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Measurement of Lubricating Oil Film Thickness between Piston Ring –liner Interface in an Engine Simulator

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ABSTRACT

The interface between the piston rings and cylinder liner play an important role in total frictional losses and mechanical wear of internal combustion engine and is increasingly coming under scrutiny as legislated particulate emission standards are getting more and more stringent. The capacitance method is used for measurement of minimum oil film thickness between piston ring and liner interface. Measurement of capacitance formed between the piston ring and a probe mounted flush in the liner provides an accurate means of determining the oil film thickness provided that the region between the probe and liner is flooded with oil and dielectric constant of the oil is known. This paper presents detailed design and measurement of lubricating oil film thickness using capacitive micro sensor in a non-firing engine simulator. Lubricating oil film thickness was found to vary between 0.2μm to 8μm in the non firing engine simulator. At a particular position, lubricating oil film thickness varies significantly in upward and downward stroke of the engine due to reversal in direction of piston tilt in the two directions of motion.

INTRODUCTION

Understanding the mechanism of lubrication between cylinder liner and piston ring is important for reducing the engine emissions as well as increasing the engine efficiency. To understand transient oil transport, research in last two decades involved measurement of oil film thickness using various methods [1-9]. The piston motion, ring profile, liner surfaces roughness and lubricating oil properties play a very important role in controlling the oil film thickness [10-11]. The oil film thickness measurement in fired engines is not only important in the numerical values of the oil film thickness but also it is fundamental to increase the knowledge about the phenomena that occur in the piston assembly and influences the piston ring and cylinder liner contact and thus the piston ring lubrication. Among the various measurement techniques used for measuring such as resistance method, inductance method, optical techniques, the minimum oil film thickness in engines, the capacitance measurement technique has been found to deliver the most reliable results [1].

DESIGN OF CAPACITANCE PROBE

For measurement of lubricating oil film thickness between piston ring and cylinder liner a small electrode (probe) is installed in the liner of the engine. A parallel plate capacitor is formed between a small probe installed in the liner and ring facing the electrode. The surface of this probe is honed flush with liner's surface so that it does not cause any undesirable distinct separate ring-liner interaction. This probe acts as a plate of capacitor. The facing area of the piston wall or ring surface acts as other plate of the capacitor. The separation between piston/land and electrode varies as different parts of the piston ring assembly come in front of electrode with the reciprocating motion of the piston. The capacitance (C) of two infinite parallel conducting plates' changes as separation between them is varied as

$$C=K\varepsilon_o A/d$$

Where K is the dielectric constant of medium between the plates, ε_o is the permittivity of space, A is the facing area of two plates and d is the gap between two plates. Piston of the engine is grounded so one plate of the capacitor is grounded. This arrangement forms two parallel plate capacitors between ground and electrode. One is between electrode and piston ring and other between back side of piston ring and piston surface.

$$1/C_{total} = 1/C_{probe\text{-}ring} + 1/C_{ring\text{-}piston}$$

But the plate area of the second capacitor is very large as compared to first capacitor so second term in above equation becomes negligible, hence

$$C \approx K\varepsilon_o A/d_{probe\text{-}ring}$$

Some assumptions are required to apply the parallel plate formula for distance measurement by measuring change in capacitance

1. The region between ring and liner is fully flooded with oil, and oil is free from voids and bubbles. Presence of voids and bubbles may cause the change in value of dielectric constant. This assumption makes the magnitude of dielectric constant higher than actual value and hence over predicts the separation distance at certain locations.
2. The separation distance is large enough so that the fringing effects (converging of electric field lines at edge of plates) can be ignored.
3. The ring face is parallel to the probe, and the separation distance is uniform over the width and height of the probe.

The actual value of K also depends upon ratio of oil and air between ring and probe since in most of the situation the ring gap is not fully flooded with oil. K is independent of temperature upto 150°C [1], Since the temperature of the cylinder liner seldom rises avove 150º C in the engine simulator and light duty engines, it can safely be assumed that capacitance change is independent of temperature for the present case.

Signal strength of capacitive micro-sensor depends on its area. Large face area of central electrode causes increased capacitance input but reduced spatial resolution. The rectangular shape of probe and shield provides better spatial resolution for same probe area as compared to circular shape of sensor but the shielding is more effective in circular probes. An optimal probe would be a rectangular with a large aspect ratio, having smaller length in axial direction of piston motion where high spatial resolution is required, and the length in the transverse direction chosen to maximize total plate surface area [1].

Rectangular probes with shorter length parallel to the axis of liner have been fabricated for this study. This results in higher spatial resolution in the direction of the ring profile. If we select a large width in transverse direction then due to circular shape of liner, the distance between two plates of capacitor (ring and central electrode) does not remains uniform, hence results in large deviation/error while using parallel plate formula. Short length in transverse direction however decreases the plate area.

The axial width of compression rings used in the engine is 2 mm; sensor width of 180 μm in axial direction ensured at least 10 data points along the face of ring. Transverse length of 6000 μm gives a capacitance of 0.8pF at distance of 20 μm. So as a compromise between spatial resolution and signal strength probe of dimension 180μm in axial direction and 6000 μm in transverse direction was fabricated as shown in figure 1. Probes were made of brass because it gives an optimum combination of conductivity, strength, ease of machinability and cost. Though metals like copper and silver are excellent conductors, their mechanical strength and rigidity is low. Probes of copper and silver may deform in firing engine. Probes made of brass have better dimensional control.

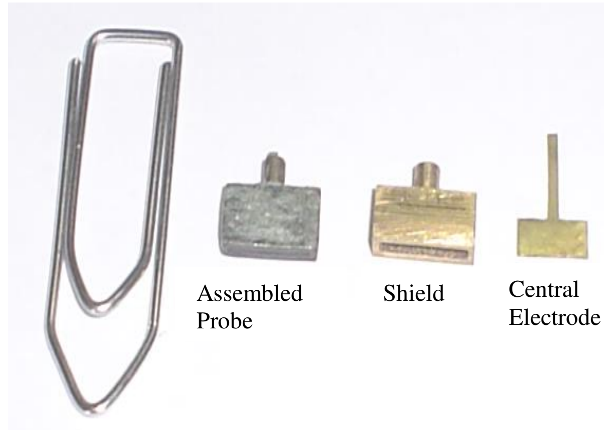

Figure 1: Assembled Probe

FABRICATION OF PROBE

Probe is fabricated in two parts: one is outer shield and other is central electrode. Figure 1 shows the outer shield, central electrode and assembled probe. Shield is machined on milling machine, then a through hole is made by drilling and rectangular slot for central electrode is machined using electric discharge machine (EDM).Central electrode is made from thin brass shim (0.18mm). Its profile is achieved by cutting approximate shape and then finishing to exact dimensions using diamond files.

Shield is required to minimize the fringing of electric field because the size of probe is very small. It increases the signal strength and minimizes error in the use of parallel plate capacitance equation. Shield is electrically insulated from the central electrode but kept at same potential as the central electrode. So during the assembly of these two components, thin pieces of mica are pasted on electrode by using high temperature epoxy. Then the gap between mica pasted electrode and shield is filled using high temperature epoxy. Fiber glass insulated copper leads of a coaxial cable are soldered to the electrode and shield for connecting them to the signal conditioning circuit. Fiber glass sleeves are used to ensure insulation between shield and electrode at soldered end.

PROBE INSTALLATION

Three rectangular slots (Figure2&3) were machined in the liner using EDM machine. Slots provide a clearance of 1.25mm in transverse direction and 0.75mm in axial direction for filling the mica and epoxy. Figure 3 shows the liner with machined rectangular slots for installing the probe.

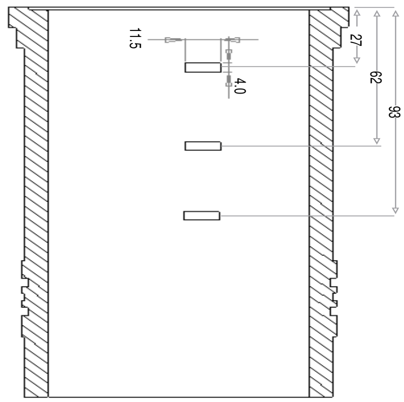

Figure 2: Positions of Rectangular Slots for Installing the Probes in the Liner

Figure 3: Liner Inner wall with installed Probes

Liner was fixed on a V-block with rectangular slots upward. Thermocol was placed inside the liner below the rectangular holes. Probe was fixed in this hole by providing them hanging support by cables soldered on them. Thin mica pieces were placed around the probe for insulating them from liner. Remaining space was filled with epoxy. Epoxy was allowed to cure for 24 hours. With solidification of epoxy, probes get fixed in the liner. After installing three probes at locations shown in Figure 3, surface honing was done on liner surface. There was a chance of damage to extruding faces of the probes inside the liner. Due to this reason, excess material was removed carefully by hand grinding using emery paper of soft grade before honing. Final finished liner is shown in Figure 3. The surface profiles of the probes inside the liner were measured by a Profilometer to confirm the proper installation of the probe.

SIGNAL CONDITIONING CIRCUIT

Measurement of capacitance is based on the principle of amplitude modulation. A sine wave of high frequency consistent with the minimum time required for the capacitance to voltage conversion is modulated in an amplifier of suitable video bandwidth. A RMS to DC converter rectifies the amplitude of this modulated wave into a DC signal. The output of RMS to DC converter is send to data acquisition system.

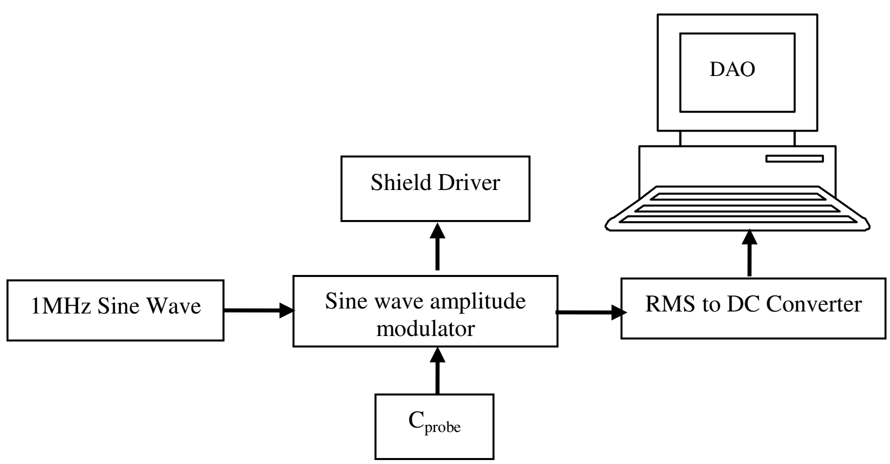

Figure 4: Signal Conditioning Circuit

Measurement of capacitance is based on the principle of amplitude modulation. A sine wave of high frequency consistent with the minimum time required for the capacitance to voltage conversion is modulated in an amplifier of suitable video bandwidth. A RMS to DC converter rectifies the amplitude of this modulated wave into a DC signal. The output of RMS to DC converter circuit is recorded by data acquisition system as a measurement of capacitance. The shield of the probe is driven at potential of central probe through a non-inverting amplifier. Figure 4 shows the circuit diagram for one channel of signal conditioning unit.

EXPERIMENTAL SET UP

Non-firing engine simulator (Figure 5) was developed for experimental study of lubricating oil film thickness variation between cylinder liner and piston rings. A single cylinder diesel engine (Make: Cooper, UK; Model: CVR-5) was converted into this simulator. The simulator was driven by 1 hp electric motor (AC). Motor speed was controlled by regulating the voltage supply using an auto transformer. The piston used in the simulator has five rings (three compression rings, and two oil rings).

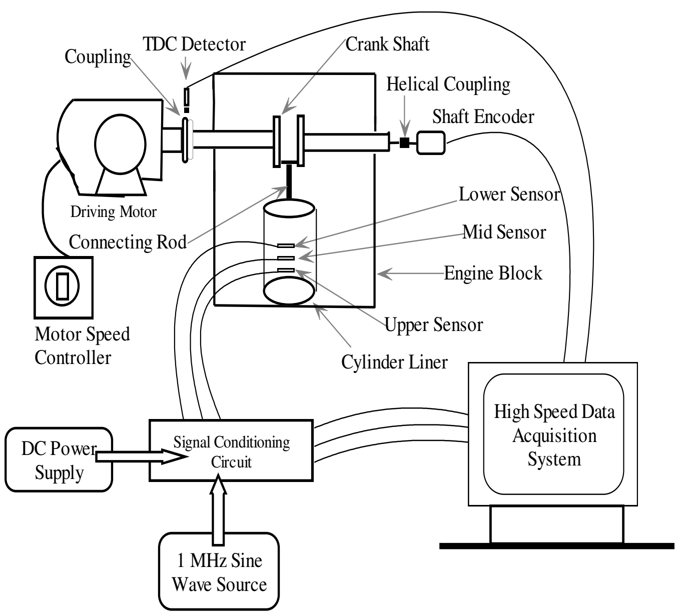

Figure 5: Experimental Setup

All experiments were performed at room temperature and 1400 rpm of crankshaft. The stroke length of the simulator is 82 mm, liner bore is 82 mm and connecting rod length is 155 mm. Piston TDC detector proximity switch and precision shaft encoder were installed on engine crankshaft. Voltage change due to change in capacitance and signal generated by shaft encoder and TDC detector were recoded by a high speed data acquisition system.

RESULTS AND DISCUSSIONS

Results shown in Figures 6-8 represent the variation in measured value of capacitance and lubricating oil thickness calculated in inward and outward stroke of the piston. A particular sensor observes increase in capacitance above a base value when a ring comes in front of that sensor hence position of rings with respect to that sensor is indicated by piston profile curve. Only top two rings cross the upper sensor as indicated by piston profile curve in Figure 6.First groove corresponds to second compression ring and second groove corresponds to top compression ring in inward stroke (-180 to 0 CAD), and order is reversed in outward stroke (0 to 180 CAD). Top four rings cross the mid sensor (Figure 7). First groove corresponds to first oil ring, and other three grooves on piston profile curve indicate the compression rings in the order in the inward stroke of the piston. This order is reversed in the outward stroke of the piston.

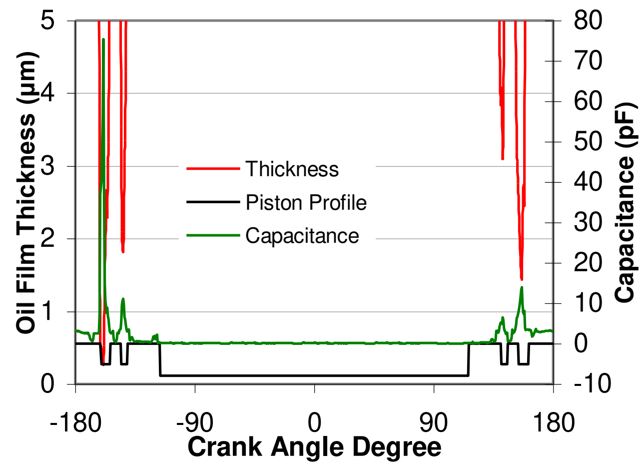

Figure 6: Thickness and Capacitance at 1395 rpm at Upper Sensor

All the five rings pass through the lower sensor (Figure 8). First grove corresponds to second oil ring, second groove corresponds to first oil ring and top three grooves represent the compression rings in the order in inward stroke of the piston, and this order is reversed in the outward stroke.

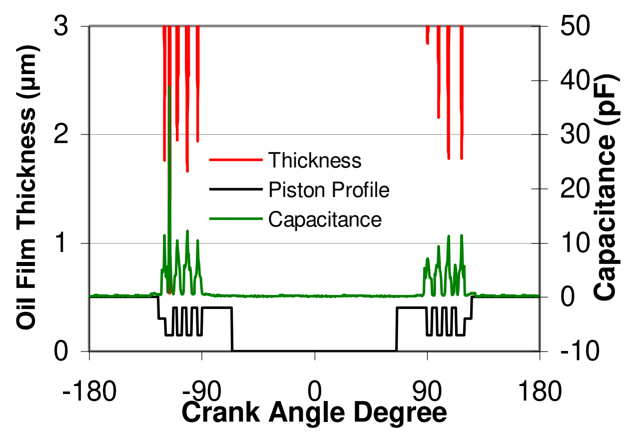

Figure 7: Thickness and Capacitance at 1395 rpm at Mid Sensor

Only minimum oil film thicknesses observed by sensors when they are facing rings are accurate. Thicknesses corresponding to interface of sensor and piston land are over predicted from actual thickness due to change in the dielectric constant of capacitor formed. At these positions, mixture of lubricating oil and air of unknown composition is present which is assumed to be lubricating oil only for thickness calculation causing significant deviation from actual thickness.

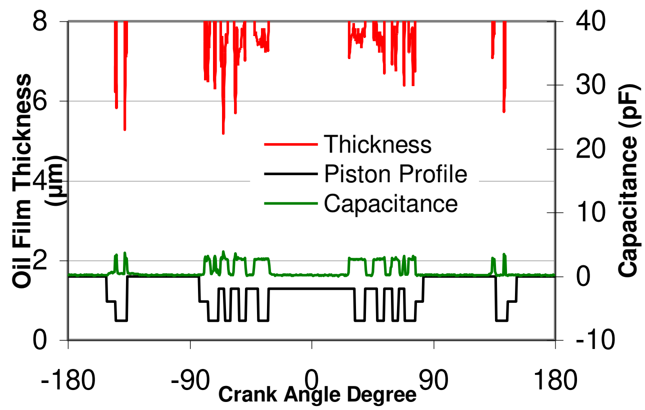

Figure 8: Thickness and Capacitance at 1395 rpm at Lower Sensor

At the location of lower sensor the liner bore is slightly enlarged during honing as compared to designed clearance, clearance is slightly large causing ring twist. Therefore, faces of rings sensed by lower sensor are not as smooth as observed by first and second sensor.

CONCLUSION

Lubricating oil film thickness was found to vary between 0.2 µm to 8 µm in a non firing engine simulator. At a particular position, lubricating oil film thickness varies significantly in upward and downward stroke of the engine due to reversal in direction of piston tilt in the two strokes. This variation was comparatively small as compared to fired engine data reported by other researchers [1-7] due to absence of gas compression and combustion pressure in the engine simulator. Thus, oil film thicknesses at in front of sensors were measured quite successfully and this capacitance probe sensors can be employed into a firing engine to understand the oil transport phenomenon.

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