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Using magnetic fluids to improve the behavior of ball bearings under starved lubrication

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ABSTRACT

In this paper, an attempt has been made to use magnetic fluids as lubricant to improve the operation performance of thrust ball bearing under starved lubrication conditions. For this purpose, magnetic field distributed on the raceway was generated by permanent magnet. The anti-spread ability of the lubricant on the bearing race was evaluated by centrifugal experiment. Friction test was performed and the result was presented as the friction moment of the bearing under the limited volume of magnetic fluids lubrication. The preliminary experiments indicate that, magnetic fluids under proper magnetic field can be used to reduce lubricant loss, and thus delay the starvation.

1. Introduction

Loss-of-lubricant operation has become an essential requirement for the transmission system of armed helicopter since lubrication and cooling contributes up to 31% transmission related accidents [1]. It is pointed out that transmission system should function for at least 30 min after complete loss of the lubricant [2]. However, this requirement has not always been met in service for current designs.

Bearings are typical components in the transmission system of helicopter. Low friction, long life, and high reliability are essential properties, which are all related to the lubrication state of the bearings. Under high-speed operating conditions, the starved lubrication usually occurs in rolling contacts, especially for the centrifugal effect [3]. For those bearing tribo-systems without replenishment, maintaining the lubricant in the contact area is particularly important.

Magnetic fluids (MFs) are one of smart colloid materials containing magnetic nanoparticles dispersed in a carrier liquid [4]. Due to the attractive van der Waals forces and dipole-dipole interactions, theses particles are often coated with a layer of surfactant. The carrier liquid can be water, mineral oil, organic solvent, ester, etc., depending on the application. The main properties of MFs are that they possess fluid nature and exhibit magnetic behavior [5]. From the physical point of view, MFs are amusing because they can interact with an external magnetic field [6]. From the lubrication point of view, such interaction may provide a way to keep the fluid in contact area quite easily. Till now, much attention of MFs lubrication was paid on theoretical analysis [7–11] and only a few on experiment. Uhlmann et al. [12] studied the boundary lubrication behavior of MFs using a modified ball-disk tribo-tester. Shahrivar et al. [13] compared the tribological performances of MFs and magnetorheological fluids. Recently, Zhao et al. [14] investigated the hydrodynamic lubrication characteristics of MFs film for spiral groove mechanical seal. Trivedi et al. [15] explored the effect of magnetite (Fe_3O_4) nanoparticles concentration on lubricating properties of MFs and Zin et al. [16] reported the influence of external magnetic field on tribological properties of goethite (a-FeOOH) based MFs. Wang et al. [17] developed a new type of MF for oil-film bearing, which could improve the load-carrying capacity as well as the lubrication performance. Besides, Andablo-Reyes et al. [18] studied the frictional properties of a soft ball-plate contact under restricted MFs supply conditions and pointed out that using MFs was an effective way to improve the lubricant replenishment. Could this mechanism be applied to restrain the lubricant loss from centrifugation and thus avoid starved lubrication for high speed ball bearings? And what is the relationship between the external magnetic field intensity and operation behaviors of the bearings? There is little knowledge about it.

In this paper, attempts have been made to use MFs as lubricant to improve the operation performance of thrust ball bearing under starved lubrication conditions. Firstly, the centrifugal experiments were carried out to evaluate the anti-spread ability of the lubricant on the bearing raceway under different magnetic field intensities. Then, friction tests were conducted to explore the effect of restricted volume of MFs lubrication on starvation control. At last, the influence of magnetic field

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intensity was further examined. During the experimental process, all the results are compared with the behaviors of the traditional oil (carrier liquid of the MFs).

2. Experimental details

Commercial Fe_3O_4-based MFs with the saturation magnetization of 15.9 kA/m are chosen. The average size of the magnetic particle is about 15 nm, with the particle fraction of 4.9 vol% in the fluid. These particles stabilized by oleic acid are dispersed in diester as carrier fluid. The viscosity of the MFs is 79 mPa•s, which is a little higher than that of the carrier liquid (diester, 50 mPa•s).

Thrust ball bearing with the type of SS51104 is used for the centrifugal and lubricating experiments. Two aluminum alloy fixtures were fabricated to clamp the flat rings of the bearing (see in Fig. 1). To generate magnetic field on the surface of the raceway, there were 8 holes (φ 5.1 mm × 6.0 mm) uniformly distributed in the lower fixture and cylindrical NdFeB permanent magnets (magnetic property: 35 MGOe) with three size groups (φ 5.0 mm × 1.0 mm, φ 5.0 mm × 3.0 mm and φ 5.0 mm × 5.0 mm) were implanted into each hole. The end surfaces of the magnets and the fixture were in the same plane by using adjusting rubber gasket. Each group of the magnets was in the same magnetic pole direction. The distribution of magnetic field intensity on the raceway was calculated by Ansys Maxwell ver.16.0 software and the theoretical basis of the calculation is Maxwell equations. Fig. 2 presents the surface magnetic field distributions on the raceway when using the three groups of magnets. Since the geometrical demagnetization factor decreases with the increase of axial dimension of the magnet, the magnetic field intensities (H) covered on the raceway increase with the increasing thickness of the cylindrical magnets. The maximum values on the raceway were $H_1 = 65$ mT, $H_3 = 120$ mT and $H_5 = 140$ mT for the magnets with different thicknesses.

The anti-spread ability of the lubricant on the raceway was evaluated by centrifugal experiments. At the beginning, a certain quality of lubricant (0.04 ml) was dropped on the raceway of a ring. Then, the ring clamped in the fixture with 8 magnets was revolved by a horizontal rotating platform at different speeds for 2 min. During the rotation process, part of the lubricant will spread and be thrown off the raceway. The quality of the lubricant remained on the ring surface was regarded as the anti-spread index parameter.

The operation performance of the bearing lubricated with MFs and diester (carrier liquid of the MFs) was carried out on a modified MMW-1 tribo-tester, as shown in Fig. 1. The fixture clamped with the ring below was stationary and the rotating ring above was driven by a belt device. Experiments were performed under the axial load of 800 N with rotational speeds of 800 rpm and 1600 rpm (mean linear velocities of 1.13 m/s and 2.26 m/s) at room temperature. Friction moment was measured by a torque sensor and the temperature variation of the stationary ring was monitored by a thermocouple. The service life of each bearing was defined as the time, when the value of friction moment appeared a sudden increase. Before each test, the bearing parts were ultrasonically cleaned in acetone for 5 min followed by purified water and then dried in oven at the temperature of 50 °C. The dosage of lubricants used in each test was strictly controlled at 0.04 ml and 0.02 ml, respectively. To ensure reproducibility of the results, each experiment was performed for three times. After that, the bearing parts were cleaned ultrasonically in acetone. The worn surfaces of the ring were analyzed by an optical microscope (Keyence Corp., Japan) and surface profilemeter (Bruker Corp., USA).

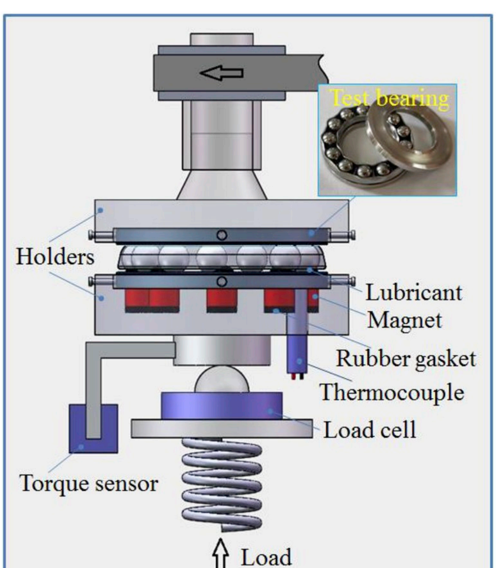

Fig. 1. Schematic diagram of the tribo-tester.

3. Results and discussion

Fig. 3 presents the images of the two groups of centrifugal experiments. To improve shooting effect, red colorant was added into diester. At the lower rotational speed of 400 rpm, most of the diester maintained on the raceway and no obvious spread was observed. With the increase of the speed, liquid mainly accumulated at the fringe of the ring and the film thickness on the raceway decayed drastically. As the speed over 1000 rpm, only very few of the lubricant left on the surface.

However, the anti-spread ability of MFs improves significantly under magnetic field. Due to the magnetic field distribution on the raceway (see in Fig. 3), MFs went to the place with the strongest magnetic field and stayed there. As can be seen from the original image in Figs. 3 and 8 drops of MFs were naturally formed and positioned on the raceway. Below 1200 rpm, compared with the centrifugal force, the magnetic force played a leading role. Most of the MFs were restricted at the initial locations and few of the fluid spread along the raceway. While further increasing the speed, the centrifugal force began to dominate the dynamic process and the volume of the MFs drops reduced gradually. Despite that, 8 small MFs drops can be faintly visible on the ring surface after undergoing the speed of 1800 rpm.

Fig. 4 shows the specific relation between the residual mass of the lubricants and rotational speed. As can be seen, the carrier liquid remained on the ring surface decreased with the increasing speed. Only 12.5 wt% of the liquid was maintained on the ring surface at the rotational speed of 800 rpm. While using MFs, the anti-spread ability was mainly relied on the external magnetic field and the residual mass remained constant when the speed was lower than 800 rpm. It indicates that the anti-spread ability of MFs may indeed be improved by the assist of magnetic field. For the raceway with the lower magnetic intensity (H_1), the residual mass started to decrease at the speed of 800 rpm. And the critical speed shifted to 1200 rpm when the higher magnetic intensities (H_3 and H_5) were applied. It indicates that the stronger magnetic fields may enhance the anti-spread ability of MFs on the ring.

For MFs, each particle can be regarded as a thermal activated permanent magnet in the carrier liquid. When subjected to a magnetic field, the magnetic moment of particle will align with the direction of the external field, inducing a magnetic body force in the fluid [19]. And the mechanism is involved in the transformation of the forces on individual magnetic particles to the bulk of the fluid. In macroscopic view, the magnetic field pulls the MFs drops firmly on the ring surface against throwing away. In the micro, the body force is conducive to enhance the cohesive energy in the fluid and prevent the drops from spreading. As is known, the relation between the magnetic body force and the magnetic field is linear [19]. Therefore, higher magnetic field maintains more fluid on the ring surface. Besides, the viscosity of the MFs will increase under the influence of magnetic field [20] and the enhanced viscosity may also obstruct liquid migration induced by centrifugal effect. When

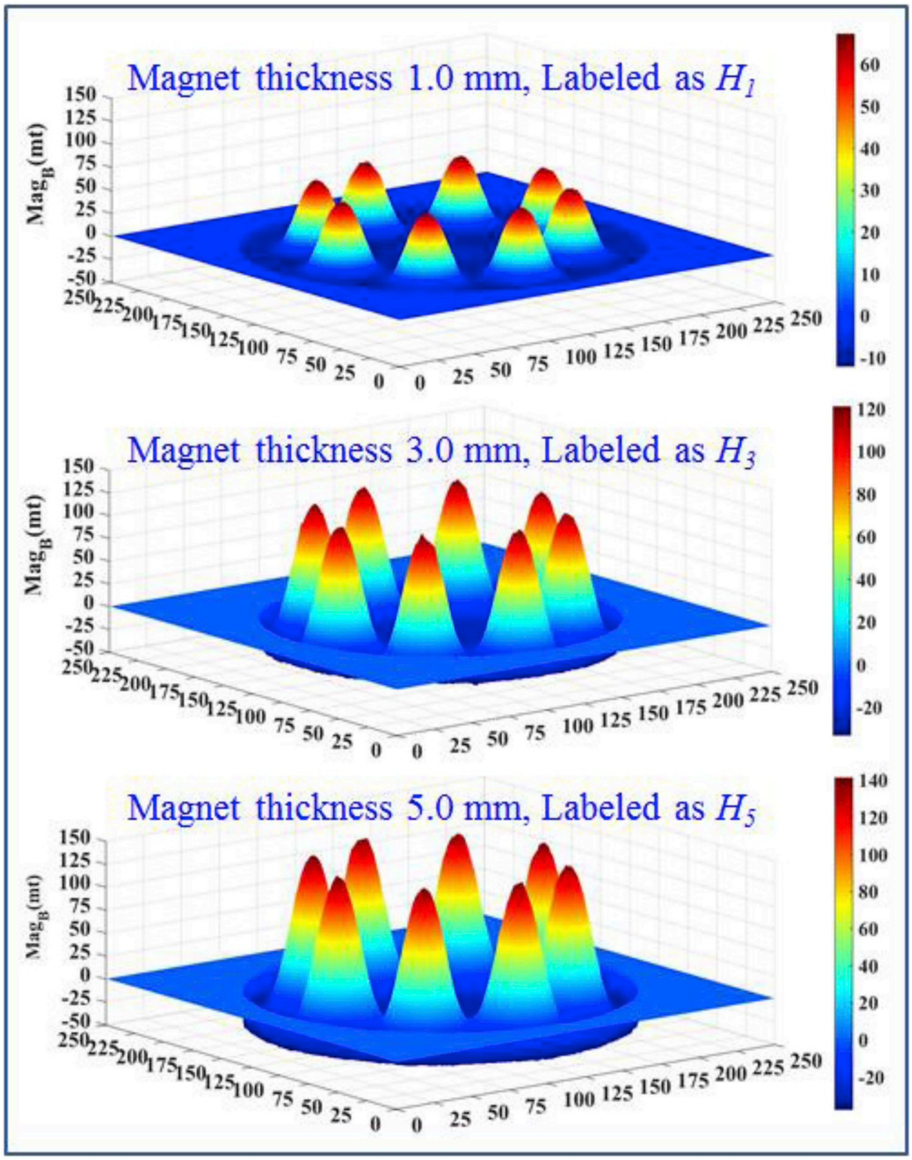

Fig. 2. The distribution of the magnetic field intensity on the ring surface with different cylindrical magnet thicknesses.

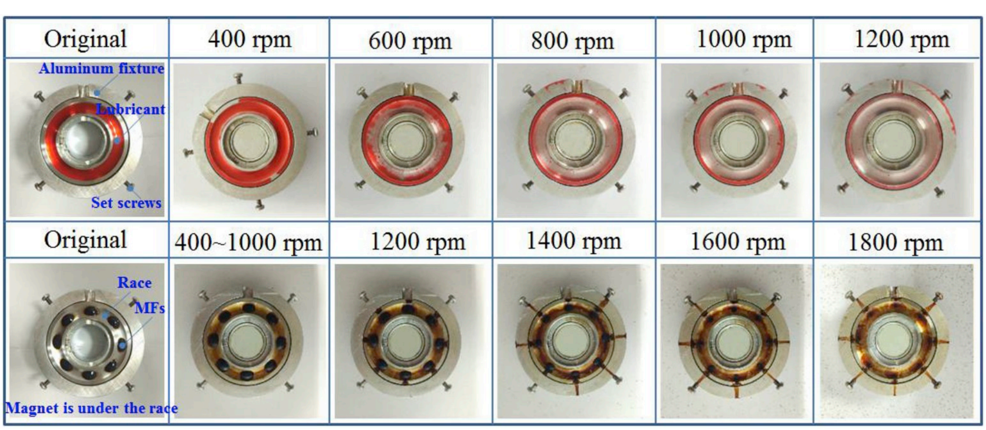

Fig. 3. Images of the lubricants on the race before and after 2 min rotation test at different speeds. (The race of the bearing was clamped in the aluminum fixture. There were 8 holes uniformly distributed in the fixture and cylindrical magnets were implanted into each hole. The magnetic field intensity on the race surface was 120 mT and 8 MFs drops were absorbed on the race surface.)

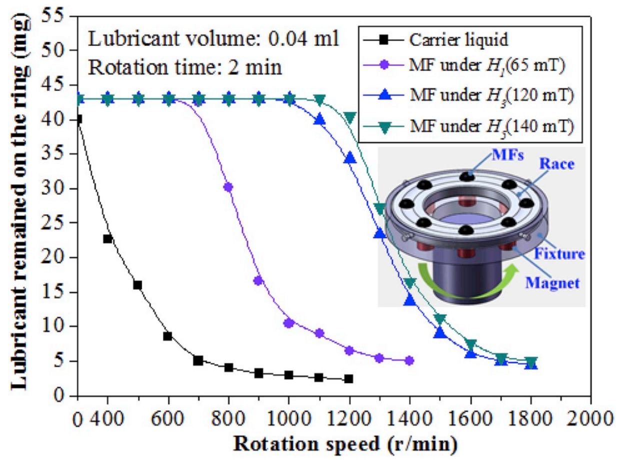

Fig. 4. The relation between the residual mass of the lubricants and rotation speed.

further increase the rotational speed, the balance between magnetic and centrifugal forces is broken and the MFs escape from the ring surface gradually.

Fig. 5 expresses the evolutions of friction moment curves of bearing lubricated with carrier liquid and MFs, respectively. Since the carrier liquid remained on the ring tends to be stable at the speed of 800 rpm (see in Fig. 4), the rotational speed of 800 rpm is chosen for the friction tests with the lubricant volume of 0.04 ml. As can be seen, the initial friction moment was about 30 N•mm for the carrier liquid lubrication. The value decreased slowly and kept in stable-state after running in for 104 s. While using MFs as lubricant, low friction moment of about 0 was achieved during the total test time and the reason may attribute to the rolling effect of the magnetic nanoparticles [15,21]. As mentioned in ref. [21], the Fe_3O_4 particles in the carrier liquid are nearly spherical in nature. Thus, the magnetic particles will enter between the bearing ball and the race surfaces and act as micro rolling elements. Therefore, friction mode of the bearing changes from macroscopic rolling friction into a mixture of macroscopic and microscopic rolling frictions both. As a result, the bearing lubricated with MFs presents lower friction moment. In addition, the particles in the fluid work as spacers and partly eliminate the direct contact between the raceway and balls. Thus, the width of the wear track lubricated with MFs reduced obviously compared with that lubricated with carrier liquid.

Due to the low and stable friction moments presented in Fig. 5, it can be deduced that under this experimental condition (rotational speed:

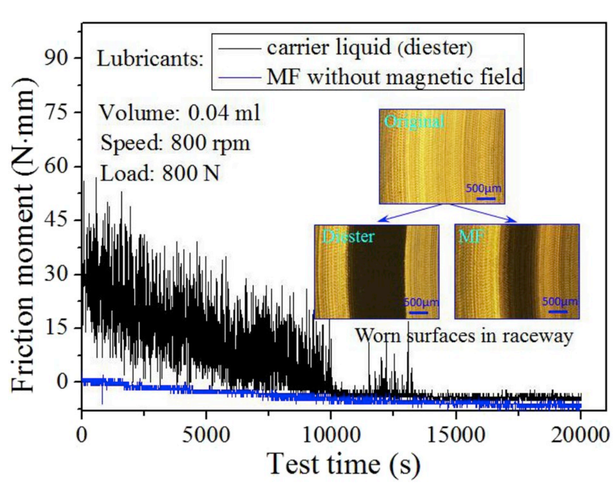

Fig. 5. Evolutions of friction moment curves of bearing under fully lubrication of carrier liquid and MF, respectively.

800 rpm, lubricant volume: 0.04 ml), the lubrication is still valid and the bearing operates in the fully lubricated regime when experienced 2×10^4 s test time. To distinguish the relative merits of the lubrication modes, a harsh condition of higher speed and less quantity of lubricant (rotational speed: 1600 rpm, lubrication volume: 0.02 ml) was applied for the further tests.

Fig. 6 shows the evolutions of friction moment and temperature (raceway surface) curves of bearing operated under harsh condition. For the four situations, the friction moments presented stable at the very beginning and then expressed a sudden increment after a short period of time. Meanwhile, the noise rose significantly. Such phenomenon usually means lubricant insufficient or starvation. The inflection point of temperature was always accompanied by the increase of the friction moment. As expected, the fastest rising of the moment was observed for the dry friction condition, shown in Fig. 6 (a). Although lubricated with 0.02 ml carrier liquid, friction moment of the bearing still rose after running for 300 s (see in Fig. 6(b)). Similar phenomenon was also found for MFs lubrication except the lower friction moment at the beginning (see in Fig. 6(c)). Based on the centrifugal experiment, it is known that 95 wt% of the carrier liquid escaped from the ring surface at the rotational speed of 800 rpm (see in Fig. 4). Thus, at the higher speed of 1600 rpm, starvation may occur in contact elements followed by a quick lubrication failure. Comparing the results in Fig. 6 (c) and (d), it was noted that though the stable operation time extended a little as the lower magnetic field of H_1 was applied, starvation can not be avoided.

The starved lubrication can also be confirmed from the images of the worn surface, depicted in Fig. 7. Compared with the original one, the raceways of the four rings exhibited different levels of wear. For the dry friction condition, severe plastic deformation, adhesion and heavy peeling phenomena were observed, indicating adhesive wear mechanism. As the lubricants used, wear as well as deformation in the races was eased obviously. However, the damage and wear were relatively serious compared with that of the flooded lubrication (see in Fig. 5). Fortunately, obvious reduction of wear could be found when applying a magnetic field (H_1) and the ring presented a much flat and smooth race according to the 3D image and profile. Such result side confirms that magnetic attraction can improve the anti-spread ability of MFs and retain more lubricant in the contact zone at higher speed.

To figure out the effect of magnetic field, operation behavior of the bearing lubricated with MFs under different magnetic fields were conducted further. As presented in Fig. 8, the lifetime of the bearing under MFs lubrication enhanced obviously compared with the original bearing system. With the increasing magnetic field intensity on the raceway, the stable operation time of the bearing was prolonged in general. Compared with the lower magnetic field (H_1), the failure time increased by 4.4 times when the higher magnetic field (H_5) was applied. Besides, the temperature rise also slowed down. As is known, the low temperature is beneficial to the chemical stability of the MFs' carrier liquid and it may also inhibit permanent magnet demagnetization, which helps to absorb more MFs in the friction area. Therefore, the experimental results reveal an improved lubrication state in the ball-race contacts. As mentioned above, the anti-spread ability of the MFs on the ring enhanced with the increased magnetic field (see in Fig. 4). Thus, it is natural to extend the lubricant-off survivable capability of the bearing as the higher magnetic fields applied. Though the starvation failed to be avoided, the design of MFs lubrication assisted by magnetic field can provide an increased life for bearings.

Fig. 9 summarizes the stable operation time of the bearing under harsh condition and the data are extracted from the results in Figs. 6 and 8. It seems that, compared with dry friction, the conventional lubricant plays a limited effectiveness under such harsh condition to avoid starvation. When MFs serves as lubricant, the appearance time of starvation can be delayed by the assisted of external magnetic field. The higher of the magnetic field intensity is, the longer of the stable running time it appears. It is suggested that MFs associated with proper magnetic field can be used to reduce lubricant loss, and thus delay the starvation.

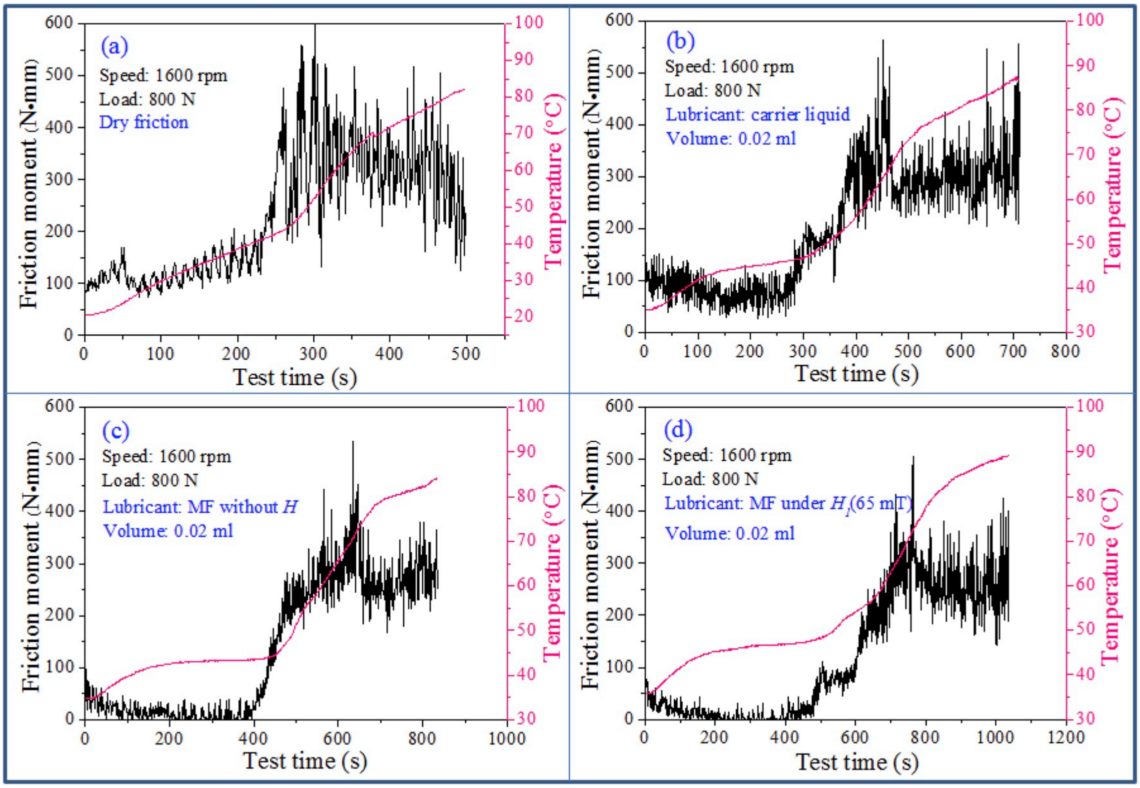

Fig. 6. Evolutions of friction moment and temperature curves of bearing under harsh condition (the pink line represents temperature) (a) dry friction, (b) and (c) lubricated with carrier liquid and MF, (d) lubricated with MF under magnetic field. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

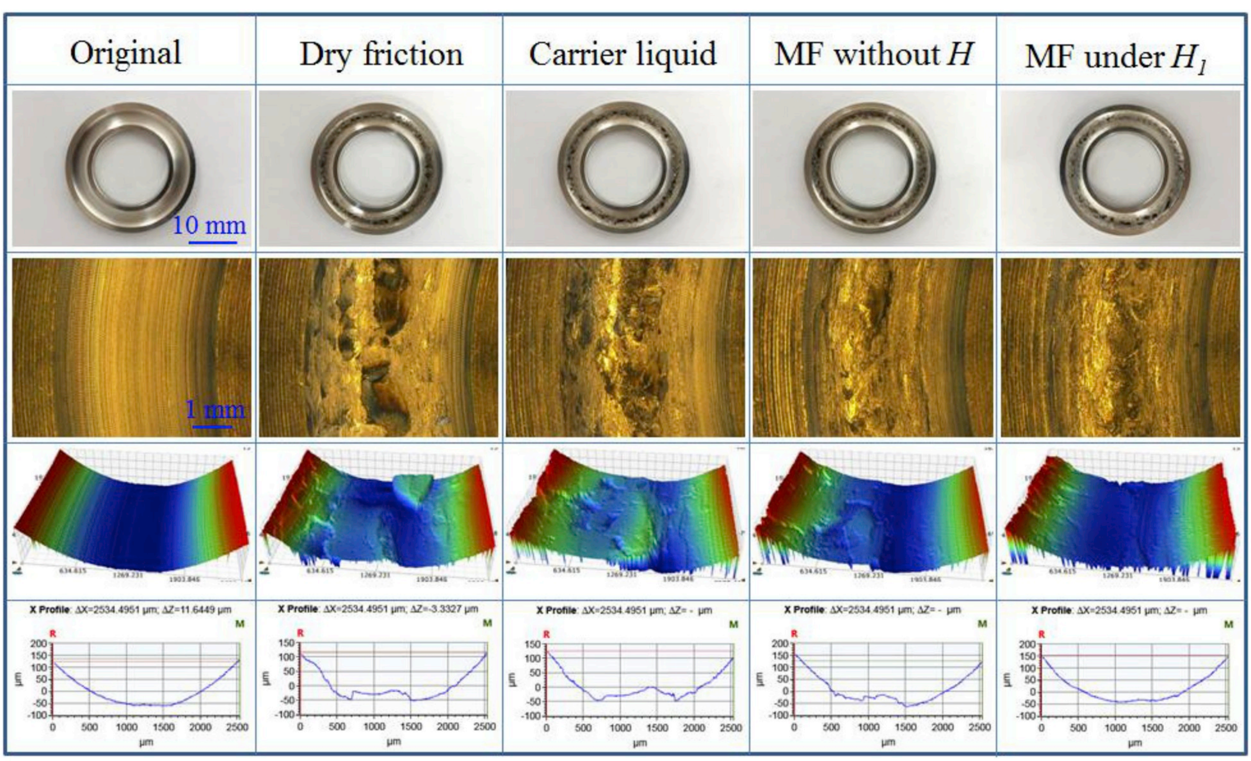

Fig. 7. Images of the worn surface in the raceway and corresponding 3D profiles.

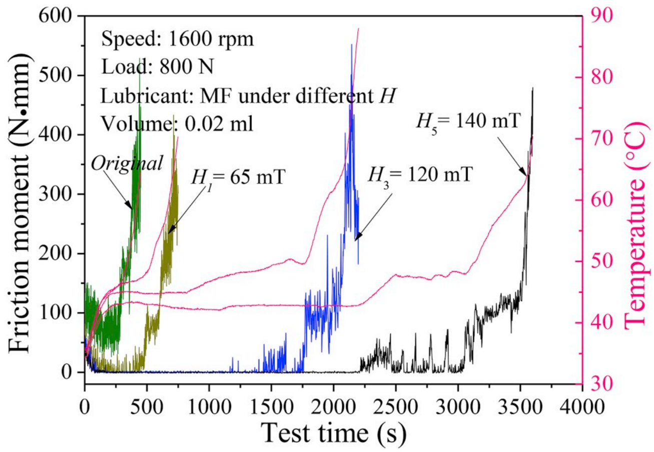

Fig. 8. The effect of magnetic field on the MF lubrication under harsh condition (The original bearing system lubricated with diester for compassion.).

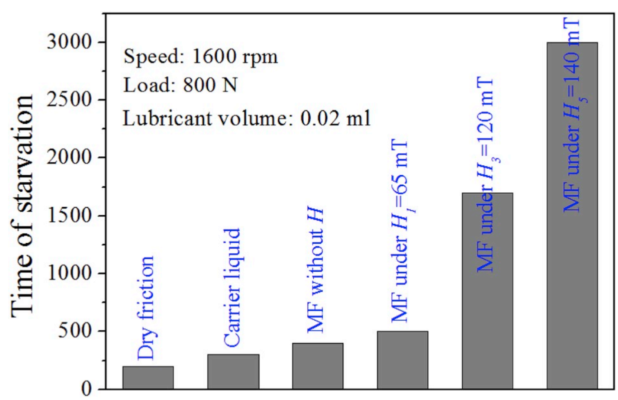

Fig. 9. Summary of the stable operation time of the bearing under harsh condition.

4. Conclusions

Starvation is usually occurred in bearing tribo-systems. In this paper, taken account of the controllability of MFs, using MFs as lubricant to control starvation was proposed. A thrust ball bearing was chosen to carry out the centrifugal and lubricating experiments. The preliminary experiments indicate that, under the magnetic fields, MFs could easily be controlled in mechanical contacts and delay the starvation. The specific results can be summarized as:

(1) Compared with conventional lubricant, MFs absorbed by magnetic field can be restricted on the ring surface at higher rotational speed. Besides, such anti-spread ability of MFs improves with the increase of the magnetic field intensity.
(2) Under the low speed and fully lubricated conditions (speed: 800 rpm, lubricant volume: 0.04 ml), the friction moment of the bearing remained stable and no starvation was observed after running for 2×10^4 s.
(3) Under harsh condition (speed: 1600 rpm, lubricant volume: 0.02 ml), all the bearings experienced lubricant starvation. However, due to the improved anti-spread ability of MFs under magnetic field, lubricant starvation can be delayed.

Acknowledgements

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