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Supporting and friction properties of magnetic fluids bearings

Zhengdong Hu, Zhuang Wang, Wei Huang*, Xiaolei Wang

College of Mechanical & Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing, 210016, China

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ABSTRACT

A driblet of magnetic fluids (MFs) falls on an annular magnet, forming a closed liquid ring. The magnetized MFs can produce liquid support due to magnetostatic force. The air cushion enclosed by the MFs sealing ring may generate gas support as the magnet bottom combines with a substrate. The supporting capacity supplied by the liquid-gas contributes to friction reduction. Research shows such supporting is affected by the surface magnetic field and field distribution. Tribological results confirm that low friction can be obtained since the tribo-pairs are separated by the supporting force and the friction originates from the fluid viscosity. Such design would be significant for solving the “cold welding” as well as the “stick-slip” phenomenon, especially in precise sliding machine.

1. Introduction

Magnetic fluids (MFs) are colloidal suspensions, which contain single domain ferromagnetic nanoparticles dispersing in a carrier liquid [1]. Brownian movement maintains these particles from sinking under gravity effect and a suitable organic surfactant is coated around each particle to overcome agglomeration due to van der Waals force and magnetic dipole interaction [2]. The behaviors of MFs mainly depend on their magnetic properties and the fluids may automatically flow and stay into regions with more intense magnetic field. This feature of magnetic controlling has attracted many scientific and industrial applications, such as rotary shaft sealing [3], grinding [4] and separation [5].

Lubrication is also a typical application of MFs [6]. Compared with traditional liquid lubricants, the superiority of MFs as lubricant is that it can be attracted in the contact zone by an external magnetic field and still possess fluidity at the same time [7]. From the lubrication point of view, this enables the supply of lubricant for the friction pairs without the use of pumps. Further more, the magnetization of the MFs interacts with the applied magnetic field to generate attractive forces on the particles. Due to the stabilized suspension of magnetic particles in the fluid, the attractive magnetic force manifests itself as a body force on the fluid [8]. Therefore, the local concentrated MFs under magnetic field can generate a controllable body force or magnetostatic force acting as a buoyancy force to separate the tribo-pairs [9,10].

Besides the magnetostatic supporting of the liquid, MFs seal may produce a kind of gas supporting [11,12], which is also beneficial for lubrication. As shown in Fig.1a, a drop of MFs was absorbed on the surface of an annular magnet, forming an enclosed liquid structure. When the bottom of the magnet is open, the magnetized MFs structure provides magnetostatic force only. While a substrate is combined with the magnet bottom without leakage, beside the magnetostatic force, the air in the chamber packaged by the MFs seal might also produce gas supporting force. Thus, the load carrying capacity will be shared by the magnetized liquid and the sealed gas together (see Fig. 1b).

Compared with magnetostatic force, the participation of the gas support will further enhance the load carrying capacity. When the gross weight of object is less than the bearing force, it may be totally held and floated up. For precise machinery, direct contact between friction surfaces can be avoided and full fluid film can be achieved. Different from hydrodynamic lubrication, the main superiority of such structure is that the load carrying capacity does not rely on the relative motion of two surfaces. Moreover, it still exists between two parallel planes. Therefore, compared with traditional fluid lubrication, the novelty of such supporting construction is that, ultralow friction can be expected even at low or relatively static state and the “stick-slip” phenomenon may be avoided, which is highly desirable in friction system.

In the previous refs. [11,12], attention was paid on the principle analysis of such supporting system and few experiments were carried out. Meanwhile, the contribution of the magnetostatic force was neglected. And in the supporting process, which one serves as the main role, the liquid or gas? Besides, are there any effective methods for upgrading the supporting force? Furthermore, can ultralow friction be achieved based on this supporting system? There is little knowledge about it.

In this paper, the load carrying capacity of the supporting

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* Corresponding author. Yudao street 29#, Nanjing, China.
E-mail address: huangwei@nuaa.edu.cn (W. Huang).

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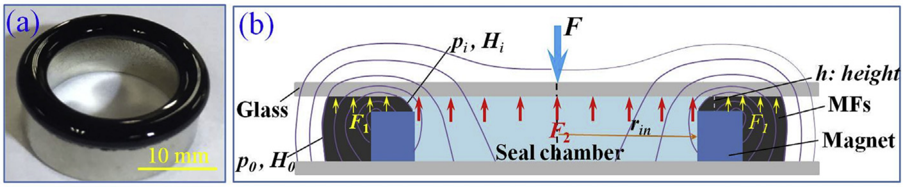

Fig. 1. (a) The image of an annular magnet covered with MFs, (b) Supporting schematic diagram.

construction was analyzed considering the magnetostatic force. The gas supporting force was obtained indirectly via experiments and the value was compared with theoretical results. After that, two simple ways were proposed to further enhance the supporting force: 1) increasing the surface magnetic property of magnet; 2) changing magnet distribution. Finally, the lubrication behaviors of such system were evaluated.

2. Theory analysis

The principle diagram of the supporting system was shown in Fig. 1b. When ignoring the weight of the upper glass, the expression, according to the force equilibrium condition, can be written as:

$$F + p_0 A_F = F_1 + p_i A_F \tag{1}$$

where F is the normal load, p_0 (bar pressure) and p_i are the hydrostatic pressures on the two sides of the MFs interface and A_F is the supporting surface area. F_1 is the magnetostatic force of magnetized MFs, which can be measured directly (see in the results section). Then, the total supporting force may be presented by:

$$F = F_1 + (p_i - p_0) A_F \tag{2}$$

here, $(p_i - p_0)$ is the pressure difference across the MFs interface. As can be seen, the load F can be written in a form of liquid-gas mixed support:

$$F = F_1 + F_2 \tag{3}$$

where F_1 is the magnetostatic force of magnetized liquid, F_2 is the force generated by the gas pressure difference across the MFs interfaces.

When ignoring the surface tension and gravity of MFs, according to MFs sealing principle, the pressure difference applied to the MFs is expressed by Ref. [13]:

$$p_i - p_0 = \mu_0 \int_{H_0}^{H_i} M\, dH = \mu_0 M (H_i - H_0) \tag{4}$$

where M is the magnetization of MFs, H_i and H_0 are the corresponding magnetic intensity on each side of the MFs interface. Usually, for a N35 NdFeB magnet, the magnetic field in the sealing gap (within 1 mm) reaches 10^5 A/m and MFs can be regarded as fully saturated (M_s) [8]. Thus, F_2 can be written as:

$$F_2 = \mu_0 M_s (H_i - H_0) A_F \tag{5}$$

where A_F is the gas supporting area ($A_F = \pi\, r_{in}^2$). As can be seen, the force produced by the gas in the chamber mainly depends on the MFs sealing capacity. As shown in Fig. 1b, displacement of the upper glass causes change of the drop shape as well as the magnetic field intensity at the MFs interfaces. The inner interface of fluid moves to the higher H_i, while the outer becomes the lower H_0 due to the squeezing and radial motion of the MFs. Thus, the smaller the height (h) between magnet surface and upper glass it is, the higher the gas supporting force it provides.

3. Experimental section

3.1. Materials

In this paper, N35 NdFeB annular magnets magnetized in the axial direction were used with the size of Φ16 mm × Φ12 mm × 6 mm. To achieve different surface magnetic intensities, the magnets were heated in vacuum oven for different times. The final surface magnetic flux densities of the magnets were 91 mT, 195 mT, 250 mT and 270 mT, respectively.

Commercial MFs consisting of Fe_3O_4 nanoparticles dispersed in synthetic hydrocarbon carrier was chosen. It has a saturation magnetization (M_s) of 23.8 kA/m with the particle volume fraction of about 6.3%.

3.2. Supporting force tests

The supporting force tests were carried out using a stress testing platform, as shown in Fig. 2. The upper indenter is rigidly fixed with a force sensor. The moving velocity of the indenter in the axial direction is controlled at 0.01 mm/s by a reducer. The measuring range and resolution of the force sensor are 5 N and 0.001 N, respectively. Before each test, the sensor was clean and reset. For each magnet, the usage of MFs volume is 0.5 mL. The curve of the supporting force over the axial movement can be recorded by a data acquisition system. The maximum supporting force is defined when the gap between the indenter and magnet is 0.01 mm.

The experiments were divided into two groups: (1) single annular magnet with different surface magnetic flux densities; (2) four magnets with different distributions. Fig. 1a presents the image of one magnet covered with MFs and Fig. 3 shows the four magnets samples embedded in aluminium plate in square array. As can be seen in Fig. 3a, when the center space of the magnets is 25 mm, each magnet can be considered as an individual. It is interesting that one more enclosed chamber in the center of the magnets is formed when the four magnets connect together as shown in Fig. 3b.

3.3. Friction tests

Friction tests were carried out using a reciprocating sliding

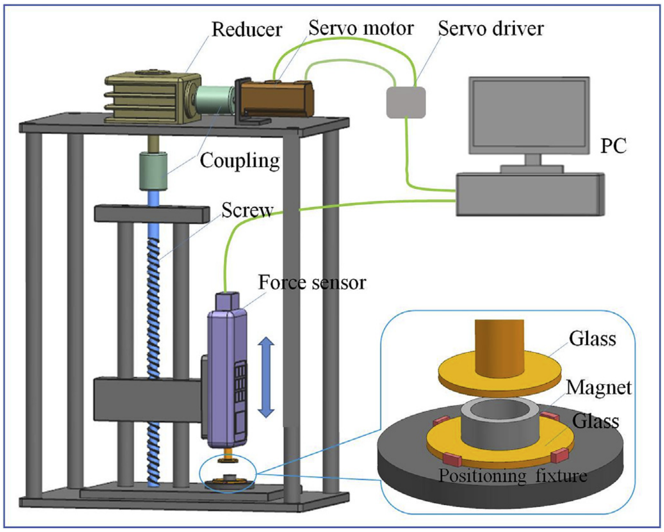

Fig. 2. The sketch map of the supporting force test system.