The Measurement of Liner - Piston Skirt Oil Film Thickness by an Ultrasonic Means

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Abstract

The paper presents a novel method for the measurement of lubricant film thickness in the piston-liner contact. Direct measurement of the film in this conjunction has always posed a problem, particularly under fired conditions. The principle is based on capturing and analysing the reflection of an ultrasonic pulse at the oil film. The proportion of the wave amplitude reflected can be related to the thickness of the oil film. A single cylinder 4-stroke engine on a dyno test platform was used for evaluation of the method. A piezo-electric transducer was bonded to the outside of the cylinder liner and used to emit high frequency short duration ultrasonic pulses. These pulses were used to determine the oil film thickness as the piston skirt passed over the sensor location. Oil films in the range 2 to 21 μm were recorded varying with engine speeds. The results have been shown to be in agreement with detailed numerical predictions.

Introduction

In-cylinder frictional characteristics are directly related to the regime of lubrication. This is governed by operating conditions and rheological properties of the lubricant. Sufficient separation of piston skirt and ring-pack from the cylinder wall reduces the frictional losses in an IC engine. It is reported that this accounts for nearly 40-50% of all such losses [1].

Clearly, it is important to optimise the lubricant film formation to minimise friction and yet limit emissions. Therefore, design of piston skirt and rings to encourage lubricant entrainment into the contact are important criteria. Their axial profiles include chamfered edges or relief radii to create the necessary wedge effect for entraining of the lubricant with relative motion of surfaces. The material composition of the contiguous surfaces is also important, particularly encouraging localised deformation under load, enhancing the separation and inducing formation of thicker coherent film [2]. Finally, cylinder bores or liners may be treated to provide lubricant retaining features. This promotes film by entrapment with cessation of entraining motion at dead centres, where there is no relative motion of surfaces.

With these considerations, numerical predictions indicate an improved regime of lubrication. However, it is necessary to ascertain the validity of these predictions through measurement of film thickness [3, 4]. This has proven to be difficult, owing to the inaccessible nature of the contact, as well as the inhospitable environment, particularly under fired conditions, especially at high speeds. This paper describes an engine test-bed, and the use of an ultrasonic sensor, bonded to a wet cylinder liner to measure the transient variation in lubricant film thickness between the liner and the piston skirt.

Background

Oil films are thin compared with the geometry of the lubricated components, and frequently of a transient nature. This makes them hard to measure. Both laser fluorescence [5, 6, & 7] and capacitance probes [8] have been used successfully for piston ring measurements. Both methods however require the penetration of the liner, either for a window, or for a surface mounted probe.

This paper concerns the use of a new ultrasonic method for measuring oil film thickness. This has the advantage that the sensors do not have to be mounted flush with the oil film and can provide localised non-invasive measurements.

A piezo-electric sensor is coupled to the outside of the cylinder liner. This is used to generate ultrasonic pulses that propagate through the liner. When the pulse strikes an oil film it is partially reflected and partially transmitted. The proportion that is reflected (known as the reflection coefficient, R) depends on, amongst other things, the thickness of the oil film.

The response of a thin layer embedded between two media is governed by a quasi-static spring model [10]. If the embedded layer is very stiff then the ultrasound passes through, whereas if it is compliant then the wave is reflected. When the ultrasonic wavelength is large compared with the film thickness (i.e. the low frequency regime), the analysis yields a simple relationship between the reflection coefficient and stiffness of the layer, K:

$$R = \frac{1}{\sqrt{1+\left(\frac{2K}{\omega z}\right)^2}} \quad (1)$$

Where ω is the angular frequency of the ultrasonic wave (=2πf), f is the frequency of the wave. The parameter z is the acoustic impedance of the material either side of the layer (the acoustic impedance is the product of the density and speed of sound in the medium). Equation (1) holds for the case when the materials either side of the layer have the same acoustic impedance. The stiffness of a liquid layer of thickness, h trapped between two flat surfaces and constrained laterally is given by:

$$K = \frac{B}{h} \quad (2)$$

where B is the bulk modulus of the liquid. The bulk modulus can be replaced by the speed of sound in the liquid, c=√(B/ρ) where ρ is the density, to give:

$$K = \frac{\rho c^2}{h} \quad (3)$$

Combining (1) and (3) leads to a simple relationship between the oil film thickness and the reflection coefficient:

$$h = \frac{2\rho c^2}{\omega z}\sqrt{\frac{R^2}{1-R^2}} \quad (4)$$

Dwyer-Joyce et al [9] demonstrated that this relationship held for typical lubricant film thickness in the hydrodynamic and elastohydrodynamic regime. This approach has subsequently been used for the measurement of oil film thickness in power station thrust bearings [10], hydrodynamic journal bearings [11], a rolling element bearing [12], and a hydraulic motor piston ring/liner [13].

In this work a piezo-electric sensor is bonded to the outer surface of a wet liner. The analysis above is used to determine oil film thickness from the ultrasonic reflection at an oil film formed as the piston skirt passes the sensor.

Apparatus

ENGINE AND DYNAMOMETER TEST BED

The test engine is a liquid-cooled, 449 cm3 4-stroke 4-valve single overhead-camshaft single cylinder engine. It produces 41 kW at 9,000 rpm, and is resisted by a transient A/C dynamometer (see figure 1). The stroke is 64 mm and the bore diameter is 96 mm. The nominal skirt clearance is 150µm. The barrel of the engine is adapted to accept wet liners as shown in figure 2, on which an ultrasonic sensor (see later) is bonded. A TDC pulse obtained from a digital rotary encoder is used to trigger the data acquisition system.

Figure 1: Single cylinder test engine

ULTRASONIC MEASUREMENT EQUIPMENT

A 10 MHz piezo-electric sensor was adhesively bonded to the wet set of the cylinder liner. The location of the sensor was such that it was coincident with the piston skirt whilst the piston is at top dead centre as shown in figure 2. The transducer is a thin element of piezo-electric material of diameter 7mm and thickness 0.2mm with ‘wrap-around’ electrodes i.e. the top face has a bonded electrode, the bottom face electrode is wrapped over to the top face. Two wires can then be soldered directly to these electrodes on the top face. The wires are fed out of the liner through the water jacket to an ultrasonic pulser-receiver (UPR).

A schematic of the apparatus is shown in figure 3. The UPR generated a series of short duration voltage pulses that excite the transducer to create an ultrasonic pulse. The pulses reflect back from the oil film, are received by the sensor, which in turn generated a voltage pulse that is received and amplified by the UPR. In this way, the transducer acted as both an emitter and receiver (i.e. pulse echo mode). The reflected signal was digitised on a storage oscilloscope and passed to a PC for processing.

Figure 2: Photograph of the cylinder liner with the ultrasonic transducer bonded to the wet side.

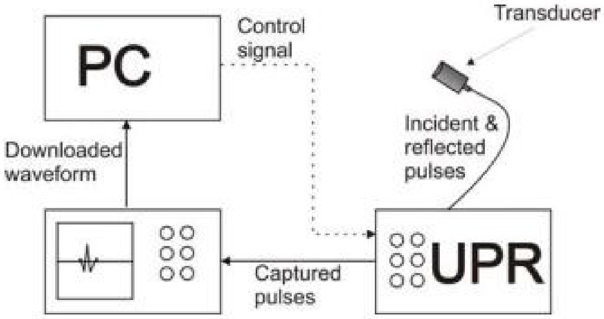

Figure 3. Schematic diagram of the ultrasonic pulsing and receiving apparatus.

A LeCroy LT342 oscilloscope was used to digitise and capture the received signal. In order to capture the waveforms at a high rate the onboard memory was divided up into a number of segments. At each trigger event the selected portion of the waveform is written to a segment. The trigger was provided from the UPR where a signal was sent to the oscilloscope at the same time as a pulse was sent to the sensor. Thus every signal from the pulser is written to the segmented memory.

The onboard memory of the oscilloscope was limited to 250k points per channel. Thus the number of data points in each segment determines the number of segments that it is possible to capture. During testing the number of points per segment was set at 1000, resulting in 250 pulses captured per capture cycle. The sensor was pulsed off its natural frequency (equivalent to 5.6 MHz rather than 10 MHz) to produce as short a pulse as possible. As a result the maximum pulsing rate was limited to 5 kHz. However, if a higher frequency sensor was used, a pulsing rate of up to 10 kHz could be achieved. The oscilloscope has the capability to capture at up to 200 kHz.

RESULTS

A pulse is recorded from a reflection from the liner front face when the piston is remote from the sensor location. This pulse is reflected from a liner-air interface. This reflected pulse is then equal to the incident signal (since a wave is almost completely reflected at a solid-air interface) and is known as the reference signal. Figure 4 shows a pulse reflected back from liner-air and liner-oil film-piston skirt systems. The later pulse is reduced in amplitude because part of the wave has been transmitted through the oil film to the piston.

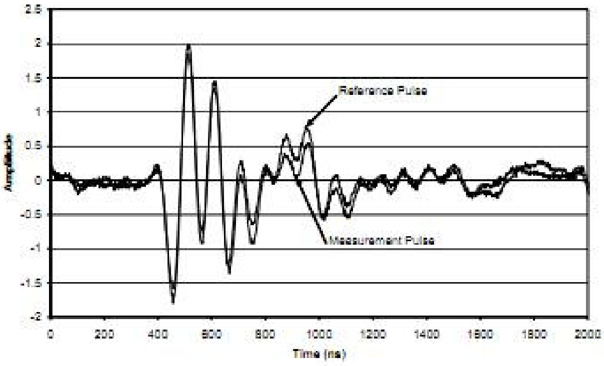

Figure 4: Sample pulses reflected from a liner-air interface and a liner-oil film-piston skirt interface

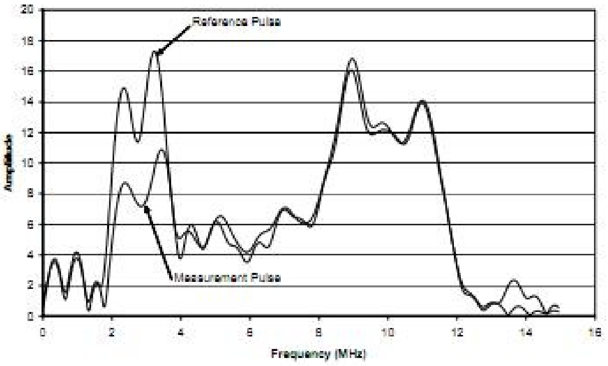

Figure 5: Amplitude spectra for the pulses of figure 4 obtained by performing a fast Fourier transform (FFT).

The next step is to pass the reference signal and reflected pulses through a fast Fourier transform (FFT) to give an amplitude spectrum. Figure 5 shows the data of figure 4 as amplitude spectra. This data demonstrates that the centre frequency of the probe was 3 MHz. The figure also shows that the transducer has useful energy in the range 2 MHz to 4 MHz. Dividing the oil film pulse by the reference pulse gives the reflection coefficient, as shown in figure 6 for a series of oil films.

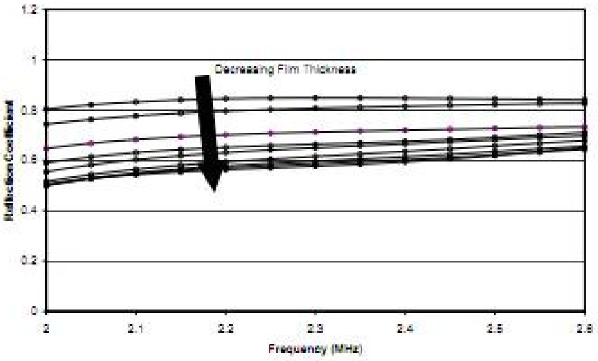

Figure 6: Reflection coefficient spectra obtained by dividing the oil film FFT by the reference FFT. The different curves represent different engine conditions and hence film thicknesses.

In principle the reflection coefficient at any of the frequencies shown in figure 6 can be used to determine the film thickness using equation (4), provided it is within the bandwidth of the transducer. Typically the film thickness is determined over a range of frequencies and a mean presented.

MOTORED TESTS

To demonstrate how the ultrasonic transducer resolves the lubricant film thickness, a series of motored tests were carried out initially. Figure 7 shows a typical measurement of the reflection coefficient recorded as the piston passes the sensor location (recorded at a motor speed of 850 rpm). Zone A represents the piston wall area above the ring zone. Zone B corresponds to the passage of the piston rings, where no measurement of oil film was recorded. Zone C represents the piston skirt passing the transducer. Minimum film thickness of 9.4 µm was recorded when at TDC. During the subsequent down-stroke the film thickness increases to 16.5 µm as the residual oil on the cylinder walls is entrained into the contact. Motored Tests were performed at 850, 1800 and 6000 rpm. Figure 8 displays the increasing oil film thicknesses with increasing engine speed.

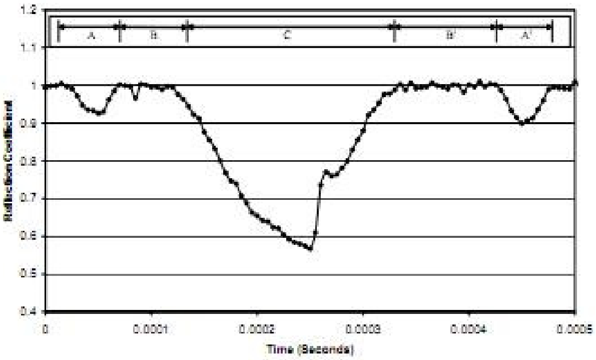

Figure 7: Plot of reflection coefficient recorded as the piston passes over the sensor location at an engine speed of 850 rpm.

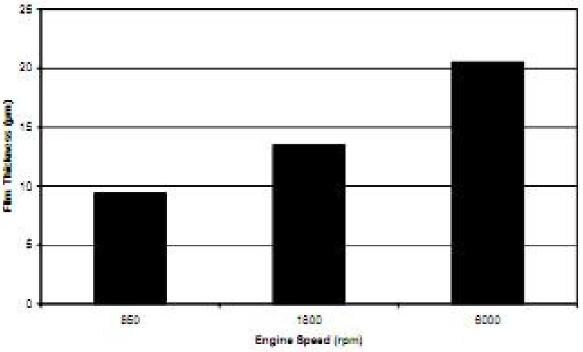

Figure 8: Measured liner – piston skirt oil film thickness for three motored engine tests.

FIRED TESTS

The engine was run at different speeds at wide-open throttle condition, fully resisted by the dynamometer. For each test, repeatable conditions were ensured by monitoring air-fuel ratio, test cell pressure, humidity, coolant, and bulk oil temperature.

Figure 9a: Area where average film measured on the piston skirt indicated by the circle

Figure 9b shows the film thickness measured at the idle speed of 1800 rpm. The measurement is recorded as the piston skirt sweeps passed the sensor (from ~0.5 to 1µs) and then back again (from ~1 to 1.5µs). At this stage it is not possible to exactly match the film measurement with the piston skirt geometry, as the piston location is not exactly defined with respect to the sensor (TDC is approximately at 1µs on the plot). Figure 9a shows the sensor location with respect to the piston skirt. A minimum film of approximately 2µm is observed towards the end of the return stroke.

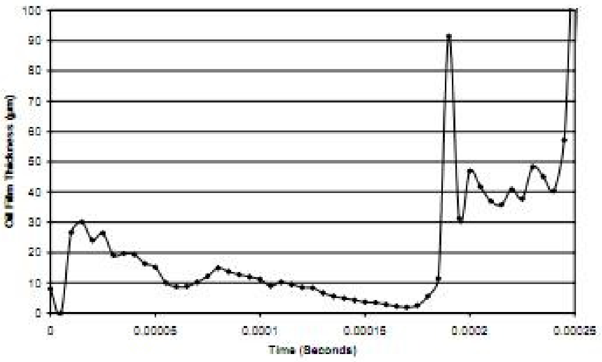

Figure 9b: Plot of measured oil film thickness for a fired test performed at an engine speed of 1800 rpm.

Prior numerical results, based on transient analysis of piston-cylinder liner contact, reported by Balakrishnan et al [14] predict a piston tilt of 0.085° with a side force of 4800N. Under this condition the analysis indicates a minimum film thickness of 1.94µm (see figure 10). Good agreement is observed between numerical prediction and measurement. Further validation could be obtained by measurements and modelling of the film at other locations on the piston stroke. This is the subject of future work.

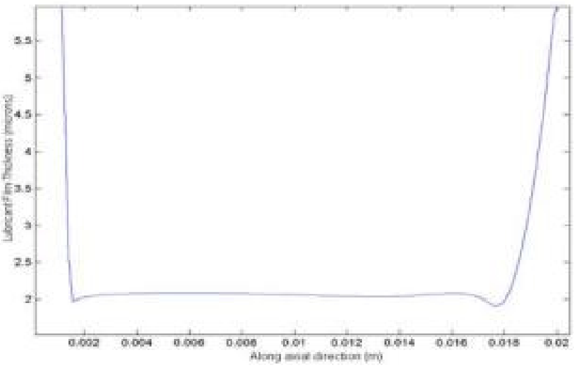

Figure 10: Axial lubricant film variation along the piston skirt at TDC.

CONCLUSION

A novel ultrasonic method for measuring oil film thickness has been evaluated for the measurement of liner-piston skirt lubrication. Reflected ultrasonic signals were recorded as the piston passed the sensor location. The reflected signals could be interpreted using a simple spring model approach to give oil film thickness directly. Oil films in the range 2 to 21 µm were measured for the piston skirt under a range of motored and fired conditions. However, since the sensor records over a relatively large area it is not possible at this stage to measure the film as the piston ring passes. Measured data agrees qualitatively with prior data from a numerical model of the film formation.

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REFERENCES

1. Andersson, B.S., (1991), Company's perspective in vehicle tribology. Leeds-Lyon Symp. on Trib. Elsevier, pp. 503-506

2. Balakrishnan, S. & Rahnejat, H., (2005), Isothermal transient analysis of piston skirt-to-cylinder wall contacts under combined axial, lateral and tilting motion, J. Phys. D: Appl. Phys. 38 pp. 787–79.

3. Brown M.A., McCann, H. and Thompson, D.M., (1993), Characterization of the oil film behaviour between the liner and piston of a heavy duty diesel engine. Tribological Insights and Performance Characteristics of Modern Engine Lubricants, SAE/SP-93/996/932784

4. Graddage, M.J., Czysz, F.J. and Killinger, A., (1993), Field testing to validate models used in explaining a piston problem in a large diesel engine. Transactions of the ASME J. Eng. Gas Turb. Power.
Vol. 115, pp. 721-727

5. Richardson, D.E. and Borman, G.L., 1991, Using Fibre Optics and Laser Fluorescence for Measuring Thin Oil Films with Applications to Engines, SAE Paper 912388.

6. Shaw, B.T., Hoult, D.P., Wong. V., (1992), Development of Engine Lubricant Film Thickness Diagnostics Using Fiber Optics and Laser Fluorescence, SAE Technical Paper 920651.

7. Seki, T., Nakayama, K., Yamada, T., Yoshida, A., Takiguchi, M., (2000), A study on variation in oil film thickness of a piston ring package: variation of oil film thickness in piston sliding direction, Jap. Soc. Auto. Eng. Review, Vol. 21, pp. 315-320.

8. Grice, N., Sherrington, I., (1993), An experimental investigation into the lubrication of piston-rings in an internal combustion engine - oil film thickness trends, film stability and cavitation, SAE Paper 920651.

9. Dwyer-Joyce, R.S., Drinkwater, B.W., and Donohoe, C.J., (2002), "The Measurement of Lubricant Film Thickness using Ultrasound", Proc. Roy. Soc., Vol. 459A, pp 957-976.

10. Dwyer-Joyce, R.S., Harper, P., Pritchard, J, and Drinkwater, B., (2003), 'Investigation into Film Formation in a Hydro-Electric Power Station Thrust Bearing', in press STLE Trib. Trans.

11. Dwyer-Joyce, R.S., Harper, P., and Drinkwater, B.,(2004), 'A Method for the Measurement of Hydrodynamic Oil Films Using Ultrasonic Reflection', Trib. Let., Vol. 17, pp. 337-348.

12. Dwyer-Joyce, R.S., Reddyhoff, T., and Drinkwater, B., (2004), 'Operating Limits for Acoustic Measurement of Rolling Bearing Oil Film Thickness', STLE Trib. Trans., pp. 366-375, Vol. 47.

13. Harper, P., Dwyer-Joyce, R.S., Sjödin, U., and Olofsson, O, (2005), Evaluation of an Ultrasonic Method for Measurement of Oil Film Thickness in a Hydraulic Motor Piston Ring, in press Proc. 31th Leeds-Lyon Symp. on Trib., Elsevier.

14. Balakrishnan, S. & Rahnejat, H., (2002), "Combined secondary piston dynamics and transient elastohydrodynamic analysis of piston skirt to cylinder contact conjunctions", AIMETA Symp., Salerno, Italy.