Development of an Oil-Air Lubrication System with a Piezoelectric Nozzle for Machine Tool Spindles*

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Oil-air lubrication is an effective lubrication method for the high-speed spindle of machine tools. However, the rate of oil supply to the bearing fluctuates markedly due to intermittent oil supply from the oil-air mixing valves. In this study, a new oil-air mixing apparatus is developed by applying a piezoelectric nozzle which has been used to the printing head of ink-jet printers. By using the piezoelectric nozzle instead of the conventional mixing valve, fluctuation of the oil supply is successfully controlled. Further, it becomes possible to attach the oil-air mixing equipment in the vicinity of the bearings. The oil supply rate can be, therefore, quickly changed in response to changes in the running condition of the bearing.

Key Words: Bearing, Machine Tool, Oil-Air Lubrication, Piezoelectric Nozzle, Oil Supply Rate

1. Introduction

Lubrication is one of the important parameters affecting the performance of high-speed spindle systems in machine tools. Grease lubrication, oil-mist lubrication, oil-air lubrication and jet lubrication have previously been applied to the spindle systems. In particular, oil-air lubrication has been frequently applied to high-speed spindle systems, because this lubrication method is free from air contamination with oil mist, and the make-up of the lubrication equipment is relatively simple. The temperature rise in oil-air lubrication⁽¹⁾⁽²⁾ and optimization of lubrication systems have also been reported⁽³⁾. In the oil-air lubrication method, a very small quantity of oil is intermittently injected at the oil-air mixing valve into the oil-air feeding tube, and the injected oil is supplied

to the bearings with through high-speed air flow. These intermittent oil injections cause fluctuation in the rate of oil supply to the bearings. In order to suppress this fluctuation of oil supply, an oil-air feeding tube is inserted between the mixing valve and the oil-air supply nozzle in the vicinity of the bearing. The intermittent oil flow is gradually averaged as the oil is carried along the inner wall of oil-air feeding tube to the bearing.

Fluctuation in the oil supply rate causes a change in the bearing temperature and disturbs the stable operation of the spindle system. In order to suppress this fluctuation attempts have been made to extend the length of the oil-air feeding tube⁽⁴⁾⁽⁵⁾. However, the use of a long oil-air feeding tube between the mixing valves and the bearings causes a time lag in the oil supply; moreover, the installation of a long tube into the spindle system is often a problem itself.

To decrease the fluctuation of the oil supply, decreasing the volume of the oil spurt and increasing the spurt frequency at the mixing valve are procedures. However, difficulties are often encountered because the spurt volume and spurt frequency are limited by the dimension and mechanism of the

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mechanical injector. These difficulties are eliminated by the application of the new oil-air mixing equipment developed in this study, which applies a piezoelectric nozzle used for the printing head of ink-jet printers.

2. The Construction of New Oil-Air Mixing Equipment with a Piezoelectric Nozzle

The construction of the piezoelectric nozzle used in this study is schematically shown in Fig. 1. A cylindrical piezoelectric device is bonded to the outer face of a glass pipe. The volume change in the glass pipe occurs by charging the electrical voltage to the piezoelectric device, and the oil drops spurt from the orifice. The frequency of the oil spurt can be varied by adjusting the frequency of the charged voltage.

The diameter of the spurted oil drop is influenced by the viscosity of the oil, the orifice diameter and the amplitude and frequency of the charged voltage. The effect of the spurt frequency on the diameter of the oil drop is shown in Fig. 2. The viscosity of the oil in this example is $22 \times 10^{-2} \text{ m}^2/\text{s}$ (40°C), which is the same as that commonly used by conventional oil-air lubrication systems, and the charged voltage is 0-400 V which is the same as that in the ink-jet printer. The

Fig. 1 Diagram of the piezoelectric nozzle

Fig. 2 The effect of the spurt frequency on the diameter of the oil drop

diameter of the oil drop is calculated from the weight of the oil which is saved in a vessel for a given amount of time and measured. The diameter of the oil drop decreases with the increase of the spurt frequency. When the orifice diameter increases, the diameter of the oil drop also increases.

A test was carried out for the various viscosities presently in use (i.e., 10cSt-30cSt). Within this given range, an oil drop (100-140 μm in diameter) was continuously spurted in response to the charged electrical pulse. The volume of the spurted drop was about one thousand times smaller than that of the conventional oil-air system (about 1.34 mm in diameter). Therefore, the spurt frequency was expected to increase by using the piezoelectric nozzle instead of the conventional mixing valves. New oil-air mixing equipment developed in this study is illustrated in Fig. 3. A piezoelectric nozzle is fixed to the inside of an acryl resin pipe in the axial direction. When pressurized air is supplied to the equipment, the pressure in the acryl resin pipe becomes higher than that in the oil feeding tank. In order to suppress the reflux of air into the piezoelectric nozzle, the acryl resin pipe and the air feeding tank are connected by a back-pressure pipe whose inner diameter is 2 mm. The oil-air supply nozzle is directly attached to the top of the oil-air mixing equipment, i.e., it is not connected to the oil-air feeding tube.

The fluctuation of oil supply was quantitatively investigated and the results were compared with the case of a conventional oil-air supply system. A hygroscopic roll of paper was fed at a fixed speed (5 mm/min) through the system. An oil-air supply nozzle was attached perpendicularly 5 mm above the paper surface. The oil-air flow was sprayed on the paper forming a belt-shaped oil-blot. The fluctuation of the oil supply rate was evaluated by measuring the time-dependent variation of the width of the oil blot. This measurement was also carried out in the same manner for the conventional type system. In this latter case, an oil-air feeding tube about 4 m long was

Fig. 3 The piezoelectric oil-air mixing apparatus

connected to the oil-air mixing valve while the oil spurt volume of the mechanical injector was set to 0.01 cm^3 which is the minimum value available commercially. The orifice diameter of piezoelectric nozzle was $106 \mu\text{m}$.

The result of the measurement is shown in Fig. 4. The vertical axis of the figure indicates the proportion of amplitudinal variation of the oil blot width (ΔW) to the average value of the oil blot width (W_m). A larger value of $\Delta W/W_m$ signifies a larger fluctuation of oil supply at the oil-air supply nozzle. The fluctuation of oil supply decreases when the piezoelectric mixing apparatus is used. When a small oil supply rate is employed, the fluctuation is successfully suppressed, while the conventional system shows a significant increase in the fluctuation level. This difference in the fluctuation level is due to the difference of the oil spurt frequency. For example, in order to obtain an oil flow rate of $0.5 \text{ cm}^3/\text{hr}$, the oil spurt frequency of the piezoelectric mixing apparatus rises to about 120 Hz while it rises only to 0.024 Hz for the conventional apparatus. In the case of piezoelectric mixing apparatus, it is unnecessary to rely on the averaging effect of the oil-air feeding tube.

3. Application to the Test Spindle System

The performance of the newly developed piezoelectric oil - air system was tested by installing it on the test spindle system shown in Fig. 5. An angular contact ball bearing (JIS : 7011C), whose inner diameter and outer diameter are 55 mm and 90 mm respec-

tively, was tested. A ISO-VG22 grade spindle oil was prepared as the lubricant. The preload (thrust load) on the bearing was adjustable. The pivot of the load cell could be pressed to the center of the bearing cap by rotating the screw plate attached to the load cell. The temperature of the test bearing was detected by a CC-type thermocouple attached to the outer face of the outer ring. An acoustic emission sensor (AE sensor) was also attached to the bearing cap in order to monitor the frictional condition between the balls and races. The amplitude level of AE signal was shown to increase when the oil supply became insufficient and the friction increased.

The relationship between the oil supply rate and the bearing temperature rise is shown in Fig. 6. The result obtained by the conventional oil-air system is also indicated. Similar behavior of the bearing temperature is noted between the piezoelectric type and the conventional oil-air system.

The bearing temperature, amplitude level of the AE signal and preload (thrust load) on the bearing

Fig. 4 The effect of the oil supply rate on the fluctuation

Fig. 5 The test spindle system

Fig. 6 The relationship between the oil supply rate and the temperature rise of the bearing

change in response to the change in the oil supply rate are shown in Fig. 7 and Fig. 8. In the case of the conventional oil-air system (Fig. 7), the interval between oil spurts is changed at $t=0$ from 16 min to 1 min; that is, the oil supply rate is increased 16 times. Corresponding to this change in the spurt interval with the conventional system, the spurt frequency in the piezoelectric mixing apparatus is also changed at $t=0$ from 9 Hz to 130 Hz (Fig. 8). After the oil supply rate increased at $t=0$, the amplitude level of the AE signal decreases because the oil film thickness between the rolling elements (balls) and outer race and inner race increases. The bearing temperature then rises due to the increase in the amount of viscous friction. With the conventional oil-air system, the response of the bearing temperature and AE level in terms of the change in the oil supply rate is lower compared to the piezoelectric type. In the case of the piezoelectric type, these changes in the bearing performance appear immediately after the change in oil spurt frequency. However, it takes more than twenty minutes to encounter a similar response in the conven-

Fig. 7 The change in the bearing performance due to the increase in the oil supply rate (conventional oil-air system)

Fig. 8 The change in the bearing performance due to the increase in the oil supply rate (piezoelectric mixing apparatus)

tional oil-air system. This time lag is due to the existence of the long oil-air feeding tube used in the conventional oil-air system.

4. Control of Oil Supply Rate by Monitoring the AE Amplitude

It is expected that the piezoelectric oil-air system can produce finer and more rapid control of the oil supply in ball bearings as compared with the conventional system. Therefore, control of the oil supply rate by monitoring the AE amplitude was attempted.

The construction of the control system proposed in this study is illustrated in Fig. 9. The system was composed of an AE monitoring system, a piezoelectric oil-air supply system and a 16-bit micro-computer system. The lubrication condition in the test bearing was monitored by an AE sensor attached to the bearing cap of the test spindle system (see Fig. 5). The amplitude of the AE signal was introduced into the microcomputer through a band-pass filter (100 kHz-1 MHz), a full wave rectifier and an A/D converter. The detected AE amplitude was compared with the standard level of AE amplitude which corresponds to the desirable lubrication condition. When the detected AE level became higher than the standard AE level, the oil spurt frequency was increased in order to provide sufficient lubrication. The spurt frequency was increased gradually until the detected AE level decreased to the standard level. Conversely, if the detected AE level becomes lower than the standard AE level, the oil spurt frequency will be decreased.

In Fig. 10, the preload on the bearing is increased

Fig. 9 The construction of the control system for oil supply

Fig. 10 An example of the control of the oil supply

from 400 N to 800 N at $t=0$. In response to the increase in the AE level, the oil spurt frequency is increased. After about thirty minutes, the AE level returns to the initial level.

When the control gain of the spurt frequency becomes excessive instability of the bearing performance results; in contrast, control gain that is too low causes a long response time. Although the optimum amount of gain can be obtained theoretically, the control gain of the spurt frequency is experimentally determined based on the difference between the standard value and the detected value of AE amplitude level.

Even though fine control of the oil supply is useless in practical application of this system, rapid control is necessary for suppressing bearing seizures. In the piezoelectric oil-air system, control of the oil supply is confirmed by monitoring the AE amplitude level as one parameter of the lubrication conditions.

5. Conclusions

In this study, a new oil-air lubrication system was developed by applying the piezoelectric nozzle as the actuator. The performance of the proposed apparatus was evaluated by attaching it to a test spindle system. The conclusions of this study are summarized as

follows.

(1) The fluctuation of oil-air supply rate in the oil-air lubrication system was successfully suppressed by using the piezoelectric mixing apparatus instead of the conventional oil-air supply system.

(2) In the case of piezoelectric oil-air system, it was unnecessary to rely on the averaging effect of the oil-air feeding tube; moreover, it was possible to attach the oil-air mixing equipment in the vicinity of the bearings.

(3) Similar behavior of the bearing temperature was obtained between the piezoelectric system and conventional oil-air system.

(4) By using the piezoelectric oil-air system, it was possible to control the oil supply rate quickly in response to the change in lubrication conditions within the bearings.

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