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Oil Film Thickness Measurement of Engine Bearing and Cam/tappet Contact in an Automotive Engine

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Abstract—The capacitance technique was used to measure the minimum oil film thickness in engine bearing and the central oil film thickness between cam and tappet. This method is based on the measurement of total capacitance of oil film. For the measurement of the oil film thickness between cam and tappet, two surfaces were assumed to be flat and parallel within the Hertzian region and all the measured capacitance originated from this region. Shear rates from the measured minimum oil film thickness are over 10^6 sec^{-1} in the greater part in both two cases. The minimum oil film thickness in engine bearing is larger than the surface roughness. Between cam and tappet it is mostly smaller than the surface roughness. In spite of the awkward restriction of the reliability of measured oil film thickness, it was known that the capacitance technique makes it possible to measure the oil film thickness in elastohydrodynamic and mixed lubrication regimes as well as in hydrodynamic regime. Therefore, it is also possible to classify the lubrication regimes based on the oil film thickness.

Key words : Engine bearing, Oil film thickness, Lubrication regime, Capacitance technique, Film parameter

1. Introduction

The oil film thickness is recognized as an important parameter to understand the lubrication characteristics of moving parts of automotive engines. However, the operating factors are so complex that the theoretical analysis of full model is restricted. Therefore, estimation of bearing performance through the measurement of oil film thickness has been an important subject to lubrication engineers.

Engine lubrication parts can be divided into three major components; engine bearing, valve train and piston and ring. Capacitive or inductive displacement transducers have been widely used to measure the oil film thicknesses of these parts. However, some problems of the measurement method using transducers are discussed as follows: it is difficult for the transducers to withstand the harsh environment of the engine, particularly at high speeds and loads. The temperatures and the physical properties of transducers change with surrounding conditions regardless of the oil film thickness. In order to overcome these problems, the capacitance technique and the resistance technique were developed. Capacitance technique, which assumes the entire oil film between bearing and shaft as a capacitor, was developed by Craig, King and Appeldoorn [1]. Bate *et al* [2,3] used this technique to study the oil rheology. Resistance technique, which regards the oil film as a resistor and measures the resistance, also provides valuable information on oil film formation and breakdown. However, Spearot and Murphy [6] suggest that the resistance technique is not suitable for oil film thickness measurement and that capacitance technique has better precision because the dielectric constant is insensitive to the variations in temperature and pressure, whereas the electric conductivity varies markedly.

Cam and tappet contacts, one of the main sources of valve train friction, are thought to operate in both the mixed and the EHL (Elastohydrodynamic Lubrication) regimes, as suggested by Barwell and Roylance [4]. Therefore, the oil film thickness of this part is difficult to measure. Ninomiya *et al* [5] observed the breakdown of oil film in the cam follower contact of a fired engine by the electrical resistance technique. However, the capacitance technique can also be applied to the measurement of oil film thickness of cam and tappet contacts, having better precision. There was little reported in the literature about applying the capacitance technique to EHL and mixed lubrication regimes like cam and tappet contacts, in recent days, Williamson *et al* [7,8] presented his work of applying capacitance technique to cam and tappet contacts.

In this research, the oil film thickness of engine bearing and cam/tappet contact were measured by capacitance technique in order to examine the lubrication characteristics which have been achieved mainly by theoretical analysis. Comparing the measured oil film thickness with the surface roughness, the lubrication regimes of these sliding parts were verified. The errors that occurred in oil film thickness measurement using the capacitance technique were also discussed.

2. Experiment

2-1. Test engine

The connecting rod bearing and No. 1 main bearing of a 1.5 liter, L-4 gasoline engine were used for measuring oil film thickness. The OHC cylinder head with a directing acting type valve train was used for the measurement of oil film thickness between cam and tappet. The experiment was performed in a motored cylinder without firing because the effects of the surrounding pressure and temperature were negligible.

2-2. Measurement of oil film thickness

The capacitance technique was used for oil film thickness measurement in engine bearing and cam/tappet contact. Simplified models are required in converting the measured capacitance into oil film thickness as shown in Fig. 1. In the bearing systems as shown in Fig. 1(a), measured capacitance, C, is obtained as;

$$C=\int_A \frac{kE}{h}dA=\int_0^{2\pi}\frac{kEBR}{h}\,d\theta \qquad (1)$$

where k : Permitivity (=8.85×10^{-12} F/m)
E : Dielectric constant (≒ 2.08)
B : Width of bearing
R : Radius of bearing

Oil film thickness according to bearing angle, θ, is given as;

$$h=C_R(1+\varepsilon\cos\theta) \qquad (2)$$

where C_R : Radial clearance
ε : eccentricity ratio
θ : Bearing angle

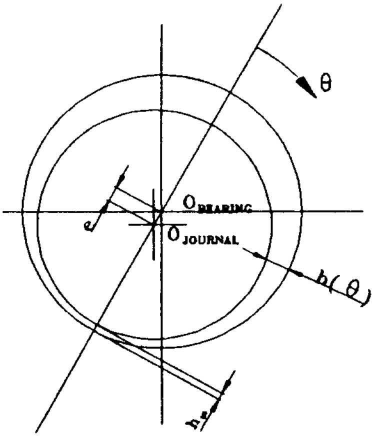
Minimum oil film thickness, hm, occurs at $\theta=\pi$ and is given as;

$$h_m=C_R(1-\varepsilon) \qquad (3)$$

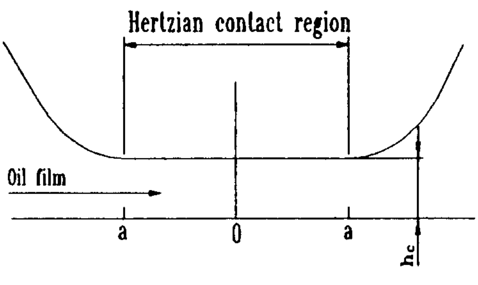
From the measured capacitance and equations (1), (2) and (3), the minimum oil film thickness is obtained as;

$$h_m=C_R\left(1-\sqrt{1-\left(\frac{kAE}{C_RC}\right)^2}\right) \qquad (4)$$

In order to measure the oil film thickness between cam and tappet, it is assumed as shown in Fig. 1(b) that all the measured capacitance originated from this Hertzian region and that the surfaces were flat and parallel within this region. From these assumptions, central oil film thickness, h_c, is given as;

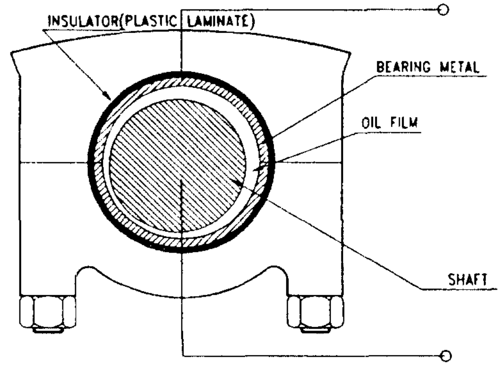


(a) Engine bearing

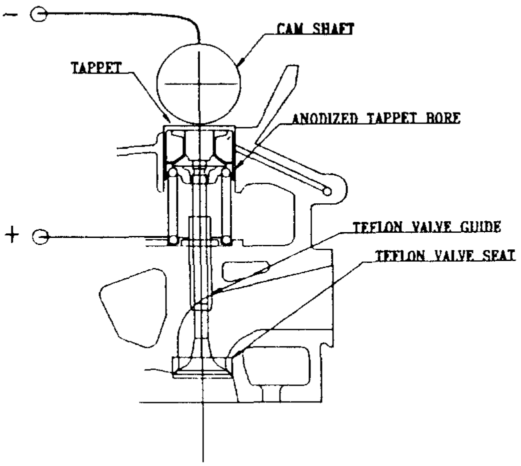


(b) Cam/tappet contact

Fig. 1. Simplified models for capacitance measurement.



(a) Bearing



(b) Cam/tappet contact

Fig. 2. Schematic diagrams of capacitance measurement system.

$$h_c = \frac{kAE}{C} = \frac{k(2a \cdot b)E}{C} \qquad (5)$$

where Hertzian contact area, 2a can be obtained as;

$$a = \sqrt{\frac{4Wr}{\pi b}\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)} \qquad (6)$$

where b : width of cam
W : applied load
E_1, E_2 : Youngs modulus of each material
ν_1, ν_2 : Poissons ratio

Schematic diagrams for capacitance measurement are shown Fig. 2.

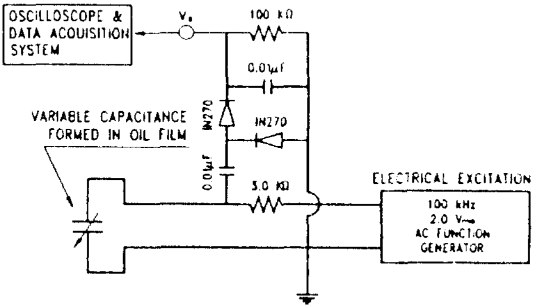


Fig. 3. Electric circuit for capacitance measurement.

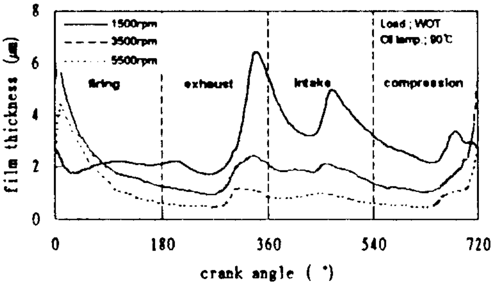
As the crankshaft and camshaft are earthed, it is important to insulate the bearing and tappet, which form capacitance with shaft, from the engine. In case of engine bearing, a 0.25 mm Fiber-Glass Plastic Laminate was interposed between the bearing shell and the housing. In the case of cam/tappet contact, the tappet, valve and spring were regarded as a conductor and insulated as a whole. Some parts of the cylinder head that touch with this conductor like valve seat and valve guide were changed to those made of Teflon as shown in Fig. 2(b). The tappet bore was anodized to have a non-conducting ceramic film so that there was no electrical connection between the tappet and the cylinder head. Slip rings at the end of the shafts were used to connect the ground wire in both cases. A scissor type linkage system was used to draw out wire from the connecting rod bearing.

Fig. 3 shows the electrical circuitry for capacitance measurement. High frequency sine wave voltage was applied to the variable capacitance. The measurement circuit was made so that the output voltage varied according to the capacitance of oil film. The relationship between the capacitance and output voltage was calibrated in advance and used during the experiment. The output signal was transmitted to a digital oscilloscope and data acquisition system composed of a personal computer and A/D converter.

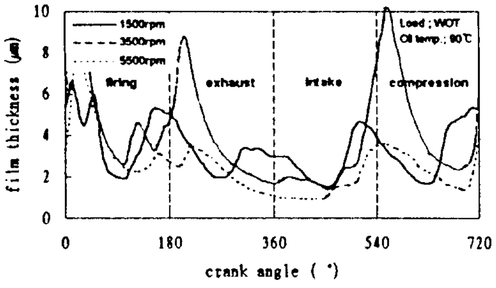
3. Results and Discussions

3-1. Measured film thickness and shear rate

Fig. 4 shows the measured minimum oil film thickness curves according to the engine rotational speed at full load with a constant oil and water tem-



(a) Connecting rod bearing



(b) No.1 Main bearing

Fig. 4. Measured minimum oil film thicknesses.

perature of 90°C. In the case of the connecting rod bearing, the minimum oil film thicknesses at most crankangles decrease with increasing engine speed, except from the end of the compression stroke to the beginning of the firing stroke. It is because the inertia force, the dominant factor on the applied load, increases in proportion to the square of engine speed. This results in reduced oil film thickness. The variation of oil film thickness reduces due to the increased oil film stiffness. In the case of the main bearing, rapid changes of oil film thickness occur around the crankangles of 180° and 540° as shown in Fig. 4(b). This is because the firing forces of No. 2, 3 and 4 cylinders influence the No. 1 main bearing. This means that engine main bearing analysis, that assumes the crankshaft is a determinate rigid body, should be recosidered.

Fig. 5 shows the comparison between the measured and calculated minimum value of minimum oil film thicknesses during a cycle. The mobility method was used in calculation. The minimum oil film thicknesses measured by capacitance technique are smaller than the calculated values in the entire cycle. The minimum values of the measured oil film thicknesses were below 0.5 μm. This shows a great discrepancy of absolute value compared with the calculated one above 1 μm even at the minimum. Assumptions included in theoretical analysis and experiment are thought to be the cause of this discrepancy.

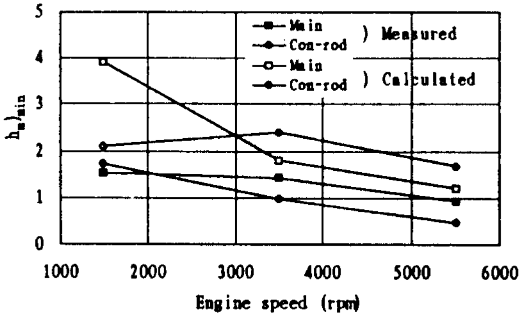


Fig. 5. Comparison between the measured and calculated $h_m)_{min}$.

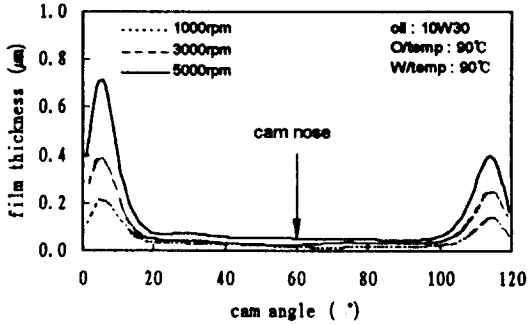


Fig. 6. Measured central film thickness between cam and tappet.

Fig. 6 shows the measured central oil film thicknesses as a function of cam angle. The oil film thicknesses increase with the increase in the rotating speed due to the increase of entainment velocity and the decrease of applied load, especially at cam nose, that is different from the engine bearing.

Recently, most of the engine lubricants are multi grade oils of lower viscosity in the quest for easier low temperature starting and improved fuel economy. As the viscosity of polymer-countaining multi grade oils depends on the shear rate, the effective operating viscosity can be obtained only if the shear rate is known at the sliding place. If the minimum oil film thickness is known, shear rate is given as;

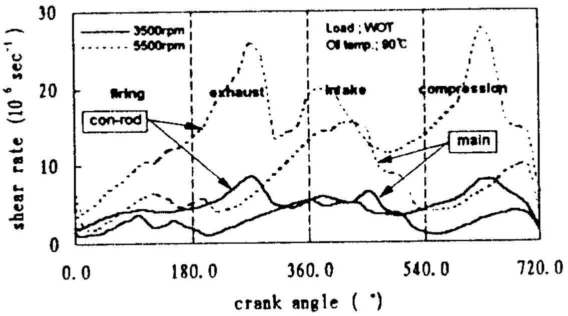
$$\gamma_m = \frac{R_{con-rod}}{h_m} \cdot \frac{2\pi N}{60}\left(1 + \frac{d\beta_b}{d\beta_a}\right) : \text{con-rod bearing}$$

$$\gamma_m = \frac{R_{main}}{h_m} \cdot \frac{2\pi N}{60} \ : \text{main bearing} \tag{7}$$

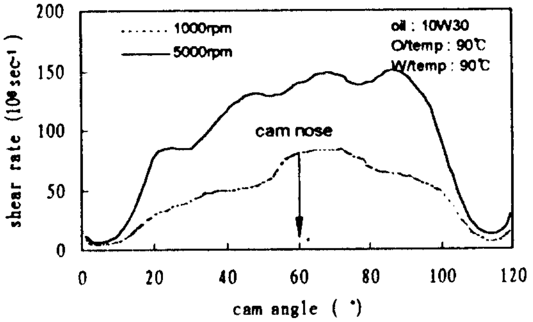
$$\gamma_m = \frac{R_{base} + LL}{h_c} \cdot \frac{\pi N}{60} \ : \text{cam/tappet}$$

where N : Engine rotational speed (rpm)
R_{base} : Radius of cam base circle
LL : Valve lift
β_a : crank angle
β_b : angle between cylinder center line and connecting rod axis

The shear rates in engine bearing and cam/tappet contact are shown in Fig. 7. The shear rates are over 10^6 sec^{-1} in almost the entire region of cam/tappet contact and engine bearing at high speed. The shear rates of the cam/tappet contact are much larger than those of the engine bearing. Moreover, it is clear that the shear rate becomes much higher at severe conditions of high speeds and high oil temperatures. It is therefore known that the conditions of shear rate for the development of polymer-containing multi grade oils should be above 10^6 sec^{-1}.



(a) Engine bearing



(b) Cam/tappet contact

Fig. 7. Plots of measured shear rate.

3-2. Comparison of measured film thickness with surface roughness

As the real sliding surfaces are not perfectly flat as assumed in theoretical and experimental analysis, it is interesting to compare the measured film thickness with the surface roughness. The ratio of oil film thickness to the surface roughness has been widely used to classify the lubrication regimes together with observing the change of friction coefficients.

Film parameter, Λ, defined as the ratio of film thickness to the composite surface roughness is given as;

$$\Lambda = \frac{h_{min}}{\sigma} \tag{8}$$

Among several theories telling lubrication regimes from the film parameter, two theories are indicated in Table 2.

Classification according to Staron and Willermet [4] indicates lower film parameters against the same lubrication regimes. Fig. 8 shows a distribution of

Table 1. Measured surface roughnesses

	Roughness of each parts. (μm) σ_1, σ_2		Composite surface
Engine bearing	bearing crankshaft	0.22 0.09	0.24
cam/tappet contact	cam tappet	0.12 0.08	0.14

※ $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$, where σ_1, σ_2 denote the rms surface roughnesses of surfaces 1 and 2.

Table 2. Classification of the lubrication regimes

Lubrication regime	Range of film parameter or film thickness	
	Dowson [9] (μm)	Staron & Willermet [10]
Boundary	$\Lambda<1$, $0.005<h_{min}<0.01$	$\Lambda \approx 0$
Mixed	$1<\Lambda<4$ $0.01<h_{min}<1$	$0<\Lambda<1$
EHL	$3<\Lambda<10$ $0.1<h_{min}<1$	$1<\Lambda$
Hydrodynamic	$10<\Lambda$ $1<h_{min}$	

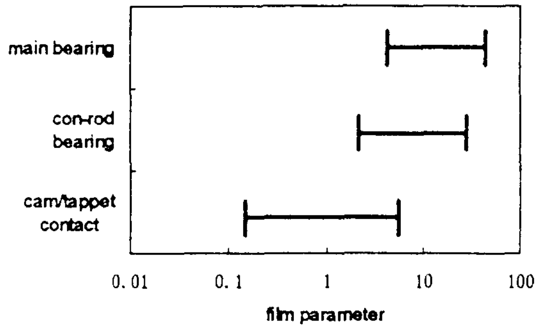
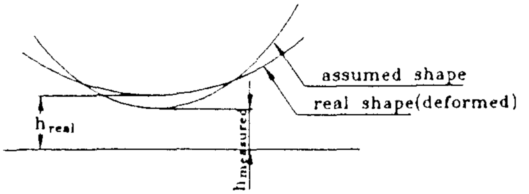
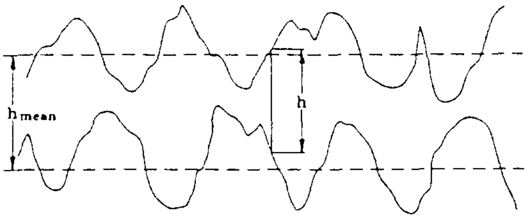


Fig. 8. Film parameter distribution of experimental engine.



(a) deformed film shape



(b) surface topography

Fig. 9. Cause of underestimation of measured film thickness by capacitance technique.

film parameters of engine lubricating parts.

Though the film parameter of engine bearing is larger than unit at all operating conditions, that of cam and tappet is partly less than unit, especially in all of cam nose regions. As there are several theories referring to the classification of lubrication regimes based on the film parameter, it is difficult to judge the right theory applicable to our experimental results. Despite the lack of an established theory, classification from Staron and Willermet was applied to this research.

Film parameter distribution of cam/tappet contact shown in Fig. 8 confirms previous works [4,10] that the lubrication regimes of cam/tappet contact ranged from mixed to EHL. The lubrication regime of engine bearing can also be judged as hydrodynamic from the film parameter, though the oil film thicknesses are less than 1 μm in some parts. The oil film thickness measured by capacitance technique and the resulting film parameter are underestimated for the following reasons and hard to take into account.

At first, it is because of the deformation of bearing shell, especially in the case of connecting rod bearing. The applied load is so great that the bearing shell is deformed and the oil film shape is changed to be flat near the minimum oil film thickness region as shown in Fig. 9(a). This makes the capacitance of oil film larger than expected. Therefore, the smaller value of minimum oil film thickness is indicated because the capacitance technique includes the assumption of a circular shaped bearing and shaft. The second reason is the surface topography. As mentioned previously, real sliding surfaces are not perfectly flat. Capacitance formed between two uneven surfaces of average distance, h_{mean}, is larger than that between two completely flat plates of the same distance, h_{mean}. Thus, larger capacitance is measured due to the surface geometry. This phenomenon results in the measured minimum oil film thickness being smaller than real one.

As a result of the above mentioned hypothesis, the real value of the minimum oil film thickness is thought to be somewhat larger than that of the measured minimum oil film thickness by capacitance technique. However, it is very difficult to know the magnitude of the underestimation.

4. Conclusions

(1) The oil film thicknesses of engine bearing and cam/tappet contact were measured by the capacitance technique.

(2) The minimum value of measured oil film thicknesses of engine bearing are below 0.5 μm. The resulted shear rates are above 10^6 sec^{-1} at most operating conditions of engine bearing. Thus, it is known that the shear rate condition of the development of polymer-containing multi grade oils should be above 10^6 sec^{-1}.

(3) The oil film thicknesses between cam and tappet were measured down to 0.1 μm and are smaller than the magnitude of the composite surface roughness. Therefore, it was confirmed that the cam and tappet contact operates in both the mixed and elas-

tohydrodynamic lubrication regimes.

(4) It was examined to evaluate the lubrication regimes by comparing the measured oil film thickness with the surface roughness. From this comparison, it is confirmed again that the engine bearing operates in hydrodynamic lubrication regime.

(5) It was proved that the minimum oil film thickness could be successfully measured by capacitance technique from mixed to hydrodynamic lubrication conditions and it is possible to classify the lubrication regimes from the resulted film parameter.

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