Theoretical studies in ferrofluid lubrication : A review

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In many lubrication situations it is required to place the lubricant at a desired position and then retain it there. Therefore, in recent years, ferrofluids have been successfully employed as lubricants in various hydrodynamically lubricated bearings. This motivated several research workers to investigate the theoretical aspects of ferrofluid lubrication. Tarapov initiated such studies in 1972, while considering ferrofluid lubrication for cylindrical bearings. Subsequently, many analytical studies have been made in this direction for different bearing situations under various simplifying assumptions. It may be noted that the presence of magnetic fluid gives rise to nonlinear coupled partial differential equations, therefore simplified assumptions have been incorporated in various studies. In most of the studies the governing equations for ferrofluid have been taken from the model of Rosensweig, and the equations of lubrication were derived under the assumption that the magnetization vector is parallel to the magnetic field vector. In a later study, the authors have considered Shliomis model to study bearing characteristics in various situations. The aim of this paper is to present a review of analytical studies in this direction.

Historically the concern of lubrication engineers has been to introduce appropriate lubricant in the desired location and keep it there. Example of lubrication retention methods are: mechanical seals, oil-impregnated retainers, pumping of lubricant etc. A new method which permits new applications and may solve hitherto impossible situations is now available i.e. ferro lubrication. Ferrolubricants represent an exciting new addition to the large family of lubricants. Ferrofluids are suspensions of very fine magnetic particles in a base fluid, consequently the viscosity of the base fluid is substantially increased. Under the effect of magnetic field, the particles become oriented which results in another viscosity variation and magnetic stresses are generated. It is also possible to retain the ferrofluid at the desired location by imposing an external magnetic field. This property gives rise to various applications of the ferrofluids one of which is a liquid seal. The use of ferrofluids as a lubricant is mainly motivated by this magnetic seal effect. Other applications include hydrodynamically lubricated journal bearings, slider of various kinds and just about any complex motion system in which two surfaces are brought in contact with each other. Under a suitable magnetic field these bearings can operate without side leakage. While in recent years a number of experimental works have been reported, the theoretical understanding of their performance is still inadequate. It may be pointed out here that most of the theoretical work done in this direction is based on the Rosensweig model of ferrofluids and it is only recently that the authors have based their studies on Shliomis model.

Tarapov\textsuperscript{1} was probably the first one to attempt an analytical study of ferrofluid lubrication in a cylindrical bearings. Infinitely long journal bearing was considered under the assumption of a full film lubrication. Walker and Buckmaster\textsuperscript{2} considered thrust bearings in which the lubricant is a ferrofluid confined by an applied magnetic field to the gap between two plates, one fixed and one mounted on a rotating shaft carrying an axial load. Various plate geometries are considered as cones, paraboloids and frustums. It was assumed that,

- the magnetic field in the plates is negligible so that the scalar magnetic potential is constant throughout the plates,
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- the magnetization in the ferroliquid is negligible compared to the field,
- the ferroliquid is saturated,
- the variations in magnetization associated with the temperature differences in ferroliquid can be neglected.

The equations of ferrofluid motion are solved under the above assumptions to determine pressure and then nondimensional form of hydrodynamic force (load) is obtained. Results indicate that paraboloid and frustums are suitable, but cones are not. FHD thrust bearing with magnetic plates are stiff i.e. large changes in axial load produce relatively small changes in gap width. It is observed that with the currently available ferroliquids, FHD thrust bearings are limited to central region, where ferrofluid is subjected to relatively small axial loads.

Tipei5-5 in a series of papers studied characteristics of ferrofluid lubricated journal bearings. The objective of this study was to show whether or not magnetic fluids are proper for the use in lubrication, and to determine the range of their applications, with emphasis on the bearing load-carrying capacity. Tipei1 analyzed the general momentum equations under the assumption that ferrofluid behaves as a Newtonian fluid and the inertia forces can be neglected with respect to viscous forces. The governing equations were derived under the usual assumptions of thin fluid films, which showed that pressures are induced by the magnetic field in the direction of the field variation and no magnetic forces are generated if the applied field is constant. Thus in order to take advantage of the effects of both magnetization and applied field, usually a field variation is taken upon a direction either parallel or perpendicular to the relative motion of the film boundaries. The generalized form of Reynolds equation for pressure was obtained and solved for zero pyromagnetic coefficient. It is further observed that, in bearing construction, it is advisable to ensure a positive gradient of the applied magnetic field in the regions where the pressure due to viscous effects is also increasing.

Fertman et al.6 presented a numerical study of hydrodynamics of high-speed magnetic fluid seals. The influence of the magnetic field configuration on the sealed pressure due to the competition between magnetic and centrifugal forces was considered. The optimum sealing volume of magnetic fluid for the investigated field distributions was found in their results.

Huang et al.7 considered the magnetic sealing capability of ferrofluid-lubricated journal bearings. Their study consisted of a magnetic field analysis and lubrication analysis to obtain closed form solutions. The pressure distribution was found by combining the short bearing approximation with long bearing one, as it was noted that bearing clearance region can be divided into two sub-regions:

- end flare region, where magnetic field varies (so only in these regions magnetic sealing effect exists)
- central region, where ferrofluid is subjected to no magnetic body force, and it behaves like an infinitely long bearing.

In the convergent part of the bearing clearance, pressure builds up and the fluid tends to flow sideways. But the tendency diminishes with the flare of the bearing clearance. In the divergent part of the bearing clearance, the pressure reduction in the central regions prompts the fluid stored in end flare regions to flow inward, and thus film rupture is prevented. Based on the above picture, the central region is treated with a long bearing approximation and the end flare region with a short bearing approximation.

Agarwal8 discussed a porous inclined slider bearing, lubricated with a magnetic fluid, in the presence of an externally applied magnetic field which is oblique to the lower surface of the bearing. The load capacity of the magnetic fluid-based porous inclined slider bearing is found to be greater than that of a viscous porous inclined slider bearing. It is shown that the magnetic fluid-based porous inclined slider bearing has a performance superior to that of the viscous porous inclined slider bearing.

Verma9 considered squeeze film lubrication of a magnetic fluid between two approaching surfaces in the presence of an externally applied magnetic field that is oblique to the lower surface. The upper surface is taken as a rigid rectangular smooth plate, while the lower one as a porous rectangular plate composed of three thin layers with different porosities. Explicit solutions for the velocity, pressure, and the load-carrying capacity are obtained by solving the governing equations for the
fluid film region. It was shown that the load capacity increases when magnetic fluid is used in the squeeze film, and the time for the upper plate to come down is found to be longer than that for viscous squeeze film. This shows that magnetic fluid based squeeze film is definitely better. Prajapatl has also discussed porous squeeze films with magnetic fluids.

Sorelge examined several cases of cylindrical bearings lubricated with ferrofluid by means of a finite difference numerical procedure. The sub-region of cavitation is determined by imposing mass conservation across the "rupture" and "reformation" boundaries of the complete film. The examined cases refer to bearing confined by sealing rings formed by the lubricant itself, for which there is no need of external supply. In each case the most significant parameter is calculated and it is possible to see that the use of these bearings is favourable when speeds are low, clearance large, and loads light, because in such conditions the magnetic effects are comparable with the pure hydrodynamic ones and the load capacity results appreciably higher.

Zhang discussed the characteristics of journal bearing with ferrofluid and concluded that the bearing load increases whereas the friction coefficient decreases in magnetic bearings as compared to those for submerged bearings. Influence of magnetic force on cavitation was also studied.

It may be pointed out that the lubrication studies conducted so far were essentially based on Nuringer and Rosensweig model of magnetic fluid. This is a fairly simple but interesting model obtained by adding a magnetic force to the flow equations. However, Shliomis pointed out that the particles in magnetic fluid have rotation which affect the ferrofluid motion. Thus, internal angular momentum was also considered due to self rotation of particles. Therefore, Shukla and Kumar presented a general theory of thin film lubrication using Shliomis model. A generalized form of Reynolds equation was derived by iterative procedure and the cases of squeeze film and slider bearing were discussed.

Subsequently, Chandra et al., Kumar et al. and Sinha et al. presented mathematical analyses of ferrolubrication for various configurations using Shliomis model. As the governing equations turn out to be coupled non-linear equations, a perturbation scheme in terms of non-dimensional Brownian time relaxation parameter was used to study the effects of various parameters on bearing characteristics. The assumptions used were,

- Plates are non-magnetic and non-conducting so that the applied field is not modified.
- Magnetization in the ferrofluid is negligible compared to the applied magnetic field.
- The ferrofluid is saturated so that \( M_0 \) does not depend upon the applied magnetic field.
- The film lubrication approximations are valid so that the derivatives of velocity, magnetization, etc. along the film are negligible in comparison to their derivatives across the film.

It was noted that while the qualitative behaviour of pressure and load carrying capacity for a ferrofluid remains similar to that of Newtonian fluid, a significant quantitative enhancement in bearing characteristics was observed in the case of magnetic fluid when a transverse magnetic field of constant magnitude is applied. Further the impact of ferrofluid parameter on cavitation point was found to be negligible by Chandra et al. and Sinha et al.

Kumar and Chandra pointed out that the suspensions in general exhibits non-Newtonian behaviour and also the carrier fluid could be of non-Newtonian nature. Thus the magnetic fluid may exhibit non-Newtonian behaviour when subjected to severe operational conditions as confirmed by experimental investigation of Kamiyama et al. Hence Kumar and Chandra analyzed squeeze film with non-Newtonian power law magnetic fluids, using Shliomis model when external magnetic field is transversely applied. However this analysis is restricted for small magnetization vector such that the product terms of magnetization vector could be neglected. Kumar et al. extended this work to consider the effect of time relaxation of particle rotation.

A detailed review of applications of magnetic fluids in sealing and lubrication has also been given by Saynatjoki and Holmberg. It can be seen that many analytical studies have not been carried out in this direction so far and there is a need for an extensive work on mathematical modelling in ferrolubrication. Some of the aspects which need
to be investigated are,

- Effect of porosity of the bearing surfaces
- Thermal effects (due to lubricant as well as the bearing surfaces)
- Elastohydrodynamic aspect
- Roughness effect of the surfaces (deterministic and stochastic models)
- Physiological applications to human joints.

It may be pointed out that the governing equations provide a coupled non-linear system of partial differential equations which are not amenable to exact analytical solution. A numerical treatment will be required to gain more insight in the problem.

References

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