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DYNAMIC CHARACTERISTICS OF LIQUID CRYSTAL FILM IN A SLIDE BEARING UNDER ELECTRIC FIELD

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ABSTRACT

This paper describes the viscosity variation of a liquid crystal under electric field, and its application to a controllable sliding bearing. Liquid crystal is known as a homogeneous organic liquid characterized by the long-range order of its molecular orientation. When an electric field is applied to a liquid crystal film as lubricant, the orientational order of molecules become parallel to the applied field, whch causes apparent viscosity variation. In this paper, a controllable slinding bearing system was constructed and its dynamic characteristics were studied. When step load or sinusoidal load was applied to the bearing pad, the film thickness was successfully controlled by a conventional PID controller. The response frequency was also studied in the experiment.

KEYWORDS

Liquid crystal, Fluid lubrication, Electroviscous effect, Control, Step bearing

INTRODUCTION

Sliding bearings support the applied load by the pressure produced in lubricating oil or air which is subjected to shear deformation [1],[2]. In such sliding bearings, there is a gap between lubricated surface, and the friction force in lubricated sliding bearings is far smaller compared with the friction in ball bearings. Though sliding bearings are superior to ball bearings from the viewpoint of friction force, the lubricating condition in sliding bearings may be strongly governed by the design of bearing assembly and their operation conditions. The lubricating film thickness may be varied by the fluctuation of applied load, sliding velocity, temperature of lubricating oil, etc.

One of the primary factors which give influence on the lubricating condition is the viscosity of lubricant which has been thought to be invariable under constant temperature and normal pressure level. We aim to control the viscosity of lubricant by the external signal introducing liquid crystal as lubricant in sliding bearings.

Liquid crystal is known to show Electrorheological (ER) effect under some electric field. The molecular shape of liquid crystal in nematic phase is considered to be elliptic cylinder and its primary direction of molecules can be controlled by the applied electric or magnetic field, and rheological properties varies in accordance with the field strength. It is also known that the main axis of molecules coincides the shear direction on lubricated surface, which induces decrement of the friction force without any electric nor magnetic field. In this sense, liquid crystal is superior to any other luburicating oil.

In the present paper, a small size model of sliding bearing system with liquid crystal was manufactured and dynamic characteristics of liquid crystal film was examined experimentally. When some fluctuating load was applied to the sliding bearing, the film thickness was controlled by the applied electric voltage to the bearing surfaces. The applied voltage was controlled by a conventional PID controller, and the film thickness was tried to be kept constant even when the applied load to the bearing was varied. The friction force variation by the applied electric field strength was also studied.

LIQUIDCRYSTAL

Liquid crystal is an organic liquid characterized by the ‘long-range’ order of its molecular orientation [3],[4]. This molecular orientation changes in either of two ways, in a certain range of concentration and in a certain range of temperature, resulting in two types of liquid crystal referred to as lyotropic and thermotropic liquid crystal, respectively. Liquid crystal is also classified into high and low molecular weight types. A finer classification is made on the basis of the structure of molecular orientation. Two models of typical phase are shown in Fig. 1, nematic and smectic phases, and the rest two are known as cholesteric and discotic phase.

The most popular and mass-produced liquid crystal is low molecular-weight nematic or smectic phase one which has cylindrical and ellipsoidal shape. The isotropic shape and particular structure of liquid crystal molecules generate some directional properties in viscosity, optical properties, or dielectric constant. The major axis of each molecule has tendency to line up in the same direction statistically due to the interaction of each molecules. And it is known that the surface of partition walls give the influence on the direction of molecules within some distance from the walls and that the direction can be controlled by the applied electric or magnetic field.

In the application of liquid crystal as a lubricant, the orientation of molecules may reduce the friction force between the surfaces, and the magnitude of friction may vary according to the direction of molecules. With the aid of the magnitude of friction force and the shear rate, equivalent viscosity can be evaluated. The viscosity of nematic phase liquid crystal is known to be anisotropic, and three limiting viscosities, called Miesowicz viscosities, have been defined for the three typical orientations of liquid crystal molecules in relation to the shear flow, as shown in Fig. 2. Miesowicz viscosities generally increase in the order of $\eta_1 > \eta_3 > \eta_2$. When the director of the molecules is controlled by applied electric field, the viscosity may vary from η_1 to η_2.

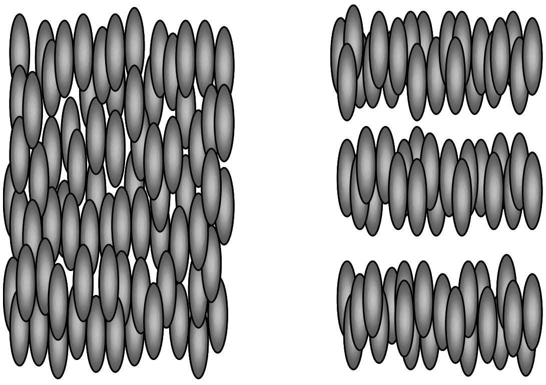
(a) Nematic (b) Smectic

Figure 1 Molecular models of liquid crystal

The liquid crystal used in the present study is a mixture of thermotropic liquid crystals of nematic phase, and originally developed for displays of computers or television sets. The main component is cyano-phenyl-cyclohexanone, whose molecular structure is shown in Fig. 3. As shown in this figure, benzene nucleus and cyclohexane are banded together directly as a main part of the molecule, connected by cyano and alkyl on both sides. The bending stiffness of the main part of a molecule in mechanical sense is said to be large enough to represent rod-like structure, where we have no tool to evaluate the stiffness at this time. Electric anisotropy is caused by the difference of electric properties of molecules connected at each side, and because of this electric anisotropy, molecular orientation can be controlled by the applied electric field.

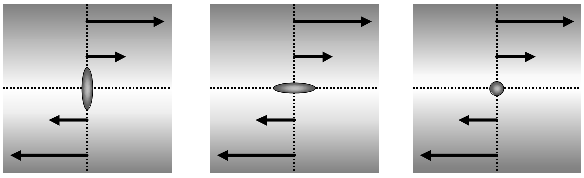
(a) η_1 (b) η_2 (c) η_3

Figure 2 Miesowicz viscosity

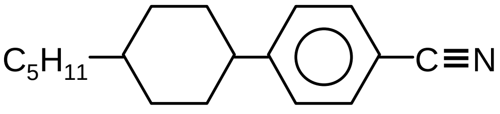

Figure 3 Molecular structure of a specimen

Table 1 Characteristics of a specimen

Clearing point	70℃
Melting point	-6℃
Viscosity (@20°C)	28 mPa·s
Dielectric anisotropy ($\Delta\varepsilon$)	10.3
$\varepsilon_{/\!/}$	15.0
$\varepsilon_{\perp}$	4．7

Typical properties of the present liquid crystal are shown in Table 1. Clearing point means a transition temperature where turbid liquid becomes isotropic and consequently optically clear. The temperature where the solid of liquid crystal changes into a rather turbid liquid, is called melting point. Between the temperature range of clearing and melting point, the mesophase is thermodynamically stable. When external electric field is applied, the dielectric anisotropy of liquid crystal which is defined as the subtraction of the dielectric constant parallel to the major axis from that perpendicular to the axis, is one of the most important properties.

RHEOLOGICAL PROPERTIES OF LIQUID CRYSTAL

The typical electroviscosity of test sample measured by the rotational-type viscometer is shown in Fig. 4. The viscosity began to increase when the electric field strength reached a value of a few hundred V/mm, followed by a sudden rise in viscosity with a further increase in the electric field strength. Finally, the viscosity asymptotically reached a constant maximum value. Increasing the shear rate did not affect this pattern in the viscosity-electric field strength relationship; only a higher electric field strength was needed to reach a constant viscosity level. The observed pattern can be explained in relation to Miesowicz viscosity shown in Fig. 2.

EXPERIMENTAL SETUP

One of the simplest shapes of slide bearings may be a step bearing. It has a step around the middle of bearing pad in the sliding direction, and the pressure produced in the lubricant has triangular distribution. The position of peak pressure coincides the location of the step. The geometry of step bearing and the pressure distribution are shown in Fig.5.

According to the basic theory of lubrication, the load capacity per unit width of a step bearing is

$$P = \frac{3(a-1)k(1-k)}{a^3(1-k)+k} \cdot \frac{\eta U B^2}{h^2} = C_p \cdot \frac{\eta U B^2}{h^2} \qquad (1)$$

where η is viscosity of lubricant, U is sliding velocity, B is length of bearing pad, and h is minimum film thickness. C_p is called ‘load factor’ and a and k are shape parameters defined as shown in Fig.5. It is well known that the load factor reaches a maximum when the shape parameters are a = 1.87, and k = 0.72 for step bearings[2]. In the present experiment, k was set to 0.5 in order to eliminate the moment around the horizontal axis perpendicular to the sliding direction.

The step height was set to 0.1 mm, because the experiment will be conducted under the condition that the minimum film thickness should be set around 0.1 mm. Though the minimum film thickness varies due to the experimental condition, the shape parameter a will be around 2.0. The width of sliding pad is 20 mm, and the length is also 20 mm.

The sliding pad was made of insulator, while copper films as electrode were attached on the surface of the pad upward and downward of the step independently. Applying some electric voltage to one or both of the copper films, the liquid crystal as lubricant was subjected to electric field perpendicular to flow direction. The lubricant was supplied by dripping just upward of the bearing pad.

The experimental setup including the bearing pad is shown schematically in Fig. 6. The step bearing pad was set on a rotating disk driven by a variable-speed motor. The bearing pad was supported by two leaf springs deformable just in horizontal direction, and the bearing pad including the leaf springs could rotate in vertical direction around the center of the shaft set at the supporting point of weighting system. The static load was applied to the

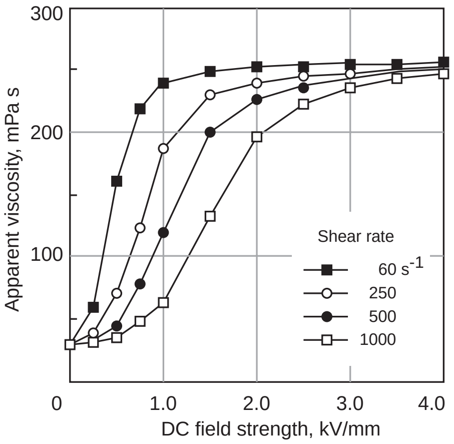

Figure 4 Apparent viscosity as a function of DC field strength under various shear rates

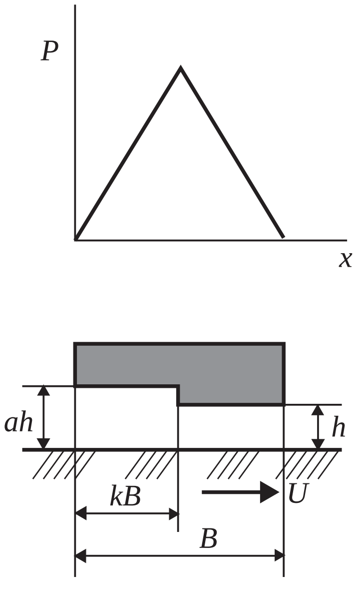

Figure 5 Step bearing and pressure distribution

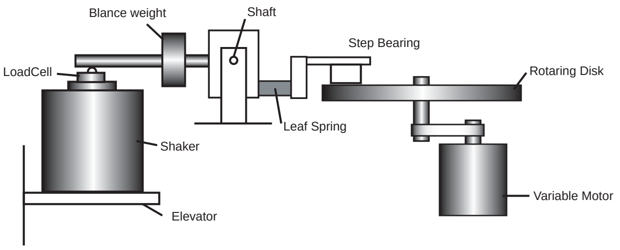

Figure 6 Experimental setup

bearing pad by setting a weight at the end of the torque arm, where a balancing weight was set at the other side of the arm. For applying fluctuating load to the sliding bearing, a magnetic exciter was installed at the end of the rod through a load cell. There were four kinds of weights, from 10 to 173 g. The diameter of rotating disk was 260 mm, and the bearing pad was set at 100 mm apart from the center of the disk. The lubricant was dripped 20 mm upward of the pad.

The film thickness of liquid crystal was measured by four eddy-current displacement sensors equipped at the corners of bearing pad. When the disk rotation was stopped and the bearing pad was slightly pressed against the disk, the film thickness (i.e. the distance between the surface of the disk and the bearing pad) was set to zero. The friction force acting between the disk and the bearing pad was measured from the strain on the leaf springs. All the data from the sensors were put into a personal computer through an A/D converter and proceeded by a conventional PID control algorithm.

RESULTS AND DISCUSSIONS

Typical properties under constant electric field

Before evaluating the properties of the bearing with liquid crystal as lubricant under some control system, the typical properties have been investigated under electric field. The film thickness and friction force were measured under constant electric field, and the applied voltage was changed stepwise from zero to 1,500 V, at the interval of 50 V. The rotating speed of disk was set to constant, and the temperature of lubricant was estimated to be constant at room temperature.

The film thickness variation under electric field is shown in Fig.7, under various applied constant load to the bearing pad. Under the applied voltage from zero to 0.4 kV, the film thickness decreased to some extent, followed by increase of the thickness with higher voltage. After the film thickness took the maximum under electric voltage of around 1.2 kV, it decreased as the applied voltage increased. This result was observed regardless of the magnitude of applied load.

The experimental results shown in Fig. 7 may be caused by mainly the force balance between Coulomb force and pressure variation due to viscosity increase. When the applied voltage is low, under 0.4 kV, the viscosity increment in electroviscosity effect is small as indicated in Fig. 4, compared with the increase of Coulomb force between the surfaces. Because Coulomb force acts as attraction force between the surfaces, the film thickness may be decreased. Further increase of applied voltage causes reversed relation between two forces, and the film thickness is increased due to viscosity increment. Beyond the applied voltage of 1.2 kV, the electroviscosity effect is decreased comparatively again, and the film thickness may be decreased. When the applied load to the bearing pad is increased, the film thickness curve shifted to downward almost in parallel. It is shown experimentally that the film thickness can be varied by the applied electric voltage to liquid crystal as lubricant.

The friction force variation under electric field is shown in Fig.8. The friction force was increased gradually as the electric voltage was increased. Further increase of electric voltage caused sudden rise of friction force, and approached to a maximal. The typical properties shown in Fig. 8 agree well with the results of viscosity variation as

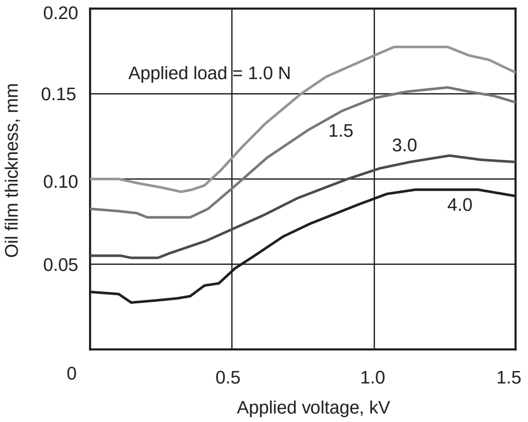

Figure 7 Oil film thickness as a function of applied voltage

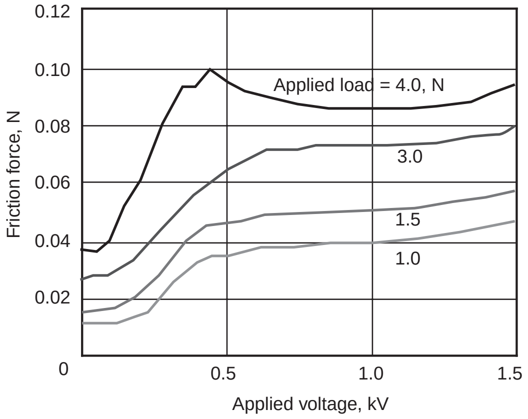

Figure 8 Friction force as a function of applied voltage

shown in Fig. 4 qualitatively. When the applied electric voltage wa high, the friction force decreased to some extent especially under large applied load, the cause of which is not revealed in this experiment.

Two identical electrodes are attached separately to the surface of step bearing, and the location effects of applied voltage to the film thickness were investigated. Three cases, voltage was applied to just inlet-side, just outlet-side, and both electrodes, were examined. When voltage was applied to both electrodes, the film thickness was increased largest of the three cases. In the case when just inlet-side electrode was effective, the film thickness was also increased, but the effect was less than that in the previous case. In the following experiment, the electric voltage was applied to just inlet-side electrode.

Film thickness control experiment

Control experiment was conducted to keep the film thickness to the appointed value regardless of the applied load variation. A controller should be constructed in addition to the experimental system shown in Fig. 6. A conventional PID controller was introduced because it is considered as one of the most reliable controller for linear systems. The required applied voltage was calculated by PID algorithm, based on all the signals from displacement sensors on the bearing pad and strain gauges on the leaf springs put into the personal computer through an A/D converter. The voltage signal was generated through a D/A converter set on the computer, and amplified for the signal for the step bearing.

When the applied load to the bearing pad was changed stepwise from 1.5 to 3.0 N, the time response of film thickness variation under constant disk rotating speed is shown in Fig. 9. The appointed film thickness was set to 0.1 mm. The result under constant voltage was also shown for comparison. As shown in Fig.9, the film thickness was controlled successfully, converged to the appointed value in 0.2 s after the sudden change of applied load.

A sinusoidal load was applied to the bearing pad by the magnetic exciter, and the results are shown in Fig.10. The frequency was set to 5.0 Hz. Before the controller started, the bearing pad was supported by the pressure produced in the lubricant and the film thickness fluctuated according to the applied load. The average film thickness was around 0.05 mm. After the controller started at 5.0 s, the film thickness was successfully controlled to 0.08 mm, which was set to the controller in advance. At the same time, the control voltage from the controller started to fluctuate synchronized to the frequency of the applied load. The upper limit of output from the amplifier was 1.0 kV, so the control voltage was also limited to the same value, as shown in Fig. 10.

The results by a sinusoidal load swept from 1.0 to 25.0 Hz are shown in Fig.11. While the film thickness fluctuated synchronized to the applied load around 0.04 mm without any control signal, the film thickness was well controlled around 0.08 mm with control signal. Under 5.0 Hz, the film thickness variation was limited up to 0.005 mm.

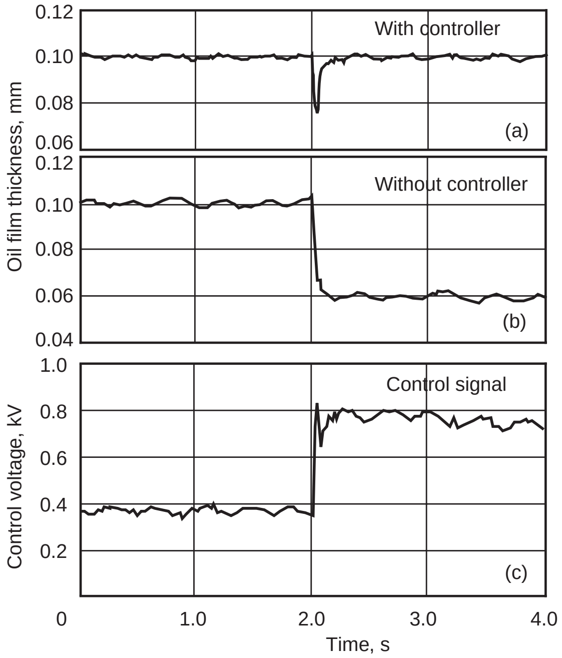

Figure 9 Oil film thickness with and without control under step load on the bearing

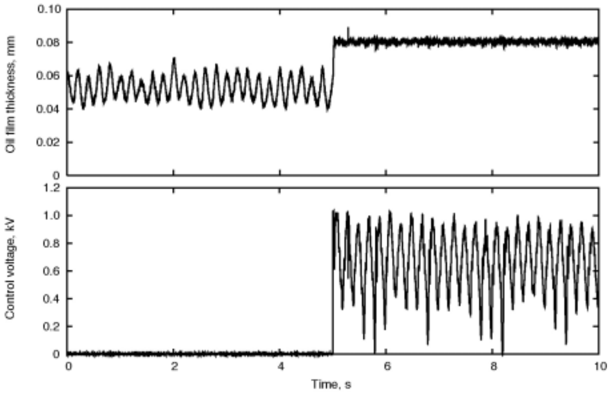

Figure 10 Oil film thickness with and without control under sinusoidal load on the bearing

The variation amplitude was well controlled up to 15 Hz by this control system compared with the results without the control signal. This may be caused by the output limit from the amplifier, and time history of the control signal had already reached to this limit around 10 Hz, as shown in Fig.11.

CONCLUSIONS

In the present paper, the control experiments of lubricating film thickness was conducted, in which liquid crystal was introduced as lubricant and electric field was applied to liquid crystal in order to control the viscosity of lubricant. Liquid crystal has a great advantage in applying to lubricating fluid, because the friction force may be decreased by the molecular orientation expected especially near the surface of bearings without any field. In addition to that, the viscosity can be varied by the applied electric field strength.

In fact, liquid crystal is generally very expensive, and it cannot be used as lubricant for general purpose. But it is shown that the state of lubrication can be controlled by external signals experimentally in this system, which is expected as a turning-point in introducing such control system in fluid lubrication problems.

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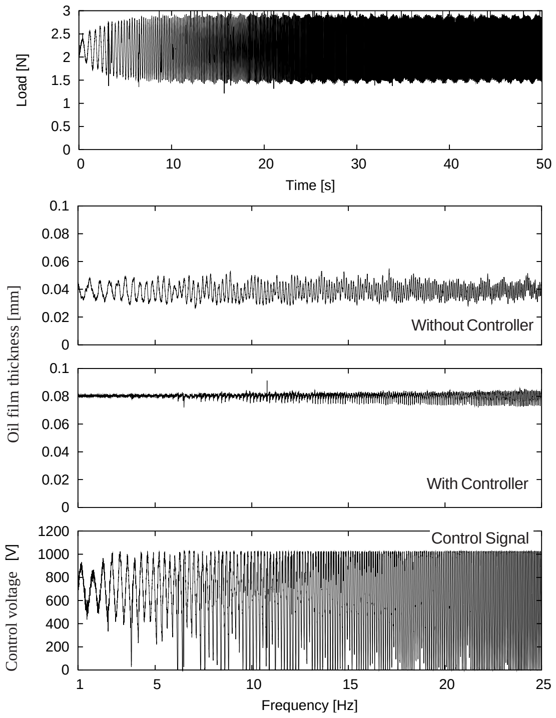

Figure 11 Results under sinusoidal applied load swept from 1 to 25 Hz