Chapter 1

Introduction

Contents

1.1 Motivation of the Present Work

The motivation of the present work comes from the observation of presence of lubrication phenomenon in various applications.

For example,

(1) In industry, it is observed in machine tools, gears, rolling elements, hydraulic systems, engines, clutch plates, etc.

(2) In human body, it is observed in the study of skeletal joints as bio-lubrication.

Due to this motivation many theoretical and experimental investigations were made on the phenomenon by several investigators from different viewpoints as can be seen from Section 1.3. Presently also many researchers are trying to develop recent advances in the developments.

1.2 Basic Terms / Definitions / Phenomenons

Before proceeding with the brief literature review, let us first understand about the main basic terms / definitions / phenomenons appear there as follows. The materials are taken from the references [1-5]

(1) Lubrication and Lubricants

Lubrication is the art of reducing frictional resistance by means of some kind of substance introduced between the two surfaces having relative motion.

Any substance which has some amount of viscosity is known as lubricant. The lubricants are used in bearings to reduce friction between the rubbing surfaces and to carry away the heat generated by friction. It also protects the bearing against corrosion. Lubricants are classified into the following three groups.

(a) Liquid Lubricants

The liquid lubricants usually used in bearings are mineral oils and synthetic oils. The mineral oils are most commonly used because of their cheapness and stability.

(b) Semi-liquid Lubricants

A grease is a semi-liquid lubricant having higher viscosity than oils. The greases are employed where slow speed and heavy pressure exist and where oil drip from the bearing is undesirable. The solid lubricants are useful in reducing friction where oil films cannot be maintained because of pressures or temperatures. They should be softer than materials being lubricated.

(c) Solid Lubricants

A graphite is the most common of the solid lubricants either alone or mixed with oil or grease.

(2) Squeeze-film Phenomenon

Squeeze-film behaviour arises when two lubricated surfaces approach each other with a normal velocity, known as squeeze velocity. Squeeze-film behaviour always have an attraction for researcher because of its appearance in many fields of real life.

(3) Surface Roughness

No solid surface is perfectly smooth on atomic scale. In other words, all solid surfaces are rough to some extent. Roughness can be defined as a measure of random distribution of surface height about a carrier profile in the surfaces.

(4) Ferrofluids / Magnetic Fluids

Ferrofluids (FFs) or magnetic fluids (MFs) 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 **H** is applied, FFs experiences magnetic body force $(\mathbf{M} \bullet \nabla)\,\mathbf{H}$ which depends upon the magnetization vector **M** of ferromagnetic particles and are oriented along field lines. The main property of FFs is that they can be made to adhere to any preferred place with the help of magnets and to move even in zero gravity regions. Owing to these features FFs are useful in many applications including bearing design systems [6-9].

1.3 Brief Literature Review

Starting with 1956, Archibald [10] studied many configurations when the two surfaces remain parallel during the approach. Jackson [11] included both viscous and inertia effects in an investigation of the squeeze-film between plane discs. Burton [12] studied the effect of surface roughness on the load supporting characteristics of a lubricant film by postulating the sinusoidal variations in film thickness. Davies [13] used the saw tooth curve to study the effect of surface roughness on the generation of pressure between rough, fluid lubricated moving deformable surfaces. An excellent review of the work in squeeze-films up to 1965 has been given by Moore [14]. Tzeng and Saibel [15] made study of surface roughness effect on slider bearing lubrication using probability density function for random variable characterizing the surface roughness. As reported by Gould [16], the study of squeeze-films was developed more rigorously by Reynolds [17]. The equations derived and integrated were applicable to the situation in which a Newtonian fluid of invariable properties was being slowly squeezed out of the space between two rigid, flat parallel plates with elliptical boundaries. Christensen [18] developed stochastic models for the study of hydrodynamic lubrication of rough surfaces in which one-dimensional circumferential and radial roughness patterns were discussed. Wu [19] in his analysis discussed the problem of squeeze-film behaviour between porous annular discs, when upper disc with a porous facing approaches the lower impermeable disc, considering no-slip boundary condition at the film-porous interface. Christensen [20] has analyzed the elastohydrodynamic problem on normal approach of two spherical bodies. According to results, the effect of elastic deformation profoundly influences all aspects of motion when the separation of two surfaces becomes narrow enough. Sparrow *et. al.* [21] extended the Wu's analysis [19] with the effect of velocity slip on the film-porous interface. Results for load-carrying capacity and time-height relation are discussed. The results show that the insertion of porous layer leads to decrease in load-carrying capacity while it is effective in diminishing the response times. In particular, substantially faster response can be attained by the use of porous materials which accentuate velocity slip. Tonder [22] made theoretical study of transition between surface distributed waviness and random roughness. Christensen and Tonder [23] studied hydrodynamic lubrication of rough journal bearings. Murti [24] discussed porous circular discs squeeze-film-bearing, where the porous layer is attached with the upper impermeable disc. Three bearing characteristics like pressure distribution, load-carrying capacity and response time are discussed in terms of Fourier-Bessel series. It is found that an enhanced value for the permeability parameter diminishes the pressure over the entire disc and also evens out the pressure distribution; however, there is an adverse effect on the load-carrying capacity and response time of approach. Christensen *et. al.* [25] derived generalized form of Reynolds equation applicable to rough bearings by assuming the fluxes to be represented by power series of a stochastic film-thickness function. Ting [26] analyzed lubricated clutch engagement behaviour of two annular discs with the elastically deformable porous facing attached with the above disc. The surface roughness is also introduced at both the discs. The bearing characteristics like pressure distribution, load-carrying capacity and film thickness versus time have been studied. Conway and Lee [27] studied the squeeze-film characteristics between a sphere and a flat plate. They found that the effect of increase in viscosity of the lubricant with pressure causes large increase of pressure near the central area as compared with the pressure obtained for isoviscous lubricant. Prakash and Tonder [28] describe a theoretical analysis of the effects of surface roughness on squeeze-film characteristics between two circular plates. It is found that the circumferential roughness reduces the sinkage rate of the squeeze plate. If the highest asperities are blunt or flat, the theoretical time to reach the rest position may tend to infinity. In the case of radial roughness, the sinkage rate is increased. Prakash and Tiwari [29] studied effect of surface roughness on the characteristics of porous bearings using Christensen's stochastic theory. Gupta *et. al.* [30] analyzed annular squeeze-film between curved upper porous facing plate and lower impermeable flat plate considering the effect of rotation of both the plates. Expressions for pressure and load-carrying capacity are obtained. It is shown that load-carrying capacity decreases when the speed of rotation of the upper plate increased up to certain value of curvature parameter and then reverse trend is observed. It is also shown that load-carrying capacity could be increased without altering the speed of rotation and increasing values of curvature parameter. Depending on the Christensen's roughness model, Prakash and Tiwari [31] studied roughness effect on the squeeze-film between rotating porous annular discs with arbitrary porous wall thickness. An exact solution, valid for arbitrary wall thickness is given for the film pressure and pressure in the bearing material. Elsharkawy and Nassar [32] found closed form of analytical solutions for three different types (parallel surface bearing of infinite width, journal bearing and parallel circular plates) of squeeze-film porous bearings. The results show that as the permeability parameter increases, both the pressure profiles and the load-carrying capacity decreases. It is also shown that the effect of the porous layer can be neglected when dimensionless permeability parameter less than 0.001. Andharia *et. al.* [33] studied the effect of surface roughness on the behaviour of a squeeze-film in a spherical bearing in transverse direction. Lin *et. al.* [34] have studied the effect of surface roughness on the oscillating squeeze-film behaviour of long partial bearings. Usha and Vimala [35] theoretically predicted the squeeze-film force in a circular Newtonian squeeze-film using the elliptical velocity profile assumption by three different approximation methods – momentum integral method, successive approximation method and energy integral method. The results show good agreement with the experimental test. Walicka *et. al.* [36] investigated inertia effects in a curvilinear squeeze-film bearing lubricated by a power-law fluid. The lower surface is attached with a porous facing. Using the average inertia method the closed form of solution of Reynolds equation is obtained. Naduvinamani *et. al.* [37] studied the roughness effect on the squeeze-film formed by a sphere and a plate using couple-stress fluid. They showed that surface roughness effect considerably influences on squeeze-film characteristics. Jaffar [38] studied squeeze-films between a rigid cylinder and an elastic layer bonded to a rigid foundation. Influences of the layer thickness, the layer compressibility and the central squeeze-film velocity on the results are investigated. Bujurke *et. al.* [39] studied surface roughness effects on the squeeze-film between circular upper porous-rough surface and lower solid rough surface using couple stress fluid. Closed form of solution of the stochastic Reynolds equation is obtained in terms of Fourier-Bessel series. They have shown that effect of couple-stress fluid and surface roughness is more pronounced as compared to classical one. Rajashekar and Kashinath [40] analyzed effect of surface roughness on MHD couple-stress based squeeze-film between a sphere and a porous plane surface. Expressions for pressure, load-carrying capacity and mean squeeze-time are obtained. It is found that load-carrying capacity increases (decreases) for azimuthal (radial) roughness patterns as compared to the smooth case. The response time is also lengthening in both types of roughnesses. With respect to porous parameter, load-carrying capacity decreases whereas squeeze time increases. Naduvinamani *et. al*. [41] studied roughness effect on squeeze-film between porous circular stepped plates using couple-stress fluid. It was shown that the effect of magnetic field increase the mean load-carrying capacity and lengthen the mean squeeze time. Basti [42] discusses the effect of surface roughness and couple-stress fluid on squeeze-films formed between curved annular plates. It was shown that the circumferential roughness pattern on the curved annular plate results in more pressure build up whereas performance of the squeeze-film suffers due to the radial roughness pattern for both concave and convex plates. Walicka *et. al.* [43] discussed effects of bearing surfaces and porosity of one bearing surface on pressure distribution and load-carrying capacity using bingham fluid. The general formulae for pressure and load-carrying capacity are derived.

In recent years, many theoretical and experimental inventions are made on the bearing design system as well as on the lubricating substances in order to increase the efficiency of the bearing performances. One of the major revolutions in the direction of lubricating substances is an invention of ferrofluids (defined above in Section 1.2). With the advent of ferrofluids, many researchers have tried to develop its applications in lubrication theory as follows.

Starting with 1986, Verma [44] discussed squeeze-film between two rectangular plates using MF lubricant. The upper surface is a rigid rectangular smooth plate while the lower one is composed of three thin porous layers with different porosities. Explicit solutions for the velocity, pressure and the load-carrying capacity are obtained. It is found that the time for the upper plate to come down is longer than viscous squeeze-film. Thus, better performance of the MF effect is observed. Agrawal [45] studied effects of MF 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. Chi *et. al.* [46] discuss new type of FF lubricated journal bearing consists of three pads. One of them is a deformable elastic pad. The theoretical analysis and experimental investigation shows that the performance of the bearing is much better than that of ordinary bearings. Moreover, the bearing operated without leakage and any feed system. Bhat and Deheri [47] theoretical studied the squeeze-film between two circular discs, where the porous layer is attached with the upper disc. It is found that pressure, load capacity and response time are increased with the increasing values of magnetization of MF. The effects due to magnetization are found to be independent of the curvature of the upper disc. Sinha *et. al.* [48] discuss about FF lubricated cylindrical rollers with cavitation. Shah and Bhat [49] studied circular squeeze-film bearing made by curved upper plate with a porous facing and impermeable flat lower plate, considering rotation of both the plates, using MF lubricant. The results show that pressure, load-carrying capacity and response time increases with the increase in curvature of the upper plate as well as magnetization parameter. Uhlmann *et. al.* [50] discuss about application of MFs in tribotechnical systems. The rheological and tribological behaviour of MFs was investigated and compared with conventional lubricants between friction pairs under boundary conditions. Shah and Bhat [51] studied squeeze-film between two parallel plates using FF lubricant with the porous facing attached with the upper plate and various bearing characteristics are studied. Shah and Bhat [52] studied combined effect of anisotropic permeability and slip velocity on porous walled squeeze-films between circular plates lubricated with ferrofluid. It is shown that load-carrying capacity and response time decreases with the increasing values of radial permeability parameter while they increase with the increasing values of axial permeability parameter. Shah and Bhat [53] analyzed squeeze-film in an axially undefined journal bearing with anisotropic permeable porous facing and slip velocity considering FF lubricant. Results show that load-carrying capacity and response time increases with the increasing values of eccentricity ratio and anisotropic parameter while they decrease with increasing values of slip parameter or material parameter. Deheri and Patel [54] discussed MF based squeeze-film between porous circular discs with sealed boundary with the porous facing attached with the upper disc. It is shown that load-carrying capacity increases significantly. Shah and Bhat [55] studied theoretical FF lubricated secant shaped squeeze-film bearing with the consideration of anisotropic permeability, slip velocity, material parameter and rotational inertia. Results show that load-carrying capacity and response time decreases with the increasing values of radial permeability, slip and rotational inertia. However, they increase with the increasing values of axial permeability and material constant.

Ahmad and Singh [56] studied about MF lubricated porous pivoted slider bearing with slip velocity. There it was discussed that the minimization of the slip parameter and permeability parameter increases the load-carrying capacity. Andharia and Deheri [57] studied MF based squeeze-film for truncated conical plates with the effect of longitudinal roughness and found that load capacity can be increased with magnetization as well as negatively skewed roughness. The pressure and response time also found to increase with magnetization. Shah and Patel [58] discussed impact of various porous structures on the squeeze-film between curved porous circular and flat plates using FF lubricant. Results show that load-carrying capacity increases in the case of globular sphere model of the porous plate. Singh and Gupta [59] studied about curved slider bearing with FF as lubricant and shown that the effect of rotation and volume concentration of magnetic particles improves the stiffness and damping capacities of the bearings. Lin *et. al.* [60] 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. Lin *et. al.* [61] studied squeeze-film characteristics of parallel circular discs with the effects of FF and non-Newtonian couple stresses using transverse magnetic field. With these effects, it was shown that higher load capacity and lengthens approaching time obtained. Andharia and Deheri [62] studied about performance of a MF based squeeze-film between longitudinally rough elliptical plates. It was observed that increase in load-carrying capacity due to MF lubricant gets considerably increased due to the combined effect of standard deviation and negatively skewed roughness. Kesavan *et. al.* [63] analyzed the surface roughness effect on the squeeze-film characteristics between finite porous parallel rectangular plates lubricated with an electrically conducting fluid in the presence of a transverse magnetic field. It is found that load-carrying capacity and response time increases with the increase of magnetic field effect. Lin *et. al.* [64] investigated effects of circumferential and radial rough surfaces in a non-Newtonian MF lubricated circular squeeze-film. Here, both the discs are solid impermeable. It was shown that the mean load-carrying capacity increases and prolongs the mean approaching time as compared to those of the smooth discs with a non-Newtonian MF. However, in the case of radial roughness pattern the above trend is reverse. Huang and Wang [65] presented a comprehensive review on FFs lubrication theory based on different flow models. More recently, Shah and Kataria [66] theoretically discussed FF based squeeze-film characteristics between a sphere and a flat porous plate. It is concluded that loss in dimensionless load-carrying capacity due to the effect of porosity is almost zero because of using FF as lubsricant for smaller values of thickness parameter of the porous layer and radial permeability parameter. Shah and Patel [67] studied FF lubricated squeeze-film characteristics between a rotating sphere and a radially rough plate and shown that better performance of the dimensionless load-carrying capacity can be obtained w.r.t. various parameters. Shah *et. al.* [68] discusses review with contributions on some porous squeeze-film bearings with FF lubricant. The bearing performances are found to be better using FF as lubricant.

1.4 Investigated Problems of the Thesis

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

In Chapter 3, a mathematical model of ferrofluid lubricated flat annular squeeze-film bearing, which is formed when a porous upper disc (plate or surface) approaches a circumferentially rough impermeable lower disc considering radially variable magnetic field (VMF), is developed. The roughness effect is presented on the basis of Christensen's stochastic theory for hydrodynamic lubrication of rough surfaces and the VMF is important because of its advantage of generating maximum field at the required active contact zone. Moreover, porosity is considered because of getting advantageous property of self-lubrication. The resultant modified Reynolds equation is solved in terms of Bessel function. This method of solving Reynolds equation is important because it violets the assumption of replacing pressure in the porous matrix by the average pressure w.r.t. bearing wall thickness and then the average pressure equal to the film pressure at any section. Expression for dimensionless load-carrying capacity is obtained and discussed from different viewpoints. The effects of micromodel patterns of two different porous structures are also discussed.

In Chapter 4 Ferrofluid lubricated squeeze-film bearing design system formed by a rotating upper spherical surface and a radially rough lower flat plate considering variable magnetic field, which is oblique to the lower plate, have been analyzed. The variable magnetic field is important because of its advantage of generating maximum field at the required active contact zone. The problem is motivated because squeeze-film behaviour is widely observed in many industrial applications like in machine tools, gears, rolling elements, hydraulic systems, engines, clutch plates, force pendulum apparatus, etc. Moreover, the squeeze-film behaviour is also observed in skeletal joints of human body. On the basis of ferrohydrodynamic theory and Christensen's stochastic theory for hydrodynamic lubrication of rough surfaces, the modified Reynolds equation is derived and expressions for squeeze-film characteristics are obtained which are calculated numerically and interpreted. While deriving Reynolds equation effects of various parameters like rotation, width of the nominal minimum film thickness and squeeze velocity are also considered.

Based on ferrofluid (FF) flow model by R.E. Rosensweig and roughness effect by Christensen's stochastic theory, circular squeeze-film bearings formed between upper solid impermeable disc and lower porous-rough disc, are studied in Chapter 5. Two roughness patterns, radial and circumferential, on the porous surface are considered. Moreover, porous surface is considered because of getting advantage of self-lubricating property. The FF is controlled by oblique radially variable magnetic field (VMF) because of obtaining advantage of generating maximum field at the required active contact zone. The VMF is considered because uniform magnetic field does not enhance bearing performances. The resultant Reynolds equation is solved for load-carrying capacity for different shapes (exponential, secant, mirror image of secant and parallel) of the upper disc. The results are compared among different shapes and the impacts of permeability and roughness patterns are studied.

In Chapter 6 Modified Reynolds equation is derived for ferrofluid (whose flow is governed by R.E. Rosensweig model) lubricated squeeze-film bearing made by flat circular porous upper and impermeable lower discs. The ferrofluid lubricant is controlled by oblique variable magnetic field (VMF). The VMF is considered because uniform magnetic field does not enhance bearing performances. Moreover, it is important because of its advantage of generating maximum field at the required active contact zone. In the present analysis the active contact zone is considered at the middle of the lower disc. Expression for film pressure is obtained in terms of Bessel function by considering the effect of existence of pressure difference at the film-porous interface and studied. The expression for load-carrying capacity is also obtained and studied.

1.5 Scope of the Present Work

Present study opens up new area of investigation and development in various subtopics as follows.

1. Different components of bearings
2. Various characteristics of the bearings
3. Surface topology of the bearings
4. Physical and chemical properties of the various systems
5. Mathematical modeling of the whole system
6. Effects of bearing deformation
7. Effect of different various porous structures
8. Effect of surface roughness patterns

etc.

The above points show that there is an ample scope from the offshoot of the present research related to various branches of engineering and science; in particular, mechanical engineering, chemical engineering, civil engineering, material science, physics, chemistry, and of course mathematics, etc.

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