

Analysis of Oil Film Generation on the Main Journal Bearing Using a Thin-Film Sensor and Elasto-Hydrodynamic Lubrication (EHL) Model

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ABSTRACT

Reducing friction in the crankshaft main bearings is an effective means of improving the fuel efficiency of reciprocating internal combustion engines. To realize these improvements, it is necessary to understand the lubricating conditions, in particular the oil film pressure distributions between crankshaft and bearings. In this study, we developed a thin-film pressure sensor and applied it to the measurement of engine main bearing oil film pressure in a 4-cylinder, 2.5 L gasoline engine. This thin-film sensor is applied directly to the bearing surface by sputtering, allowing for measurement of oil film pressure without changing the shape and rigidity of the bearing. Moreover, the sensor material and shape were optimized to minimize influence from strain and temperature on the oil film pressure measurement. Measurements were performed at the No. 2 and 5 main bearings. Results confirmed that main bearing oil film pressure is primarily influenced by the combustion pressure of adjacent cylinders, but the range of influence varies between bearings. For comparison with measured results, we calculated bearing load and oil film pressure distribution for each bearing. The analysis showed that oil film pressure is affected by housing stiffness and crankshaft bending rigidity, resulting in a different load distribution at each bearing. Analysis also showed that deformation at the sliding surface induces changes in the bearing load distribution in the direction of rotation.

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INTRODUCTION

In recent years, engine components have become compact and lightweight to satisfy fuel efficiency and reduced emissions targets all the while cylinder peak pressures have increased. As a result, oil film pressures on the main bearing have increased, leading to ever more severe lubricating conditions between bearing and crankshaft. The conventional approach to improving lubrication was to expand bearing clearances, optimize bearing shapes, and rely on improved-strength bearing materials. From now on, we will need to understand the main bearing lubrication conditions to achieve low friction between the crankshaft and main bearings while maintaining durability against bearing seizures. In the past, main bearing lubrication has been estimated from oil film pressure experiments [1, 2, 3] and calculations [4, 5, 6, 7, 8]. However, there are few examples of bearing load and oil film

pressure distribution analysis at each bearing. In this study, we applied a thin-film sensor to a fired, 4-cylinder, 2.5 L gasoline engine. Oil-film pressure was measured at No. 2 and 5 main bearings, where the housing rigidity differs due to a difference in material. We also calculated bearing load and oil film pressure distributions using FEM (Finite Element Method) and an EHL (Elasto-Hydrodynamic Lubrication) model to compare with actual measurement results.

THIN-FILM PRESSURE SENSOR

Principle of Measurement

The thin-film sensor uses a metal resistive element with a pressure-dependent electrical resistance. The sensor is connected to a Wheatstone bridge circuit (Figure 1) where voltage changes corresponding to pressure changes are amplified and recorded. The basic principle is the same as for



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a strain gauge. Pressure measurement errors arise if temperature and strain changes induce large resistance changes. So minimizing sensitivity to strain and temperature is an important design objective.

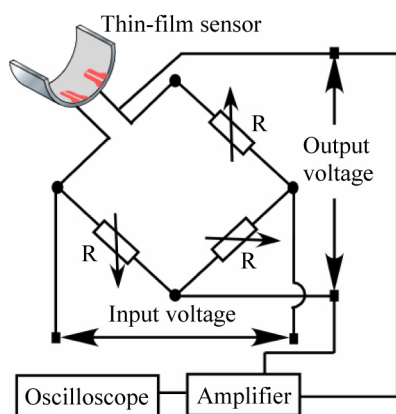


Figure 1. Measurement circuit

Sensor Structure and Shape

Figure 2 shows the structure of the thin-film sensor. The film is deposited together with other isolation films by the PVD (Physical Vapor Deposition) method of sputtering onto the desired location on the bearing surface. The pressure-sensitive Cu-Mn-Ni alloy film (0.2 micron) is sandwiched between an upper 2.0 micron protective film of Al_2O_3 and a lower 3.0 micron insulating film, also of Al_2O_3 , that act to isolate and protect the sensor, and prevent seizures and sensor detachment due to rotating contact with the crankshaft journal.

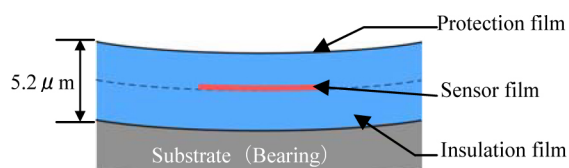


Figure 2. Structure of thin-film pressure sensor

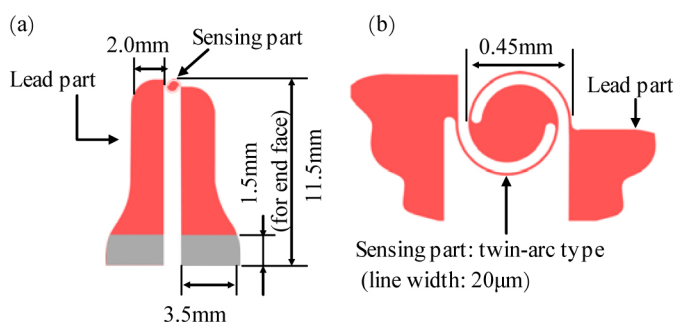


Figure 3. Shape of thin-film pressure sensor

Figure 3 shows the shape of the thin-film sensor. The sensor film is composed of a lead part (a) to lead the signal to the edge of the bearing and a sensing part (b) to detect pressure. The leads have a total length of 11.5mm, a width of 2.0mm at the sensor end, and a width of 3.5mm at the end face. The sensing part consists of two semi-arcs with 0.45mm radius and 20 micron width. The central round area electrically connects the two arcs.

Table 1 compares gauge factor K between straight line type and twin arc type sensors. While the longitudinal sensitivity of a straight line Cu-Mn-Ni alloy is smaller than the commonly used Cu-Ni alloy, its lateral sensitivity is very much larger. On the other hand, when used in a twin arc type sensor, the Cu-Mn-Ni alloy sensitivity is small in both longitudinal and lateral directions.

Table 1. Comparison of gauge factors K

	Straight line type		Twin-arc type	
(Y)				
(X)				
Direction	(X)	(Y)	(X)	(Y)
(a)Cu-Mn-Ni	$K_{swc}=-1.19$	$K_{slc}=0.59$	$K_{twc}=-0.31$	$K_{tlc}=-0.30$
(b)Cu-Ni	$K_{swa}=-0.05$	$K_{sla}=1.95$	$K_{twa}=0.90$	$K_{tla}=0.95$

K_{swc}/K_{swa} : Lateral sensitivity of straight line type

K_{slc}/K_{sla} : Longitudinal sensitivity of straight line type

K_{twc}/K_{twa} : Lateral sensitivity of twin-arc type

K_{tlc}/K_{tla} : Longitudinal sensitivity of twin-arc type

Pressure and Temperature Sensitivity

Pressure sensitivity was measured by placing the sensor in a pressure vessel and noting the change in resistance as a hydraulic pump raised the pressure from 0 to 200 MPa. As shown in Figure 4, the pressure sensitivity is $\alpha_{P20}=18$ ($\mu\Omega/\Omega$)/MPa, achieved with non-linearity and hysteresis under 1%.

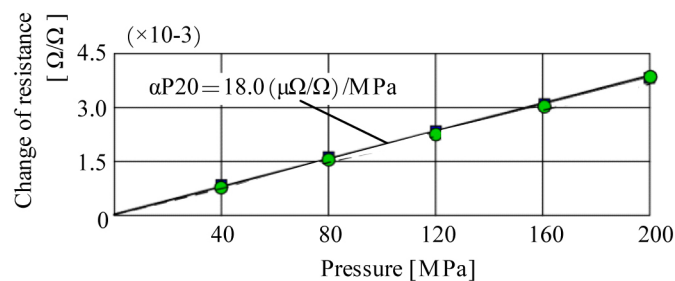


Figure 4. Pressure-output characteristics

Temperature sensitivity was measured by placing the sensor in an oven and noting the change in resistance as the oven temperature was raised from 20 to 120 deg.C. As shown

in Figure 5, the temperature sensitivity of the thin-film sensor is $\alpha_T = 1.0 (\mu\Omega/\Omega)/^\circ\text{C}$. The resulting temperature induced pressure error, 0.06 MPa/deg.C, was judged to be negligible.

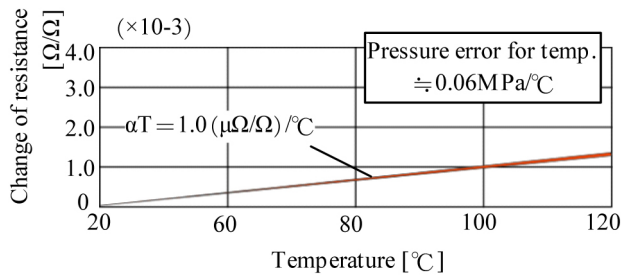


Figure 5. Temperature-output characteristics

TEST METHOD

The in-line, 4-cylinder, water-cooled test engine gets 2,488 cm³ of displacement from an 89 mm bore and 100 mm stroke. The crankshaft is held by a ladder frame against the cylinder block. The aluminum ladder frame has cast-in iron bearing caps at the No. 1, 3, and 5 journals. The main bearings have a width of 20 mm and a shaft diameter of 55 mm with 23 microns of clearance as shown in Table 2. For test conditions, 2000 rpm was selected to represent a speed occurring frequently in market use, and full load was selected to give a high bearing load.

Table 2. Main bearing specification

Item	Value	Units
Shaft diameter	55	mm
Bearing length	20	mm
Diameter clearance	0.023	mm

Measurement Point and Wiring to Outside of Engine

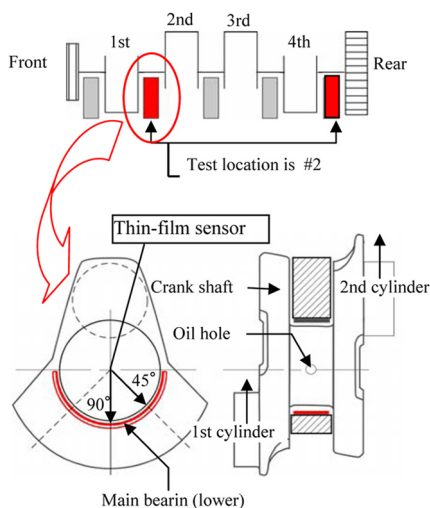


Figure 6. Measurement point of oil film pressure

Figure 6 shows the oil film pressure measurement points at the No. 2 and 5 main bearing bottom halves. The sensitive points of the sensors are located at the axial centers of each bearing, one at 45 degrees, and one at 90 degrees, relative to horizontal.

The thin-film pressure sensor signal lines are connected as shown in Figure 7. At first, the lead film (1) is brought to the bearing edge flange where 50 micron gold wires (2) are connected by spot welding. Next, the copper lead wire (4) is connected through terminal (3) and brought along the wall of the ladder frame (Figure 8) and led outside of the engine where it is connected to measuring instruments.

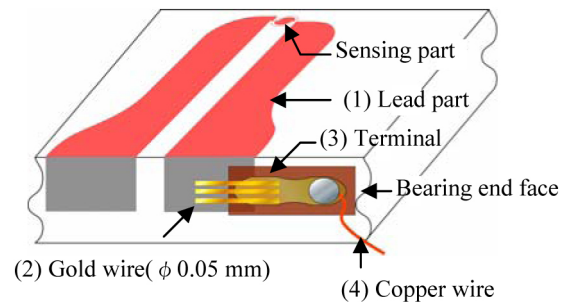


Figure 7. Wiring from thin-film pressure sensor

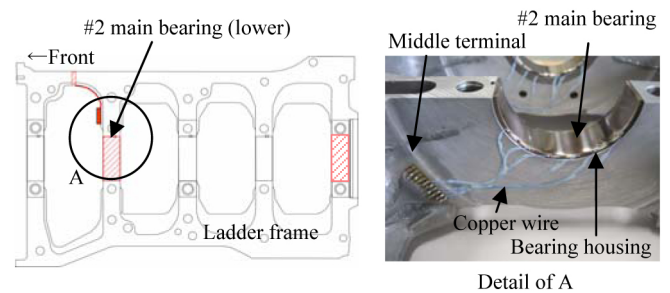


Figure 8. Wiring from main bearing to outside of engine

MEASUREMENT RESULTS

Figure 9 shows measurement results of oil film pressure taken at the 90 degree locations. Measured oil pressure results and cylinder pressure for each cylinder as a function of crank angle. The peak oil pressure is larger for No. 5 bearing than No. 2. Focusing on No. 2 main bearing, the timing of the two main oil pressure peaks correspond to combustion pressure peaks in No. 1 and No. 2 cylinders, the adjacent cylinders on either side of No. 2 main bearing. The oil film pressure for No. 1 cylinder combustion is larger than that for No. 2 cylinder combustion. Presumably, oil film pressure should be equivalent for equivalent combustion pressures if the load for each combustion event were distributed evenly between adjacent main bearings. Therefore, the data suggests that the bearing load distribution is different. A sudden drop in oil pressure can be found near crank angle 0 degree. This measured pressure drop occurs when the oil hole in the crank journal passes over the thin-film sensor. Focusing on No. 5