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Loss of Torque on Magnetic Fluid Seals with Rotating-shafts

Jianhui Hu*, Meng Zhao, Lu Wang, Jibin Zou, and Yong Li

Department of Electrical Engineering, Harbin Institute of Technology, Heilongjiang, China

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The effects of loss of torque on magnetic fluid seals with rotating-shafts and the general difficulty of studying magnetic fluid seals are the focus of this work. The mechanism underlying loss of torque on such seals is analyzed using theoretical methods that show that loss of torque can be affected by several factors, including the velocity of the rotating-shaft, the structure of the sealing device, the characteristics of the magnetic field, and the characteristics of the magnetic fluid. In this paper, a model of the loss of torque is established, and the results of finite element analysis and testing and simulations are analyzed. It is concluded that (i) the viscosity of the magnetic fluid increased with the intensity of the magnetic field within a certain range; (ii) when the magnetic fluid was saturated, the increase in loss of torque tended to gradually slow down; and (iii) although the axial active length of the magnetic fluid may decrease with increasing speed of the rotating-shaft, the loss of torque increased because of increasing friction.

Keywords : magnetic field, magnetic fluid, torque, sealing

1. Introduction

Rotating-shaft seals [1, 2] are an important type of magnetic fluid seal. Because of the centrifugal force, it is not clear whether the magnetic fluid in the sealed axial distribution comes into contact with the surface when the sealing shaft is rotated. Establishing strong rotating-shaft seals is difficult in magnetic fluid sealing since the specific type of magnetic field and velocity of the rotating-shaft can directly affect the capacity of the magnetic fluid seal. Furthermore, the characteristics of the magnetic fluid can also be affected by the type of magnetic field [3, 4], e.g., the density of the magnetic fluid and the viscosity of the magnetic fluid [5], among other factors [6-10]. In addition, the boundary of the magnetic fluid seal [2] can be varied by changing the velocity of the rotating-shaft. Because of the movable boundary of the magnetic fluid seal, the distribution of the magnetic field can be affected. There is also friction between the rotating-shaft and the magnetic fluid, which can cause loss of torque. The viscosity of the magnetic fluid can vary with changes in the magnetic field, and friction can be varied by changing the viscosity of the magnetic fluid [5]. Thus, the degree of loss of torque can be changed by changing the characteristics of the magnetic field and the velocity of the rotating-shaft. The type of loss of torque can affect the type of magnetic fluid seal. The loss of torque of the magnetic fluid is the focus of this work, and the mechanism that generates the loss of torque is evaluated through theoretical analysis. Mathematical and physical models of the loss of torque are established based on the theoretical analysis. The feasibility and correctness of the analysis are validated using finite element simulation and experimental testing.

2. Theoretical Analysis

In general, a single magnetic particle in a magnetic fluid can be considered a small ring current. In the presence of an external magnetic field, the direction of the magnetic field induced by the ring current can be consistent with the direction of the external magnetic field [11]. When the direction of the magnetic field caused by the ring current is changed, the external magnetic field can prevent the inner magnetic field from changing direction in response to the ring current. The inner magnetic field is caused by the ring current. When there is relative movement between magnetic particles and carrier liquids, the viscosity of a magnetic fluid can be increased [12, 13]. The range of motion of magnetic particles can be controlled by magnetic force under the influence of an

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*Corresponding author: Tel: +86-451-86413613-603
Fax: +86-451-86413613-600, e-mail: hujianhui@hit.edu.cn

external magnetic field, and the viscosity of a magnetic fluid can be varied under the external magnetic field as well [14]. In the presence of an external magnetic field, the viscosity of a magnetic fluid is expressed as

$$\eta = \eta_0(1 + f(H)) = \eta_0\left\{1 + \frac{n_2}{n_1}\sqrt{\frac{m_2}{m_1}}\left[\frac{\frac{m_2}{m_1}(\lambda^2 - 1) + \delta\left(\frac{\lambda^2 m_2}{m_1} - 1\right) - 1}{\lambda\sqrt{1 + \frac{m_2}{m_1} + \delta}}\right]\right\} \quad (1)$$

where

$$\lambda = 4\sqrt{2}\frac{a^2}{(a+b)^2}, \quad \delta = \frac{\mu_0 \overline{M}t}{\overline{v}m_2}\left\{\begin{matrix}(\partial H/\partial x)^2 + (\partial H/\partial y)^2 + \\ (\partial H/\partial z)^2\end{matrix}\right\}.$$

Here, m_1, m_2 denote the mass of the carrier liquid molecules and magnetic particles, respectively; n_1, n_2 the number of carrier liquid molecules and magnetic particles, respectively; a the average diameter of the carrier liquid molecules; b, the average diameter of the magnetic particles; t, the average time of continuous collisions between the magnetic particles; $\overline{M}$, the magnetic moment per magnetic particle; H, the external magnetic field intensity; and $\overline{v}$, the average speed of the magnetic particles. These inherent parameters of the magnetic fluid and can be obtained from the suppliers of the magnetic fluid.

δ is dependent on the grades of intensity of the external magnetic field shown in Eq. (3), and $\sqrt{1+\delta}$ is the influence of the viscosity of the external magnetic fluid. The viscosity of the magnetic field is not the same in the random dot area when the grades of field intensity are functions of x, y, and z in the entire field.

Figure 1 shows the model of rotating-shaft sealing on the magnetic fluid: 1) rotating-shaft; 2) magnetic fluid; 3) and 5) magnetic poles; 4) permanent magnet; 6) mechanized sealing member; 7) sealing area. The pressure in the sealing area is altered by increasing or reducing air via the looped pipeline.

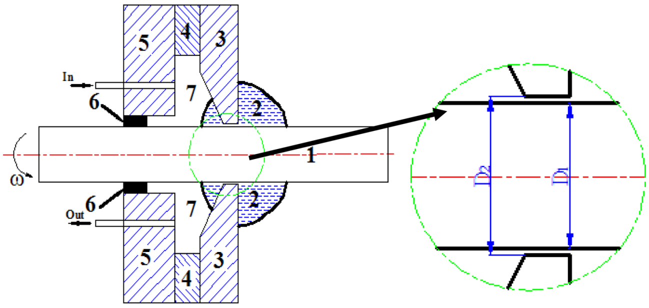

Fig. 1. (Color online) Model of rotating shaft-type magnetic fluid seal.

Because the gap in the seal is very small, the loss of torque can be approximated as

$$M = \frac{\pi\eta\varpi D_1^3}{4g}$$

Where, $g = D_1 - D_1$.g is the twice of the gap in the seal. The power loss caused by friction is given as

$$p = M \cdot \varpi = \frac{\pi\eta D_1^3\varpi^2}{4g}$$

The loss of power is directly proportional to the viscosity of the magnetic fluid, the square of the shaft angular velocity, and the cube of the shaft diameter. The loss of power is inversely proportional to the size of the gap in the seal. The type of viscosity of the magnetic fluid, diameter of the rotating-shaft, angular velocity of the rotating-shaft, and size of the gap in the seal can directly affect the degree of power loss.

Substituting (2) into (3) leads to

$$p = p_0 + p' = \frac{\pi\eta_0 D_1^3\varpi^2}{4g} + \frac{\pi D_1^3\varpi^2}{4g}\eta_0 f(H)$$

Where, $P_0 = \frac{\pi\eta_0 D_1^3\varpi^2}{4g}$, $P' = \frac{\pi D_1^3\varpi^2}{4g}\eta_0 f(H)$

η_0 is the basic viscosity of the magnetic fluid without the magnetic field. P_0 is the basic loss of torque produced by the basic viscosity. P' is the additional loss of torque produced by the additional viscosity. The additional viscosity is produced by the external magnetic field.

The loss of torque on the magnetic fluid seal with a rotating-shaft makes up the basic loss of torque and the additional loss of torque shown in (4). The basic loss of torque is constant when the diameter of the rotating-shaft, angular velocity of the rotating-shaft, size of the gap in the seal, and basic viscosity of the magnetic fluid are also constant. However, the additional loss of torque does not remain constant because the viscosity of magnetic fluid can be varied by varying the external magnetic field.

3. Simulation Analysis

Owing to viscous effects, tangential stress–in the form of shear stress–as well as normal stress appears in the magnetic fluid. Shear stress on the gap in the magnetic fluid creates constant motion along the circumference of the gap. The magnetic fluid can be affected by centrifugal force generated by the rotation of the rotating-shaft, in addition to the magnetic force, gravity, and applied pressure. The model of the simulation about loss of torque

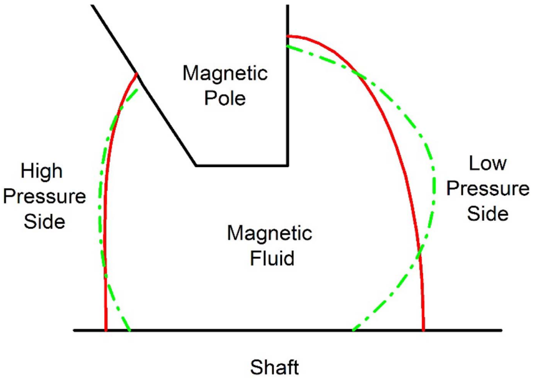

Fig. 2. (Color online) Cross-sectional shape of the magnetic fluid seal.

on magnetic fluid seals with rotating-shafts is established according to Figure 1. The field problem is solved by boundary shape approximation of the magnetic fluid with iteration method [15]. Dirichlet boundary condition is used in this research.The simulation analysis is carried through under the boundary condition set as infinity and its value as zero. Depending on the centrifugal force, the surface of the magnetic fluid can be released outwards along the radius direction of the rotating-shaft, and close to the magnetic pole. The shape of the cross section of the magnetic fluid seal ring can be varied; this cross-section is shown in Fig. 2. The red line shows its shape when the rotating-shaft is still, and the green line shows it when the rotating-shaft is moving.

When the volume of the magnetic fluid is kept constant, the axial active distance between the magnetic fluid and the surface of the shaft is significantly shorter than when it is allowed to vary. Because the difference in the intensity of magnetization between the higher- and lower-pressure sides is reduced, the effectiveness of the seal is also reduced. In general, the higher the velocity of the rotating-shaft, the weaker the seal.

Figure 3 shows the relationship between the volume of the magnetic fluid and the difference in pressure between a still and moving rotating-shaft. The diameter of the rotating-shaft is 20 mm, the gap in the seal is 0.5 mm, and the seal's active length is 14 mm. The saturation magnetization of the magnetic fluid is 356 Gs, and the velocity of the rotating-shaft is 400 rpm. When the shaft is still, the seal continues to come into being until the volume of the magnetic fluid reaches 2500 mm^3. When the shaft is in motion, the seal continues to form until the volume of the magnetic fluid reaches 5300 mm^3. When the volume of magnetic fluid is 6000 mm^3, the difference in pressure under rotating shaft conditions is 1340 Pa and the difference in pressure under still-shaft conditions is 335 Pa.

When the volume of the magnetic fluid is 7000 mm^3, and the sealing shaft is still and the magnetic fluid fills the sealing gap, the axial active length between the magnetic fluid and the surface of the shaft is 30.8 mm. When the volume of the magnetic fluid is kept constant, the axial active length between the magnetic fluid and the surface of the shaft can be decreased gradually as the velocity of the rotating-shaft and the pressure in the sealed area increase. When the velocity of the rotating-shaft reaches 1000 rpm and the seal pressure difference is 1770 Pa, the axial active length can be reduced to 23.7 mm. Figure 4 shows the relationship between axial length and the speed of moving rotating shaft. When the pressure in the sealing area or the velocity of rotating-shaft is increased further, the magnetic fluid seal fails.

Figure 5 shows the relationship between the pressure difference and the axial active length of the magnetic

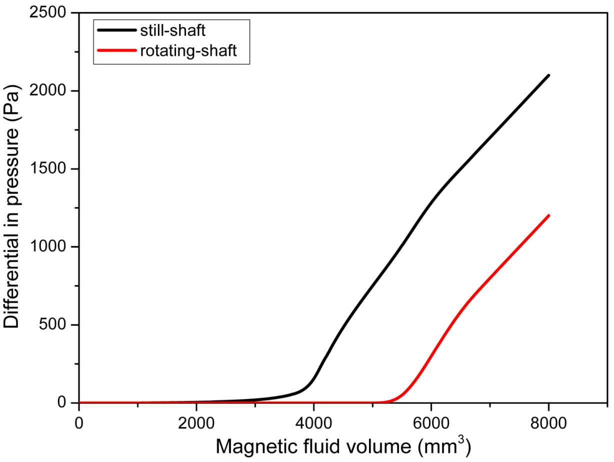

Fig. 3. (Color online) Relationship between magnetic fluid volume and difference in pressure.

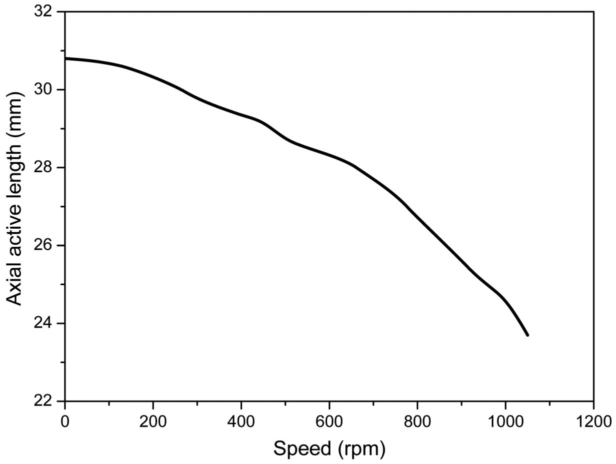

Fig. 4. Relationship between the speed of the rotating-shaft and the axial active length.

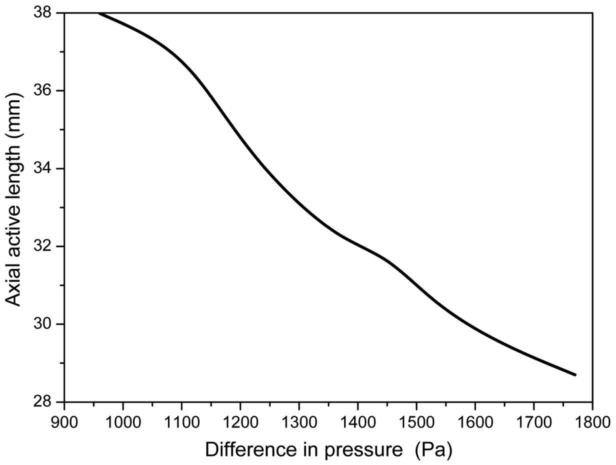

Fig. 5. Relationship of the difference in pressure and axial active length.

fluid when the speed of the rotating-shaft is 500 rpm. The volume of the magnetic fluid is constant. The higher the difference in pressure, the shorter the axial active length of the magnetic fluid.

4. Test Results

As shown in Fig. 6, test device is designed according to the theoretical analysis and simulation analysis. The test device is composed of a rotating-shaft sealing device, a force pump, and a DC motor. The magnetic fluid is injected through the magnetic fluid injection hole. The DC motor connects with the rotating-shaft through the flexible coupling. The pressure in the sealing area is showed by the pressure gauge.

The magnetic fluid tested was comprised of Fe_3O_4 nanoparticles; its density was 1.25×10^3 kg/m^3, its viscosity 81×10^{-3} Pa·s, and its saturation magnetization 356 G. For this DC motor, the rated power, number of pole-pairs, speed and voltage are 400 W, two pairs, 1500 rpm and 200 V separately. When the DC motor's voltage is changed, the motor's velocity also changes. In the tests, the speed ranged from 0 rpm to 1500 rpm. The pressure on the sealing area can also be varied by changing the power of the force pump.

In the experiments, the volume of the magnetic fluid, the difference in pressure, and the speed of the rotating-shaft always remain the same. When the rotating-shaft rotates, the pressure difference in the sealing area will change. The difference in pressure is constant by changing the intensity of the magnetic field. The degree of the loss of torque can be obtained by comparing how the torque changes with different magnetic field intensities. In this research, the results from simulation process and experiment analysis are compared. The interim parameters which are necessary for the research are also calculated during the simulation process.

Figure 7 shows the relationship between the intensity of

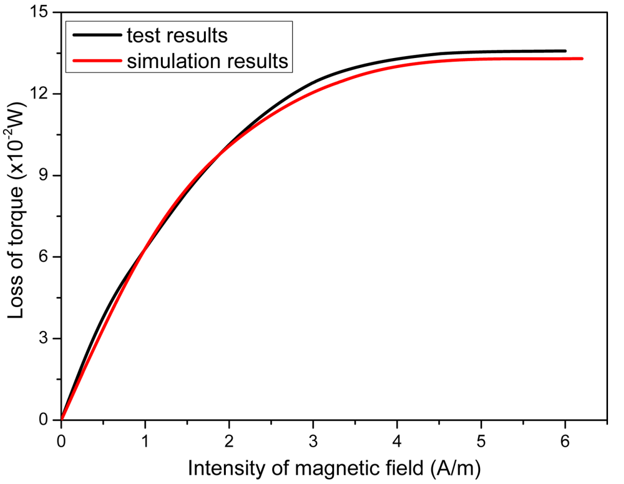

Fig. 7. (Color online) Relationship between intensity of the magnetic field and loss of torque.

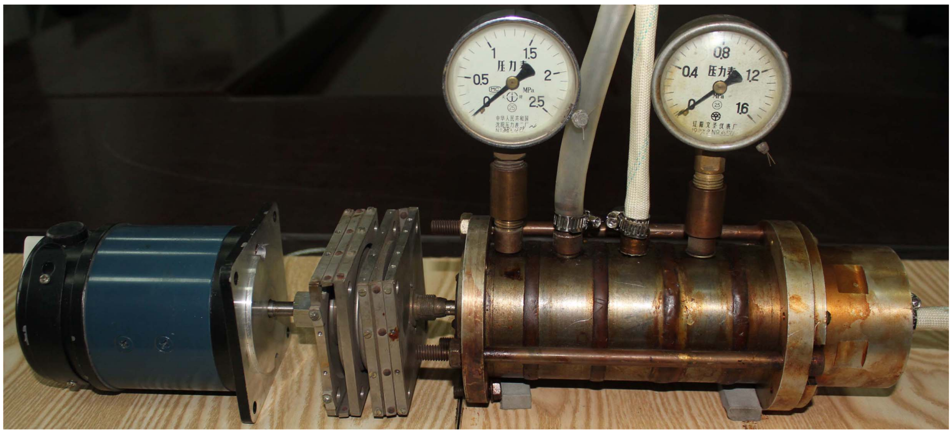

Fig. 6. (Color online) Test device.

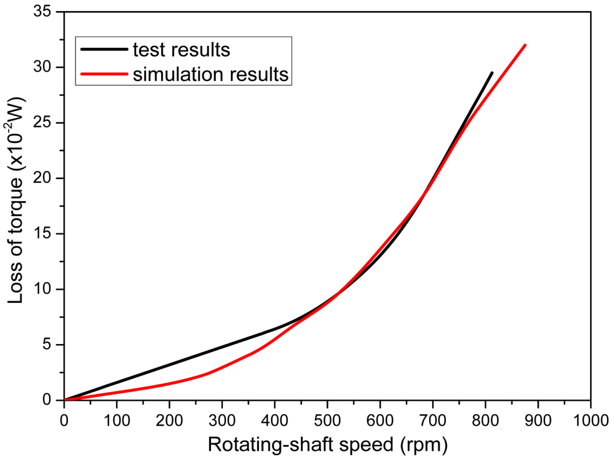

Fig. 8. (Color online) Relationship between rotating-shaft speed and loss of torque.

the magnetic field and the loss of torque of the magnetic fluid when the difference in pressure is 1500 Pa and the speed of the rotating-shaft is 600 rpm. The black line shows the test results; the red line shows the simulation results. The loss of torque becomes more pronounced as the intensity of the magnetic field increases. The viscosity of the magnetic fluid increases with increasing magnetic field intensity within a certain range. Initially, the magnetic fluid is not saturated. When the effect of the intensity of the magnetic field on the viscosity of the magnetic fluid is more pronounced, the torque increases rapidly. The magnetic fluid gradually becomes saturated as the magnetic field increases in intensity. At the same time, the loss of torque tends to gradually slow down, which is typical of the decreasing effect of the magnetic field intensity on the viscosity of the magnetic fluid.

When the speed of the rotating shaft is varied, the difference in pressure can be varied as well. Under different rotation speeds, the pressure difference can be kept constant by changing the intensity of the magnetic field. Comparing changes in magnetic field intensity under different shaft-rotation speeds, the degree of the loss of torque can be obtained. Figure 8 shows the relationship between the speed of the rotating shaft and the loss of torque of the magnetic fluid when the pressure difference is 1500 Pa and the volume of the magnetic fluid is constant. The black line shows the test results; the red line shows the simulation results. The results of testing and simulation show that the higher the speed of the rotating shaft, the more pronounced the loss of torque of the magnetic fluid. Although the axial active length of the magnetic fluid can be decreased by increasing the speed of the rotating shaft, the torque increases because of increased friction.

5. Conclusions

The loss of torque on a magnetic fluid seal utilizing the rotating-shaft can be affected by the velocity of the rotating-shaft, the structure of the sealing device, the characteristics of the magnetic fluid, and other factors. It is noteworthy that the viscosity of the magnetic fluid increases with the intensity of the magnetic field within a certain range. When the magnetic fluid is saturated, the torque increase tends to gradually slow down. Although the axial active length of the magnetic fluid can decrease upon increasing the speed of the rotating-shaft, the loss of torque becomes more pronounced owing to increased friction.

Acknowledgments

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