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Hydrodynamic bearing lubricated with magnetic fluids

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Abstract. This paper summarizes the work carried out in the development of hydrodynamic lubricated journal bearings with magnetic fluids. Two different fluids have been analyzed, one ferrofluid from FERROTEC APG s10n and one magnetorheological fluid from LORD Corp., MRF122-2ED. Theoretical analysis has been carried out with numerical solutions of Reynolds equation, based on apparent viscosity modulation for ferrofluid and Bingham model for MR fluid. To validate this model, one test bench has been designed, manufactured and set up, where preliminary results shown in this paper demonstrate that magnetic fluids can be used to develop active journal bearings.

1. Introduction

Lubricated bearings are well known in industrial applications, and their main advantages compared with rolling and friction bearings are their low friction and very high precision. Lubricated bearings can be externally pressurized, as hydrostatic bearing [1], or they can get the load pressure by relative movement of their pieces, as hydrodynamic bearing [2]. One of the main problems in both types of bearings is the working velocity range. The generated heat into the bearing due to viscous friction can block the mechanism if the dilatation of the shaft is higher than bearing’s clearance. To avoid this drawback and with the aim to get high performance smart bearings, lubricated bearings have been developed in different ways. Hydrostatic bearings have implemented semi-active or active valves to work in closed loop [3]. In this field can be classified the work presented by Kuzhir et al. and Leicht et al., in this ERMR08 Conference. In the case of hydrodynamic bearing, the load capacity is in function of the geometry, mainly the gap (technically almost impossible to change in process), the rotational velocity (imposed by operating conditions) and fluid properties. This work is centered in the development of smart and large operating range hydrodynamic bearings lubricated with magnetic fluids [4, 5].

2. Plain journal bearing

A journal bearing consists of two elements, namely the shaft with a radius \( R_a \) and the bearing with a radius \( R_c \) and width \( L \). Following parameters characterize radial clearance \( C = R_c - R_a \), \( \overline{O_c O_a} \) distance called eccentricity \( e \), relative eccentricity \( \varepsilon = e/C \) and the angle between the load \( \overrightarrow{W} \) and the center-line \( \overline{O_c O_a} \) called attitude angle \( \phi \). The plane section through the bearing can be seen in figure 1.
If the angular speed is \( \omega \), the Reynolds equation [2] for infinitely long journals can be written in polar co-ordinate system shapes as following:

\[
\frac{\partial}{\partial \theta} \left( h^3 \frac{\partial p}{\partial \theta} \right) = 6 \mu \rho R^2 \omega \frac{\partial h}{\partial \theta}
\]  (1)

Thus the pressure field with parabolic distribution in axial axis (Z-axis) is given by:

\[
p = \frac{6 \mu \omega (R/C)^2}{(1 - \epsilon^2)^{1/2}} \left( \frac{L^2 - 4 \epsilon^2}{L^2} \right) \left[ \psi - \epsilon \cos \psi - \frac{2 \psi - 4 \epsilon \sin \psi + \epsilon^2 \psi + \epsilon^2 \sin \psi \cos \psi}{2(1 - \epsilon \cos \psi)} \right]
\]  (2)

Where \( \psi \) is calculating angle and \( \psi_s \) corresponds to the film breaks down location angle. And by integration of the pressure field at boundary conditions, the load and attitude angle are obtained:

\[
W = 2 R L \mu \omega \left( \frac{R}{C} \right)^2 \frac{1}{\sqrt{1 - \epsilon^2(1 - \epsilon \cos \psi_s)}} \left[ \frac{\epsilon^2(1 - \cos \psi_s)}{1 - \epsilon^2} + 4 \left( \sin \psi_s - \psi_s \cos \psi_s \right)^2 \right]^{1/2}
\]  (3)

\[
\tan \phi = \frac{2\sqrt{1 - \epsilon^2(\sin \psi_s - \psi_s \cos \psi_s)}}{\epsilon (1 - \cos \psi_s)^2}
\]  (4)

3. Magnetic fluids: Magnetorheological fluids and ferrofluids

Two different magnetic fluids have been used in this work, one ferrofluid from FERROTEC APG s10n and a magnetorheological fluid from LORD Corporation, MRF-122-2ED. The model used for the ferrofluid characterization has been a simple modulation of fluid viscosity:

\[
\mu_{\text{app}} = k \cdot \mu_{\text{base}}
\]  (5)

Where \( \mu_{\text{app}} \) is the apparent viscosity of the fluid, \( k \) is the viscosity change of the fluid in function of magnetic field, and \( \mu_{\text{base}} \) is the viscosity of the fluid without magnetic field. For the case of magnetorheological fluid, Bingham model seems the simplest but the most similar to analyze the MR fluid.

\[
\tau = (\tau_0 (H) + \mu \cdot \dot{\gamma}) \text{sgn}(\dot{\gamma})
\]  (6)

The characteristics of this fluid have been taken from manufacturer data sheet, information available in the web: http://www.lordfulfillment.com/upload/DS7027.pdf
4. **Journal bearing test bench**

The test bench designed and manufactured for this work is composed by a plain journal bearing with two coils to develop the magnetic field into the bearing. The bearing is manufactured in bronze and the pieces around the field in aluminum to focus the field in the desired direction. The bearing is mounted on an aerostatic bearing to avoid any friction. The load is applied with a screw and the relative displacements are measured with two Eddy-current sensors. The load cell (INTERFACE SM 20.000) has ten Newton precision, and displacement sensors (Brüel&Kjær SD-081) measures well than one micron. The main dimensions of the bearing are: Diameter, 50mm; Length, 50mm; and radial clearance, 100microns. In the figure 2 the pictures of the bearing are shown, with the main elements of the test bench.

![Figure 2. Test bench (a) bearing with two shafts (b) and magnetic pole view (c)](image)

The shaft has been manufactured in two different materials, stainless steel and carbon steel, this way there will be compared magnetic and non-magnetic materials for the shaft. Magnetic poles cover around 73º of the bearing and their coils have 500 wire turns.

5. **Theoretical and experimental results**

First step in experimental analysis is to determine magnetic field in function of current intensity in the coils. For this task a Gaussimeter MAGNET-PHYSIK FH-54 has been used. The maximum current intensity is three Ampere, and at this current the magnetic field into the bearing is of 40kA/m.

First experiments have been carried out with the ferrofluid, at rotational speed of 100r/min. In the figure 3 can be seen the expected and measured path of the bearing (left side) and the eccentricity of the bearing for applied load (right side), using carbon steel shaft.

The results of the experiments show that the ferrofluid used in this work cannot be used as tunable lubricant. The rheological change of the ferrofluid is very low so its effect in the bearing is negligible.

![Figure 3. Bearing path (a) and load (b) versus eccentricity at 100r/min, Ferrofluid.](image)

Seeing the results with the ferrofluid, the following experiments have been carried out with magnetorheological fluid, that its shear stress is really high. In the figure 4 are shown the results for stainless steel shaft, and in the figure 5 for carbon steel shaft, in both cases for several speeds (50r/min, 200r/min and 400r/min):
Results for stainless steel shaft show that magnetic effect is only detectable in bearing path (figures 4 a, b, c). Meanwhile the experiments with carbon steel shaft give an increase of bearing’s load capacity (figures 5 d, e, f), and its displacement (figures 5 a, b, c) becomes linear and stable.

6. Conclusions
It has been set up a test bench for plain journals bearings lubricated with magnetic fluids. Theoretical calculations agree with experimental data for the first half of bearing’s clearance. The ferrofluid used in this work cannot be used as active lubricant in journal bearings. Magnetoreological fluids achieve good performance as active fluids in the bearing, this way they could be a good solution to increase the operation range of hydrodynamic bearings.

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