

Measurement of Oil Film Thickness in the Main Bearings of an Operating Engine using Thin-Film Electrode

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ABSTRACT

Oil film thickness is one of the most important issues for optimization of bearing design. A technique has been developed to measure oil film thickness by noting the change in capacitance between the shaft and a thin-film electrode of several micrometers thickness formed on the surface of a bearing. The authors applied this technique to the main journals of an automobile engine and measured the oil film thickness up to maximum speed and full load. The oil film thickness became thinner with increased engine load, and then turned thicker with increased engine speed.

INTRODUCTION

In recent years, engine power has increased while bearing size has decreased in order to reduce friction and engine size, resulting in an increased need for optimized bearing design. To optimize bearing design, it is essential to clarify the oil film behavior in the bearings under engine operating conditions.

Recent progress in simulation techniques has made it almost possible to clarify oil film behavior in bearings by calculation [1]. However, the engine main bearing load changes as the engine block deforms and the crankshaft rotates, making oil film behavior in the main bearings extremely complex. Actual measurement of oil film behavior is expected to improve the accuracy of oil film behavior simulation. The authors have developed a technique for measuring the oil film pressure distribution in an operating engine main bearing using a thin-film sensor [2]-[4].

Oil film thickness is also a physical quantity having the same importance as oil film pressure for analyzing oil film behavior in engine bearings. Many papers have been published on oil film thickness measurement

results using the gap sensor, laser induced fluorescence (LIF), optical interferometry, and other methods [5]-[8]. These methods, which require probe insertion into sample bearings, are not suited for measuring engine bearing oil film thickness of several micrometers. Because of differences between probe surface and bearing surface properties, probe insertion would negatively affect measurement performance.

The total capacitance method is known as one technique that minimizes the above negative effects, with many papers discussing the results of oil film thickness measurement using this method [9]-[12]. However, the total capacitance method determines the minimum oil film thickness on the assumption that the bearing being measured is completely circular; therefore, this method is unsuitable for measuring oil film thickness on a bearing that is heavily loaded and whose elastic deformation is not negligible.

As an alternative, a measurement technique using ultrasonic waves has been proposed for measuring oil film thickness [13]. In this technique, the transducer is installed on the back side of the measured object, and the oil film thickness is determined from the reflected ultrasonic waves; so this method is also known as a technique that minimizes the negative effects of probe insertion. However, few reports have been written on bearing oil film thickness of automotive engines using the ultrasonic technique. In conclusion, a technique that can reliably measure oil film thickness in engine bearings while the engine is in operation has not yet been developed.

Under these circumstances, we investigated a technique for determining oil film thickness based on the capacitance between the crankshaft and a thin-film electrode formed on the surface of the bearings. This technique does not produce any steps on the bearing surface and enables the probe to

perfectly follow the bearing deformation. This technique was used to measure oil film thickness on a bearing tester and the results were compared with the values calculated based on the elasto-hydrodynamic lubrication theory. The measurement results agreed well with the theoretical values. This technique was also applied to the main bearings of a 1.4 L diesel engine to quantitatively clarify the dependence of oil film thickness on bearing load and engine rotational speed. The results are discussed in this paper.

MEASUREMENT METHOD OF OIL FILM THICKNESS USING THIN-FILM ELECTRODE

Oil film thickness in engine main bearings was determined from the capacitance between the crankshaft and a thin-film electrode formed on the surface of the bearing. Since the thin-film electrode completely follows the bearing deformation, this technique is effective for measuring oil film thickness in engine bearings whose elastic deformation is not negligible. The new oil film thickness measurement technique is hereinafter called the "thin-film method."

THIN-FILM ELECTRODE

The thin-film electrode (Fig. 1) was formed by the sputtering method. In this method, the intermediate layer, insulation layer, and electrode layer were formed one by one on the mirror-polished surface of the sample bearing. The electrode layer was etched to form a certain pattern, and then a protective layer was added. The insulation layer and protective layer were made of SiO_2 . As shown in Fig. 2, to ensure durability of the sensor, an overlay consisting of MoS_2 and resin was formed on the surface as a buffer layer.

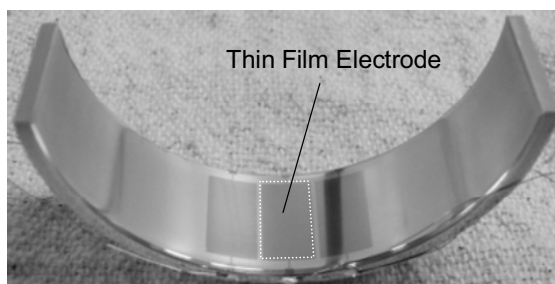


Fig. 1 Bearing appearance before overlay formation

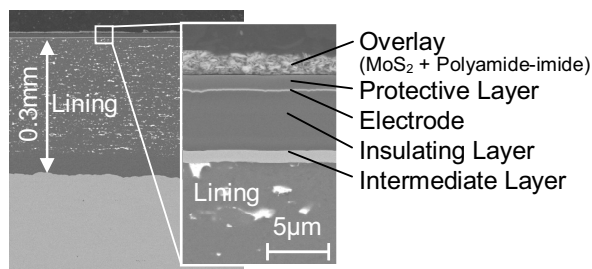


Fig. 2 Partial cross-sectional view of a bearing with thin-film electrode

An example of the thin-film electrode pattern is shown in Fig. 3. This pattern was a 4 mm × 10 mm rectangle, with a 0.2 mm wide lead section extending to the side surface of the metal bearing that is connected to lead wires (enamel wire) on its side surface. The lead section width was determined to be narrow enough to neglect the capacitance produced by the lead section. The shape of the electrode can be arbitrarily changed depending on the measurement objective. Two or more electrodes can be formed on the surface of a metal bearing. It has already been confirmed that an electrode area of at least 10 mm² is enough to measure the change in capacitance.

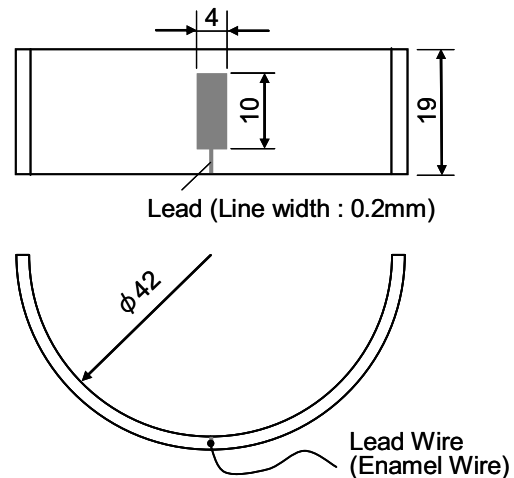


Fig. 3 Example of thin-film electrode pattern

OIL FILM THICKNESS MEASUREMENT METHOD

The oil film thickness h_i can be determined from the capacitance C_{OIL} of the oil film between the thin-film electrode and crankshaft, using the following equation:

$$h_i = \epsilon_0 \epsilon_r \frac{S}{C_{OIL}} \quad (1)$$

where ϵ_0 represents the dielectric constant of vacuum, ϵ_r represents the relative dielectric constant of engine oil, and S represents the area of the thin-film electrode. Since the relative dielectric constant of engine oil is almost independent of temperature (Fig. 4), oil film thickness can be measured independently of the effect of oil temperature. It has also been observed that the relative dielectric constant of engine oil remains virtually constant even when oil pressure changes [9].

However, the dielectric constant of the engine oil is influenced by the amounts of fuel, water, and carbon contamination. To verify these influences, we measured the dielectric constant of the aged oil obtained from an engine that had operated for about 60 minutes. The change in the dielectric constant was 2% or less compared with that of the fresh oil. This confirmed that the influence of contamination is negligible because fresh oil is used in the test.

measurement, and the measurement is completed within 20 minutes.

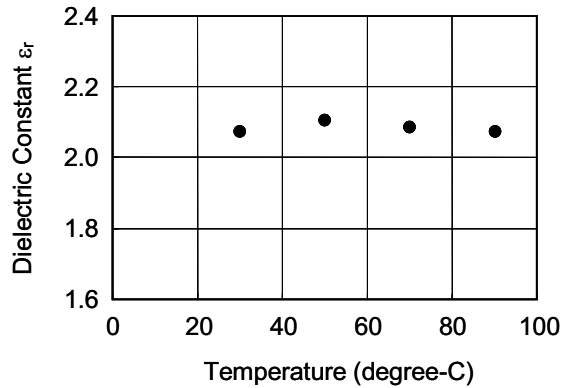


Fig. 4 Dielectric constant of SAE 10W-30 engine oil

The circuit shown in Fig. 5 was used to measure the capacitance. A voltage of 100 kHz AC was applied between the lead wire connected to the thin-film electrode and the lead wire connected to the crankshaft via a slip ring. The capacitance C_M was determined from the voltage obtained by rectifying the above AC voltage. The resistance R was adjusted in response to the magnitude of the capacitance being measured.

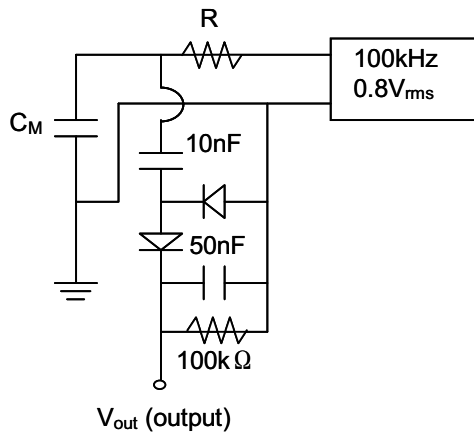


Fig. 5 Capacitance detection circuit

The configuration around the thin-film electrode and the approximate equivalent circuit for actual measurement are shown in Figs. 6 and 7, respectively. The capacitance C_M between the lead wire led from the thin-film electrode and the lead wire connected to the crankshaft can be calculated from the following equation:

$$C_M = C_{INS} + C_{STR} + \frac{C_{OIL} C_{PRO}}{C_{OIL} + C_{PRO}} \quad (2)$$

This equation shows that the capacitance C_M is affected by the capacitance of the oil film to be measured C_{OIL} , the capacitance of the insulation layer and overlay C_{PRO} , the capacitance of the insulation layer C_{INS} , and the stray capacitance of the lead wires

and other devices C_{STR} . The oil film thickness h_i can be calculated from the following equation (3), which can be derived from equations (1) and (2):

$$h_i = \epsilon_0 \epsilon_r S \left(\frac{1}{C_M - C_{INS} - C_{STR}} - \frac{1}{C_{PRO}} \right) \quad (3)$$

When the crankshaft is displaced by nearly its clearance from the thin-film electrode, C_{OIL} will become negligibly smaller than C_{PRO} . Therefore, equation (2) can be simplified as follows:

$$C_M(h_i \approx \text{Clearance}) = C_{INS} + C_{STR} + C_{OIL} \quad (4)$$

In this case, C_{OIL} generated by the 4×10 mm electrode will decrease to as small as approximately 0.02 nF, and this capacitance is little affected by oil film thickness change. Therefore, $C_{INS} + C_{STR}$ can be simplified as follows:

$$C_{INS} + C_{STR} = C_M(h_i \approx \text{Clearance}) - 0.02 \text{ nF} \quad (5)$$

It is expected that the space between the crankshaft and electrode expands to approximately the bearing clearance at least once during one engine cycle, we determined $C_{INS} + C_{STR}$ by substituting the actually measured minimum capacitance in one engine cycle into $C_M(h_i = \text{Clearance})$.

To determine C_{PRO} , we applied conductive paste over the test bearing and measured the capacitance between the paste and the thin-film electrode. We determined h_i by substituting these values into equation (3) and using the capacitance C_M that was measured between the lead wires. Thus, we could determine the oil film thickness that was independent of the effects of the protective layer, stray capacitance, and other factors.

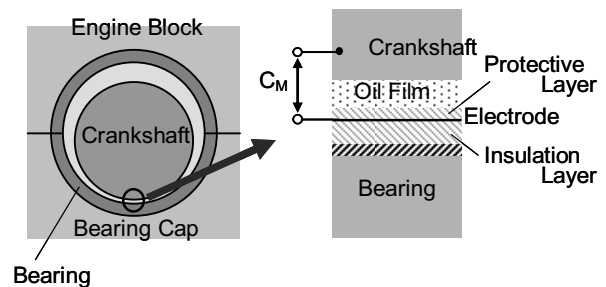


Fig. 6 Schematic illustration of thin-film electrode configuration

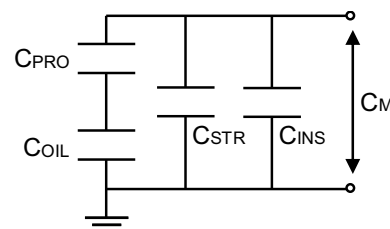


Fig. 7 Approximate equivalent circuit