Ferrofluid-Based Tilted Deformable Rough Porous Pad Bearing

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Abstract:

An innovative mathematical model to analyse the impact of slip and transverse roughness on a hydromagnetic squeeze film in a porous, tilted pad bearing. Stochastic model of Christensen and Tonder is used to account for surface roughness, while the Beavers and Joseph slip model addresses the slip effect. Govern fluid pressure, are solved to calculate the load support. A closed-form solution is derived for both pressure and load capacity as functions of various physical parameters. Effects of these parameters are discussed with the help of graphical representations. Results show that minimizing slip is crucial for improving bearing design. Additionally, even in the absence of fluid flow, the bearing can still support a substantial load, unlike traditional lubricants.

Keywords:

Tilted Pad Bearing (TPB) , Porous Structures (PS), Ferro Fluid (FF), Deformable Roughness (DR)

Slip Velocity (SV), Load Carrying Capacity (LCC),Squeeze Response Time (SRT)

Literature review and introduction:

In 1905, Michell introduced the concept of tilted-pad bearings. In 1910, Kingsbury revisited this bearing design, providing a slightly modified context. Rouleau and Steiner [1] studied the slip effect under similar boundary conditions and compared their findings with those derived from Darcy's lawbased methods. Miyan [2] developed a mathematical model to analyze the load capacity of fitted bearings, considering both low and high rotation numbers. The study revealed that the load capacity increased with the rotation number. In the 1960s, NASA developed kerosene-based magnetic fluids to enhance the efficiency of rocket engine propellant storage and use in zero-gravity environments. A magnetic field was employed to control the fluid's position, and the fluid consisted of a stable colloidal suspension of magnetic nanoparticles. In the early 1970s, Rosensweig [3] explored the properties of ferrofluids, emphasizing their potential in seals and bearings. Ferrofluid-based bearing systems were particularly beneficial for low-load applications requiring high-speed and precision positioning, such as in microscopy, wafer/chip inspection, and pick-and-place machines. Urreta et al. [4] provided a summary of research on journal bearing performance when lubricated with ferrofluid. More recently, Farhad et al. [5] conducted an analysis to investigate the effects of magnetohydrodynamic flow in blood, modeled as a Casson fluid, using a fractional model approach. Over the past two and a half decades, the characterization of surface roughness on lubricated surfaces has been extensively studied. It is now well-established that both load support and friction are significantly influenced by the composite roughness of surfaces. Adamu and Sinha [6] studied both stochastic and Gaussian roughness models, focusing on the thermal effects in infinitely long tilted pad bearings. This work proposes to explore the load-bearing behavior of a transversely rough tilted-pad porous bearing with slip, in the presence of a magnetic fluid. A model is developed using this approach and validated against another setup model by Shukla and Deheri [7]. The resulting analysis can help optimize the design of ferrofluid-based bearings to achieve the desired load capacity, considering the effects of slip and porosity.

Mathematical Modelling:

The bearing structure is presented in Figures (A) and (B), in which the runner feeds oil into a converging wedge. The gap h increases with increasing x, that is why runner has to move towards the origin with velocity $-U$ the position of h_0 is a distance H_1 from the origin while h_1 is away by a distance $_1 +$.

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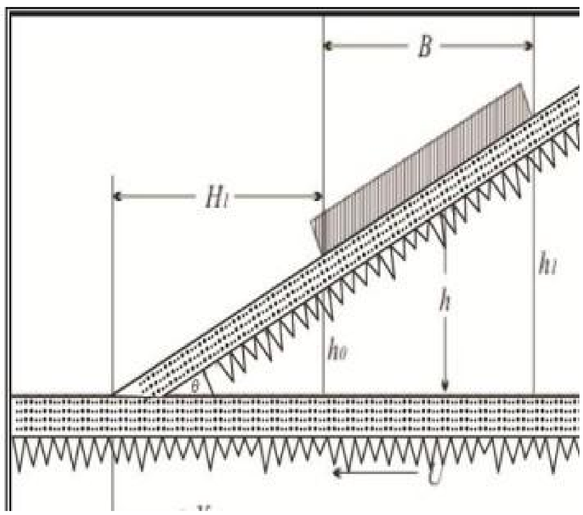

Figure A: The Schematic Sketch of the Pattern

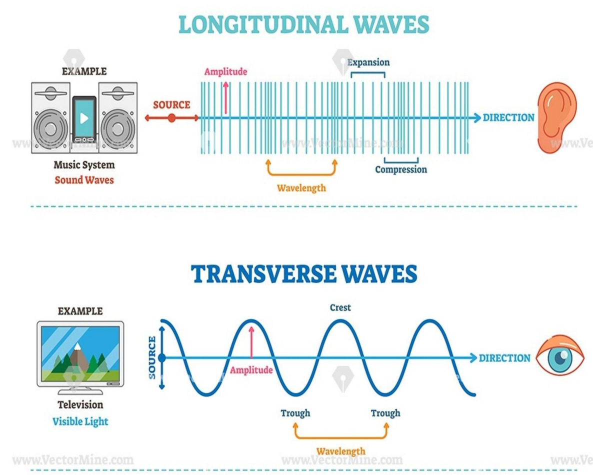

Figure B: Geometry of roughness

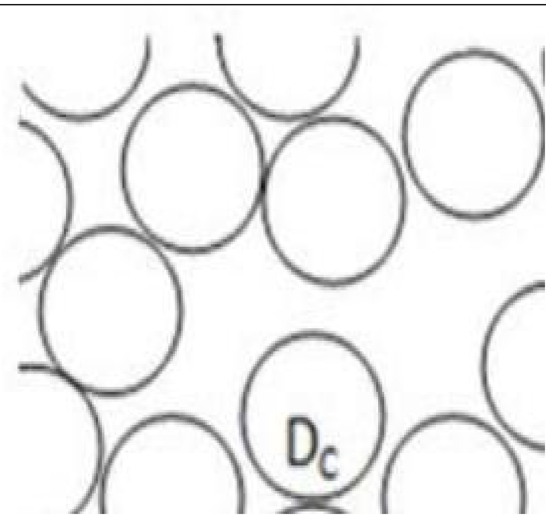

Figure – C Kozeny-Carman's model of porous sheets

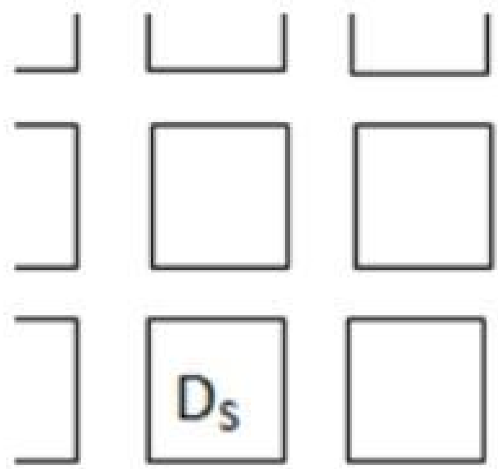

Figure – D Irmay's model of porous sheets

Making use of similarity of triangles

$$h = \frac{x h_0}{H_1} \tag{1a}$$

$$H_1 = B\left(\frac{h_0}{h_1 - h_0}\right) = \frac{B}{K} \tag{1b}$$

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$$K = \frac{h_1 - h_0}{h_0} \tag{1c}$$

In view of Christensen and Tonder [8] the film thickness is given by

$$h(x) = h(x) + h_s \tag{2}$$

The magnitude of the magnetic field is given by considering $k = 10^{14} A^2 m^{-4}$ with the magnetic strength over 10^5 (Bhat [9]).

$$H^2 = kB\left(\frac{h}{h_0} - 1\right)\left(K + 1 - \frac{h}{h_0}\right) \tag{3}$$

The Reynolds' type expression with inclined slider bearing is (Cameron [10]) written as

$$\frac{dP}{dx} = -6U\eta \frac{h - \bar{h}}{h^3} \tag{4}$$

Inclusion of porosity (Prajapati [11]) in the above equation

$$\frac{dP}{dx} = -6U\eta \frac{h - \bar{h}}{h^3 + 12\phi H_0} \tag{5}$$

By applying Neuringer and Rosensweig [12] model based ferrofluid lubrication transfer to equation

$$\frac{d}{dx}\left(P - \frac{\mu_0 \bar{\mu} H^2}{2}\right) = -6U\eta \frac{h - \bar{h}}{h^3 + 12\phi H_0} \tag{6}$$

Now, with the aid of stochastic average model of Christensen and Tonder [8], one is inclined to obtain

$$\frac{d}{dx}\left(P - \frac{\mu_0 \bar{\mu} H^2}{2}\right) = -6U\eta \frac{[a(h)]^{1/3} h - \bar{h}}{a(h)} \tag{7}$$

Here;

$$a(h) = (h + p' p_a \delta)^3 + 3\alpha (h + p' p_a \delta)^2 + 3(\alpha^2 + \sigma^2)(h + p' p_a \delta) + 3\sigma^2\alpha + \alpha^3 + s + 12\phi H_0 \tag{8}$$

Lastly, in view of Beavers and Joseph [13] slip model one arrives at

$$\frac{d}{dx}\left(P - \frac{\mu_0 \bar{\mu} H^2}{2}\right) = -6U\eta \frac{1}{S} \frac{[a(h)]^{1/3} h - \bar{h}}{a(h)} \tag{9}$$

where

$$S = \frac{4 + sh}{2 + sh} \tag{10}$$

Feasible boundary conditions are

$$P = 0,\ h = h_1 \text{ and } h = h_0 \tag{11}$$

Making use of the following dimensionless parameters:

$\sigma^* = \frac{\sigma}{h_0}$	$\alpha^* = \frac{\alpha}{h_0}$	$\delta^* = \frac{\delta}{h_0}$	$s^* = \frac{s}{h_0^3}$	$\psi = \frac{12\phi H_0}{h_0^3}$
$S^* = Sh_0$	$h^* = \frac{h}{h_0}$	$\mu^* = \frac{\kappa\mu_0\mu_0 B h_0^2}{U\eta}$	$P^* = \frac{h_0^2 P}{6U\eta B}$	$W^* = \frac{W h_0^2}{6U\eta L B^2}$
$A(H^*) = (1 + p^*\delta^*)^3 + 3(1 + p^*\delta^*)^2\alpha^* + 3(1 + p^*\delta^*)(\sigma^{*2} + \alpha^{*2}) + 3\sigma^{*2}\alpha^* + \alpha^{*3} + s^* + 12\psi$				

The non-dimensional pressure variation in the bearing system is found to be

$$P^* = h^*(h^* + 1)\frac{\mu^*}{2}\ \frac{1}{KA(H^*)}\ \frac{1}{h^*}\ \frac{k+1}{(k+2)h^{*2}}\ \frac{1}{K+2}\ \frac{1}{S^*} \tag{12}$$

The load carried per unit length W/L is the integral of the pressure over the pad, leads to

$$W^* = \frac{\mu}{18}\left[3K - 2k^3\right] + \frac{1}{K^2 A(H^*)}\ \log(k'\ 1)\ \frac{2k}{(k+2)}\ \frac{1}{S^*} \tag{13}$$

General results and discussions:

It is clear from the expression of the distribution of pressure and load support that the effect ferro fluid lubrication is linear, while the transvers rough affects adversely. Further, the roughness associated with longitudinal pattern provides the better results in general. This improved performance is due to the increase in viscosity of the lubricant. Which leads to an increase in pressure as well as LCC. The standard deviation has a substantial effect on the presentation of the squeeze film bearing system. It reveals that ε ∗ (+ve) decreases the load, while ε ∗ (-ve) increasing in load capacity. The next important parameter, which should be taken into account, is the behaviour of load support trends with variance. It is found that the variance follows the trends of the skewness. It is appealing to note that the effect of the porosity on distribution of the load support with respect to variance is negligible up to 0.001. Furthermore, it can be visualized that the combined effect of $\varepsilon *$ (-ve) and α * (-ve) is significantly positive in most of the situations. One of the main goal of this investigation is to constrain effect of porosity on the distribution of load capacity. It is clear that porosity affects the bearing system adversely. However, the system remains enhanced under the effect of $\varepsilon *$ (-ve) when smaller values of S* are considered.

Validation:

In order to order to validate the accuracy of our findings our mathematical modeling scheme has been applied to the problem considered by Shukla and Deheri [7] with relation to the titled pad slider bearing amid porous surfaces under slip effect. The Results are compared and as can be seen, there is a good degree of accuracy and the results fell with the findings of Shukla and Deheri [7].

Fruitful and feasible conclusions:

One of the conclusions of this paper is that even if there is a suitable magnetic field, the roughness must be treated carefully. The current investigation may remain suitable for designing optimal rotor dynamics. From this investigation, remarkable out-comes have been marked: The magnetization has a limited option in lowering the negative effect of roughness and slip. The adverse influence of standard deviation and slip becomes more even for lower to moderate values of porosity. For any type of improvement in the performance characteristics, one is inclined to use lower values of slip. Although, there are many parameters reducing the bearing load, the ferrofluid lubrication turns in a better situation when the effect of trio porosity, slip and standard deviation; is at considerably low level.

Nomenclature:

h	Film thicknesses any point
x	Co-ordinate in axial direction

B	Length of bearing
H	Magnitude of field
L	Breath of bearing
P	Lubricant pressure
S	Slip parameter
U	Runner-Velocity
W	Load support
h_0	Minimum film thickness
h_1	Maximum film thickness
Hs	Randomly portion
$\bar{h}$	Mean film thickness
P*	Dimensionless pressure
S*	Dimensionlessparameter
W*	Dimensionless support
σ	Standard deviation
ε	Skewness
α	Variance
δ	Deformation
φ	Porosity
η	Viscosity
σ*	Non-dimensional Standard deviation
ε*	Non-dimensional skewness
α*	Non-dimensionalvariance

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δ^*	Dimensionless deformation
φ^*	Non-dimensional porosity
μ^*	Non-dimensional Magnetization parameter
μ	Magnetic susceptibility

Data Availability:

There is up to certain extent data has been used for this research and cited at the proper place/s.

Declaration of Competing Interest:

All the authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Credit Authorship Contribution Statement with Justification/s:

Name	Description	%
Rakesh M. Patel	Writing the research article	20
Prin. Dr. Pragna A. Vadher	Conceptualization, Methodology	30
Dr. Bharatkumar N. Valani	Feasible justification of the problem	30
Dr. Gunamani B. Deheri	Mathematical justification of the problem	20

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A **Ferro fluid-Based Tilted Deformable Rough Porous Pad Bearing** represents a sophisticated mechanical system used in applications such as high-precision machinery or systems where traditional bearings might not provide the necessary performance under extreme conditions. To understand this concept better, let's break down the key components:

1. Ferrofluid:

- Ferro fluids are liquids that contain magnetic particles suspended in a carrier fluid (often oil or water). These magnetic particles respond to magnetic fields and can alter the fluid's properties (e.g., viscosity, flow resistance) when exposed to a magnetic field.
- In the context of a bearing, Ferro fluid can act as a lubricant that adapts dynamically to changes in external conditions (such as applied forces or temperature), improving performance and reducing wear and tear.

2. Tilted:

- Bearings often operate under specific geometrical conditions. A **tilted bearing** means the bearing surface is at an angle to the load or shaft rather than perfectly horizontal. This can help distribute the load more effectively, reduce friction, or achieve specialized movement or alignment in certain machinery, like in high-precision or adjustable systems.

3. Deformable:

- **Deformable** surfaces can change shape under load or pressure. In bearings, this property allows the bearing surface to adjust to the load conditions in real time, maintaining optimal contact and minimizing wear. The deformability of the bearing pad can help accommodate misalignments, imperfections, or external forces that might cause traditional bearings to fail or become inefficient.

4. Rough:

- The term **rough** refers to the texture or surface finish of the bearing pad. Instead of having a perfectly smooth surface, rough bearings have microscopic or even macroscopic irregularities. These roughness elements can help enhance the lubrication process by providing areas for the lubricant (in this case, the ferrofluid) to be retained. It also helps in damping vibrations and improving load distribution.

5. Porous:

- A **porous** surface refers to one that has tiny holes or pores, often designed to enhance the bearing's ability to retain and distribute lubricants (such as the ferrofluid). The porosity can also contribute to a more efficient load-bearing capacity, as the pores allow for better pressure distribution and potentially greater capacity for holding the ferrofluid.

Key Applications and Benefits:

- **Enhanced Performance**: A ferrofluid-based bearing can adjust dynamically, providing superior lubrication under varying conditions. This can be especially useful in high-speed or high-load applications.
- **Wear Reduction**: The deformable nature, combined with ferrofluid lubrication, reduces wear and tear by allowing the bearing to maintain an optimal lubricating film, even under shifting loads.

- **Precision Engineering**: The tilt and deformability allow for fine-tuned control of motion and load distribution, ideal for applications requiring high precision, like robotics or aerospace components.
- **Customization**: By varying the magnetic field and ferrofluid properties, the bearing can be adapted to different conditions, further enhancing its versatility and performance.

Potential Challenges:

- **Magnetic Field Control**: Maintaining precise control over the ferrofluid's behavior requires a well-managed external magnetic field, which might introduce complexity.
- **Cost and Manufacturing**: Designing and manufacturing such complex systems can be more costly compared to traditional bearings.
- **Heat Management**: Ferrofluids can become affected by temperature, which could alter their properties and affect performance. Effective thermal management systems would be necessary to maintain optimal functionality.

In summary, a **ferrofluid-based tilted deformable rough porous pad bearing** is a highly advanced mechanical component that uses a combination of magnetic fluid dynamics, surface engineering, and material properties to achieve superior performance in certain high-demand applications.