Study of Flow Characteristics of Lubricant in Spiral Groove Bearings by the Fluorescent Method

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Abstract

The hard disk drive spindle is one of the critical mechanical components in hard disk drives (HDDs). It has great influence on overall performance, including track density, data transfer rate, energy consumption and noise, etc. Nowadays, HDDs with higher density and speed, larger capacity and smaller size are under active development. This requires that HDD spindles have fast rotating speed, excellent accuracy and small size. However, ball bearing spindles, which are widely used in current HDDs, cannot meet these requirements. HDD spindles supported by oil-lubricated spiral groove bearings are considered to be a candidate to replace ball bearing spindles. There is no oil supply device in the bearing, and the flow characteristics of the lubricant in the bearing have a great effect on the performance of the spindle.

In this paper, the fluorescent method is used to study the flow characteristics of lubricant in a spiral groove bearing. The establishment and recovery of the lubricant film during start/stop of the spindle are observed. The effects of working conditions on the thickness and distribution of the lubricant film are investigated. The influence of oil supply on the performance of the bearing is also studied.

Keywords

Flow characteristics, Fluorescent method, Hydrodynamic bearing

Introduction

The fluorescent method was invented in the 19th century and has been described and used by many investigators. With the development of laser techniques, microprocessors and electronic devices, the fluorescent method has become an important and effective spectral analysis method and has been widely used in film thickness measurement. Smart and Ford[1] brought forward a principle of measuring the film thickness of a rotating cylindrical surface by the fluorescent method. Ford and Ford[2] simplified the optical system and added fluorescent dyes to the lubricant to increase the intensity of the fluorescence. This expanded the application range of the fluorescent method. Ting[3] measured the film thickness between a piston ring and cylinder wall using the fluorescent method. Hou[4] proposed a method for calibrating the film thickness between the piston ring/cylinder wall. Tanimoto[5] used a highly sensitive film to observe the distribution of lubricant on a disk surface. Inagaki[6] replaced the photoelectric cell by CCD camera to obtain information from a small area. The greatest advantage of CCD is that it can collect information over an area without the necessity for a scanning system. Du[7] developed a fluorescent measurement method for EHL film distribution and studied starved lubrication of oil and grease under point contacts.

In this paper, the fluorescent method is adopted to study the flowing characteristics of the lubricant in spiral groove bearings used in hard disk drives. Great progress has been made in hard disk drives (HDDs) in increasing storage capacity and reducing both size and access time in recent years. However, ball bearing spindles cannot meet the requirements of the development of HDD because of high non-repeatable runout, large size and short lifetime at high speed. Recently, many HDD companies and spindle motor manufacturers have been looking for a substitute for ball bearings. Ku[8] compared the dynamic characteristics of HDD spindle motors supported by ball bearings and hydrodynamic bearings. Zou, Meng and Wei[9] studied the dynamic characteristics of the spindle systems supported by spiral groove bearings and investigated the influence of running speed, load and lubricant. It was found that hydrodynamic liquid lubricated bearings are promising candidates to replace ball bearings due to their excellent dynamic characteristics. Because of the limit space, there is no oil supply device in the bearing. Therefore, the flow characteristics of lubricant in the bearing have great effect on the performance of the spindle.

These researchers studied either air or oil lubricated spiral groove bearings. In their analysis they assumed, during operation, that the bearing is fully separated by an oil film or air film. In the present research, there is no oil supply system. During operation the bearing is lubricated by both air and oil. The fluorescent method is used to study the flow characteristics of the lubricant in the bearing. The establishment and recovery of the lubricant film during start/stop of the spindle are observed. The effects of working conditions on the thickness and distribution of the lubricant film are investigated. The influence of oil supply on the performance of the bearing is also studied.

Experimental setup

The experimental setup is shown in Figure 1. For the mechanical part of the setup, the spindle was driven by a motor, whose running speed was adjustable. The magnet. 2, can move up and down to change the gap between the magnet and the steel nut, 11, so as to change the load applied to the spindle. In the optical part of the setup, the light from the lamp passes through the lens and then the irradiation filter. 7. The central wavelength of the irradiation filter is 442 nm, which corresponds to the absorption wavelength of the fluorescent dye coumarin-6, used in this test. After passing through the irradiation filter, only the light with a wavelength of 442 nm remains. This light is reflected to the interface of the thrust bearing by the light beam separating filter, 9. After being irradiated, coumarin-6 produces an emission light with central wavelength of 496 nm. The emission light passes through the separating filter and the emission filter, which has a central wavelength of 496 nm. The images are collected by CCD and then sent to the computer for further processing.

The size and detailed structure of the spiral bearing is shown in Figure 2 (see page 28). Here, the upper thrust disk is made of glass so that we can observe how the lubricant flows between two surfaces. This is one of the main advantages of optical methods (i.e., visibility). But it is also a limitation of optical methods because one of the surfaces must be transparent. We know that the properties of glass are different from those of stainless steel. However, for the flow characteristics of lubricant, the effect of using glass is expected to be small. Therefore, we can neglect the effect caused by the material change.

Calibration of the lubricant film thickness

Figure 3 (see page 28) shows the schematic for the fluorescent method. A certain kind of fluorescent coumarin-6, is added into the lubricant. An inspiring light is used to
number of grooves \( k = 12 \)
groove depth \( h_0 = 10 \mu m \)
axial gap \( b = 5 \mu m \)
inner radius \( r_1 = 4.5 \text{ mm} \)
outer radius \( r_2 = 9 \text{ mm} \)
\( r_0 = 5.8 \text{ mm} \)
spiral groove angle \( \alpha = 12.1^\circ \)
groove width \( a_1 = a_2 \)
bearing material: stainless steel 1Cr18Ni9Ti

irradiate the fluorescent dye in the lubricant, which then gives off emission light. The intensity of the emission light has a direct relationship with the lubricant film thickness. After calibration, we can obtain the film thickness of the lubricant.

The lubricant film thickness calibration device is shown in Figure 4. The substrate and the glass plate are made of the same materials and with the same surface finishing as the thrust bearing used in the spindle system. The lubricant and the fluorescent dye are also the same as used in our test. Here, the lubricant is SIO4. The viscosity of SIO4 at 20°C is 22 mPa.s. The fluorescent dye is coumarin-6. The wavelengths of its irradiation and emission light are 442 nm and 496 nm, respectively. A block is placed between the glass plate and the substrate to form a wedge shape. The length and the height of the wedge are known. Thus we know the film thickness at each point. Then the whole calibration device is placed under the optical system and the image of the emission light is collected (shown in Figure 4). The image was processed by computer and the relation between the intensity of the emission light and the film thickness was obtained as follows:

\[ h = 0.1848 \times (I - 16.5) \]

where \( h \) is the film thickness in \( \mu m \) and \( I \) is the digitized intensity of the emission light ranging from 0 to 255.

**Results and Discussions**

**Establishment of lubrication film at startup**

Figure 5 shows the flow of lubricant during the startup of the spindle. Here the load is 1.0 N and the steady state rotational speed is 3000 rpm. Figure 5(A) shows the image when the spindle is not rotating. The bearing surfaces are separated by a full oil film. At the grooves, the film is thicker. Therefore, the intensity of the emission light is higher. Figure 5(D) shows the image when the spindle runs at the steady state speed. From Figure 5(A) to Figure 5(D), we can see the pump-in effect of the spiral grooved bearing clearly. When the spindle starts up, the lubricant moves toward the center of the bearing and forms an oil ring around the axis. There is a round lubricant/gas interface. Within the interface, the bearing surfaces are separated by oil. Outside the round interface, the two surfaces are separated by air. The oil ring and the gas film share the whole load.

**Recovery of lubrication film at stop**

Figure 6 shows the recovery of the lubricant film after the spindle stops. Figure 6(A) shows the image when the spindle runs at the working speed and then stops suddenly. Figure 6(A) to Figure 6(D) show the entire recovery process of the lubricant film after the spindle stops. It is interesting to see the oil, which was pumped to the center, spread out gradually along the ridges between the spiral grooves. However, the oil cannot return to the spiral grooves because of the surface tension of the oil. The edge of the spiral grooves is very clear. The recovery of the lubricant film is very important for the start/stop performance of the spindle. When the spindle stops, there is still a lubricant film between the two surfaces that can prevent direct contact and avoid wear.

**Effects of running speed on flow characteristics of lubricant**

Figure 7 shows the effect of running speed on oil film thickness within the oil ring. The axial load is 1.0 N. The running speed of the spindle varies from 0 rpm to 4500 rpm. The film thickness of the oil ring is measured at the position that is in the middle of the inner edge and the oil-air interface. The readings are taken from the same position when the running speed changes. From Figure 7 we can see that, with the increase of the running speed, the film thickness of the oil ring decreases gradually. This is because the faster the spindle runs, the further the oil will be pumped to the center. The oil ring becomes smaller and smaller. The area of the oil that shares the load decreases, while the area of air increases. Therefore, the entire film thickness decreases.

**Effects of oil supply on flow characteristics of lubricant**

Although there is no oil supply device in the spindle system, we still want to know how oil supply affects the flowing characteristics of the lubricant (see Figure 8 on page 30). Here, load is 1.0 N and rotating speed of the spindle is 3000 rpm. Figure 8(A) shows the image when the spindle runs at working speed. In Figure 8(B), we add some oil on the edge of the disk. We can see that there is a bright ring around the outer side of the disk. Some of the oil is pumped to the center and the oil ring around the center becomes brighter and larger. Figure 8C shows that more
and more oil is pumped in and the outer edge of the disk becomes dark again. Finally, in Figure 8(D) we can see that the oil ring returns to its original status as in Figure 8(A). From the study we can see that if there is an continuous oil supply, the bearing will be fully lubricated by oil. However, when oil supply is stopped, air will be pumped in and the bearing will be lubricated by oil and air together. If the working conditions remain the same, the amount of the oil between the two surfaces is fixed. The extra oil will be spun away from the gap.

Conclusions
In this paper, the flow characteristics of the lubricant in spiral grooved bearings without an oil-supply system are studied. Conclusions from this study are as follows:

- The lubricant is pumped in when the spindle starts up and forms an oil ring around the center. When the spindle runs at a stable condition, the oil ring remains stable. There is an interface of oil and air. The load is shared by an oil and an air film.

- When the spindle stops, the lubricant spreads out along the ridges between the spiral grooves, but it does not enter the grooves. The recovery of the lubricant is very important for preventing wear.

- When the running speed of the spindle increases, the film thickness decreases. This is due to the decrease of oil film area and the increase of air film area.

- For the bearing without an oil supply, the amount of the oil that can be contained in the bearing is fixed if the working conditions remain the same. However, if there is an oil supply, it will greatly change the flow characteristics of the lubricant in the bearing.

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References


