Tribology International 129 (2019) 46–54

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Increasing the load capacity of planar ferrofluid bearings by the addition of ferromagnetic material

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ARTICLE INFO

Keywords:
Precision engineering
Hydrostatic bearing
Mathematical modelling
Magnetics
Optimization

ABSTRACT

Ferrofluid pocket bearings are a type of bearing that are able to carry a load using an air pocket encapsulated by a ferrofluid seal. Previously designed ferrofluid bearings show the great potential of the stick-slip-free and low viscous friction bearings, however until now the load capacity is limited. In this article a method is presented to increase the load capacity in a simple and cost effective way by the addition of ferromagnetic material around the magnet. First, a mathematical model of the bearing is presented and is validated by experiments using an axially magnetized ring magnet surrounded by two steel rings. The model is used to optimize the dimensions of the added ferromagnetic material for maximum load capacity. Depending on the fly height, the load capacity has been increased by a factor three to four by the addition of steel rings to the ferrofluid pocket bearing configuration.

1. Introduction

The kerosene based magnetic fluid or so called ferrofluid that NASA developed in the 1960s appeared to be interesting to apply in seals and bearings as shown by Rosensweig et al. in the 1970s [1–4]. A ferrofluid can be defined as a fluid with paramagnetic properties that are generated by being a colloidal suspension of small magnetic nanoparticles (10 nm) [5,6]. The application of an external magnetic field increases the pressure inside the fluid after which the fluid is capable of carrying loads [7–9], thus can act as an actuator [10–16] or seal [17–21]. Ferrofluid can be used to yield mechanisms that have complete absence of both stick slip and mechanical contact resulting respectively a potential high precision and high lifetime [7,8,22,23].

Because the fluid in ferrofluid bearings is contained by the presence of a magnetic field that is generated by for example a permanent magnet, no seals or active components are required. Therefore, a ferrofluid bearing is a passive, simple, and cost effective alternative to traditional bearings. Examples of these ferrofluid bearings can be found in literature, but despite the great potential, application is still very limited [7–9,24–29]. One reason for this is that the load capacity and stiffness is relatively limited. Lampaert et al. recently developed a mathematical model to describe the load and stiffness characteristics of ferrofluid bearings, which makes it now possible to design for maximum load capacity [7,8,22,23,26,30–33].

The load capacity of a ferrofluid bearing is created by the pressurized air pocket(s) encapsulated by the ferrofluid seals. The shape of the magnetic field and the number of air pockets between non-connected seals seem to be of great importance to the load capacity. The goal of this article is to increase the load capacity of ferrofluid bearings by the addition of ferromagnetic material.

The addition of ferromagnetic material, in this case steel, has the ability to concentrate the magnetic field generated by the permanent magnet and could therefore increase the load capacity [34,35]. Furthermore, steel could alter the shape of the magnetic field such that multiple air pockets can be created. Steel has a high magnetic saturation and a high relative permeability which makes this material suited for improving the load capacity.

First, a model is presented to calculate the load capacity of a ferrofluid double pocket bearing. This model is validated by experiments and will then be used to optimize the geometries of the steel rings. The acquired knowledge can be used as design rules for increasing the load capacity of planar ferrofluid bearings by the addition of ferromagnetic material.

2. Methods

First, an analytical model for the load capacity of a ferrofluid double pocket bearing is presented based on the available literature. Second, the four different bearing models, model A through D, are presented after which the FEM analysis, using COMSOL Multiphysics, is

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https://doi.org/10.1016/j.triboint.2018.07.048
Received 7 May 2018; Received in revised form 18 July 2018; Accepted 30 July 2018

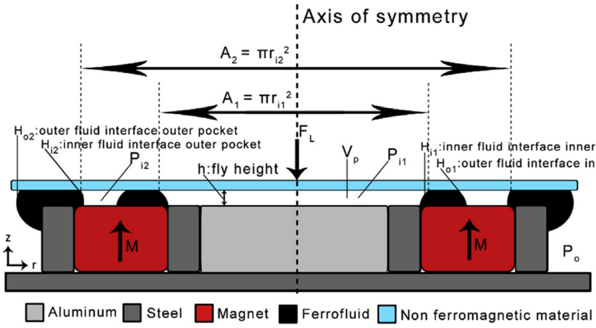

Fig. 1. This figure presents the cross section of the ferrofluid bearing with the defined parameters. The ring magnet is surrounded by two ferromagnetic rings, in this case steel, with an aluminum disk placed inside. The entire setup is mounted on a steel baseplate. Important parameters are the pressures and areas of the air pockets and the magnetic field intensities at the different fluid interfaces.

introduced to calculate the magnetic field intensities. These magnetic field intensities in combination with the analytical model are used to calculate the load capacity. Next, the experimental setup used for the validation of the described model is presented after which the optimizations of models A-D are described.

2.1. Analytical model

The analytical model for a ferrofluid single pocket bearing [8,9,24] is extended to a model predicting the load capacity of a ferrofluid double pocket bearing, schematically represented in Fig. 1. The Navier-Stokes equations for incompressible magnetic Newtonian fluids can be simplified to equation (1) assuming a stationary, low Reynolds number incompressible flow with a Newtonian fluid model. The relation presents the pressure gradient ∇p as the product of the magnetic permeability of vacuum μ_0, the magnetization strength of the fluid M_s and the magnetic field gradient ∇H.

$$\nabla p = \mu_0 M_s \nabla H \tag{1}$$

Application of the Fundamental theorem of calculus gives the relationship used for calculating the load capacity of the air pockets, equation (2).

$$F_{pocket} = \int_A (p_i - p_o) dA_{pocket} = \mu_0 M_S \Delta H \, A_{pocket} \tag{2}$$

Both the pressure inside the air pocket and the pressure inside the ferrofluid ring contribute to the total load capacity of the bearing. Although the load carrying contribution of the seal is relatively small in comparison to that off the pocket, it will be included in the calculation to get the most accurate prediction of the total load capacity. Equation (3) shows the approximation of the load capacity of the seal as described by Lampaert et al. [7].

$$F_{seal} = \int_A (p_s - p_0) dA_{seal} \approx \mu_0 M_S \, \Delta H \, \frac{A_{seal}}{3} \tag{3}$$

For a bearing configuration with two seals and two pockets the total load capacity is simply obtained by adding the load capacities of both pockets and both seals. Each contribution to the total load capacity is calculated by integrating the pressure difference over the area, as can be seen in equation (4). This is visually shown in Fig. 5, where the load capacities of the ferrofluid bearing for the magnet only and for the magnet with steel rings correspond to the orange and red surface respectively. The pressure distribution is a result of the magnetic field intensities of the fluid-air interfaces (H_{i1} H_{i2} H_{01} H_{02}), see Fig. 1. By integrating this pressure distribution, the total load capacity is calculated.

Implementation of a second ferrofluid seal has the advantage that the pressure can be increased twice, one time over each ferrofluid seal. It is important to note that the pressure contribution of the doughnut shaped second pocket, A_{p2}, as given in equation (4) can be rewritten to equation (5), in which the pressure contributions of both pockets act on a circular surface as defined in Fig. 1. To illustrate this, the pressure distribution which is given in Fig. 5 corresponds to the magnetic field intensities at the interfaces between ferrofluid and air, given in Fig. 4.

$$F_{load} = \int (p_{i1} - p_0) dA_{p1} + \int (p_{s1} - p_0) dA_{s1} + \int (p_{i2} - p_0) dA_{p2} + \int (p_{s2} - p_0) dA_{s2} \tag{4}$$

$$F_{load} \approx \mu_0 M_S \left((H_{i1} - H_{o1}) \left(A_1 + \frac{A_{S1}}{3} \right) + (H_{i2} - H_{o2}) \left(A_2 + \frac{A_{S2}}{3} \right) \right) \tag{5}$$

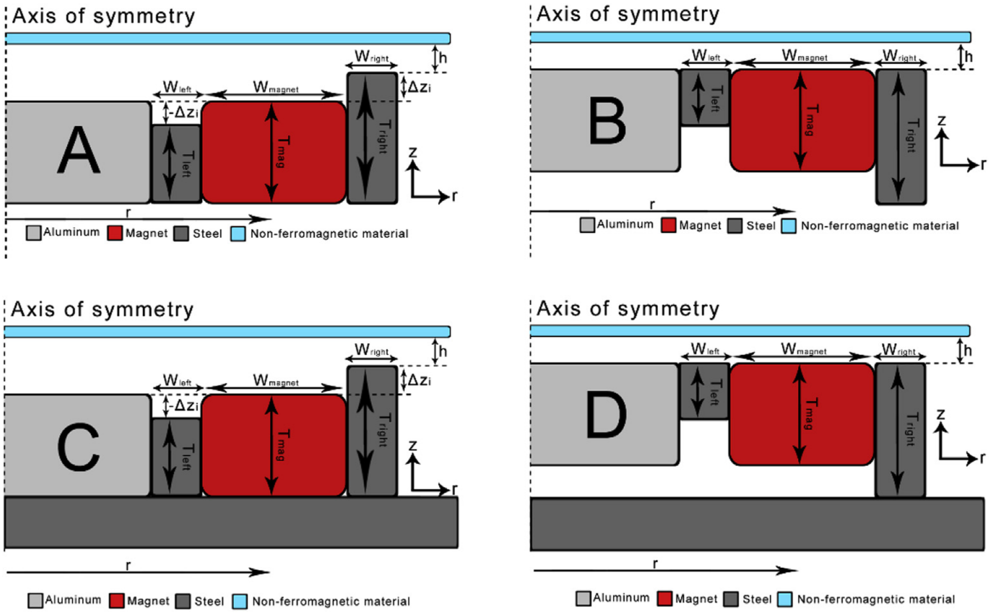

Fig. 2. This figure presents the four different bearing models and their design variables. In contrast to Model C and D, model A and B have no ferromagnetic baseplate. Model A and C are defined from bottom up and model B and D are defined from top down.