying capacity are obtained from Reynolds's type equation. The dimensionless load carrying capacity $\overline{W}$ is calculated for various values of porosity, slip velocity, anisotropic permeability and rotation for both the plates. Moreover, the effects of squeeze velocity and different strength of magnetic field are also considered for the study of $\overline{W}$.

From the results it was concluded that efficient and durable bearings in the sense of increase of $\overline{W}$ can be produced when width of upper and lower porous layer thickness decreases, magnetic field increases, squeeze velocity decreases and permeability decreases considering small rotation of the upper plate. The best performance is obtained in the case of exponential concave upper plate and parallel plate.

In **Chapter 5,** the problem on double porous layer axially undefined journal bearing is discussed considering the effects of anisotropic permeability, slip velocity and squeeze velocity. Expressions are obtained for dimensionless pressure and load capacity for this newly designed journal bearing. The values of dimensionless load capacity are computed using water based FF as lubricant with magnetic field defined in (1.1), and compared it with the values which are obtained using conventional lubricant (that is, without using FF). From the results, we say that with using FF as lubricant, the dimensionless load capacity increase up to 206.86 %. Thus, with the use of FF as lubricant, it is found that the bearing performance is much better than that of a conventionally lubricated bearing.

Chapter 6 concerns with squeeze film bearing with the insertion of various porous structure given by

i. Kozeny-Carman (a globular sphere model) in which the permeability defined as

$$\psi = \frac{D_c^2 \varepsilon^3}{180(1-\varepsilon)^2} \, , \qquad \ldots (1.3)$$

where ε is the porosity and D_c porous size (diameter) in a globular sphere model.

ii. Irmay (a capillary fissures model) in which the permeability defined as

$$\psi = \frac{(1 - m^{\frac{2}{3}}) D_s^2}{12m}, \qquad \ldots (1.4)$$

where $m = 1 - \varepsilon$ and ε is the porosity, D_s porous size (diameter) in capillary fissures model

Expressions are obtained for pressure and load capacity under an external magnetic field oblique the lower plate as defined in (1.2). It is found that the load capacity is increased in both the cases with the increase of magnetization. It is also found that the load capacity increased substantially in the case of concave plates and in the case of porous structure given by Kozeny-Carman. The load capacity is more for the porous structure given by Kozeny-Carman.

Chapter 7 deals with the study of pivoted slider bearing with squeeze and slip velocity. In this chapter, problem on “MF lubrication of porous-pivoted slider bearing with slip velocity by

N Ahmad *et.al*. [2]" has been recapitulated using Jenkin's model [34] with the additional effect of squeeze velocity of the above plate. It is found that while discussing the above problem, [2] has stated but ignored the term in their study

$$\rho\alpha^2\nabla \times \left(\frac{\mathbf{M}}{M} \times \mathbf{M}^*\right),$$

… (1.5)

where

$$\mathbf{M}^* = \frac{D\mathbf{M}}{Dt} + \frac{1}{2}(\nabla \times \mathbf{q}) \times \mathbf{M},$$

where $\rho, \alpha^2, \mathbf{M}, t, M$ and $\mathbf{q}$ are fluid density, material constant, the magnetization vector, time, magnitude of magnetization vector and fluid velocity respectively.

This paper reconsiders the above neglected term with

$$\mathbf{M}^* = \frac{1}{2}(\nabla \times \mathbf{q}) \times \mathbf{M},$$

where $\mathbf{M} = \bar{\mu}\mathbf{H}$ ($\bar{\mu}, \mathbf{H}$ are magnetic susceptibility and magnetic field vector respectively).

Since $\mathbf{M}^*$ is the corotational derivative of magnetization vector, so it has an impact on the performance of the problem [71]. With the addition of the above term and under an oblique magnetic field as defined in (1.1), it is found that the dimensionless load carrying capacity can be improved substantially with and without squeeze effect. The paper also studied in detail about the effects of squeeze velocity and sliding velocity. It is observed that dimensionless load carrying capacity increases when squeeze velocity increases and sliding velocity decreases.

In all above problems, a mathematical model has been formulated and Reynolds's type equation is derived, which is solved for suitable boundary conditions.

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 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.