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Piezo-electric sensors to monitor lubricant film thickness at piston-cylinder contacts in a fired engine

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Abstract

The contact between the piston ring and cylinder liner is the most important sealing interface in an automotive engine. Understanding the contact interactions and lubricant film formation at this interface is crucial for the development fuel efficient and low emission engines. This paper outlines the development of an ultrasonic approach to enable non-invasive measurement of the lubricant film thickness formed between piston and cylinder wall of a fired engine.

The sensor system consisted of a series of small, low cost piezoelectric elements which were bonded to the external surface of a four-stroke, single cylinder engine. Each element could be individually energised with a short duration voltage pulse and reflections from the cylinder inner bore recorded. By using high frequency pulsing and data capture it proved possible to image individual ring and skirt contacts at full engine speeds. These captured reflections were processed to give lubricant film thickness directly and without the need for independent calibration. The results show high repeatability between cycle sets at specific running conditions. The lubricant films at each of the ring contacts can be measured at sufficient resolution such that individual rails of the oil control ring can be monitored. In addition, the film generated at the skirt was measured, the results from which, suggest the occurrence of 'piston slap' and highlight the potential for this ultrasonic method to enable indirect measurements of piston secondary dynamics.

Introduction

The interfaces between the piston and cylinder are arguably the most complex in an internal combustion engine. The capability of these contacts to provide optimal sealing and thrust support whilst minimising frictional losses and lubricant consumption directly affects parasitic energy loss and associated emissions. As computational capabilities increase, there is a strong desire for much of the development of the piston assembly to be carried out using software, but the complex dynamics and transient nature of an engine requires robust empirical data be available to

provide validation for such codes.

There are many parameters that can be monitored with relative ease (such as break mean effective pressure, BMEP) to give an indication of efficiency performance of the engine as a whole. Delving into more specific regions can present more of a challenge and the direct measurement of lubricant film thickness within contacts is one such example. Various methods have been developed to enable the direct monitoring of lubricant film thickness and applied to laboratory based engines. These include techniques such as laser induced fluorescence [15], [19], resistance [3], [9], [4], capacitance [10], [17] and inductance

based [20]. Each of these techniques has had varying degrees of success [16], however all are invasive, requiring penetration of the cylinder wall and significant modification of the cylinder and for this reason tend not to be used outside of the laboratory.

This paper outlines the application of an ultrasonic method [6] to measure lubricant film formation between the piston assembly and cylinder wall of a fired engine. The approach is based on transmitting discrete ultrasonic pulses through the cylinder wall using externally mounted sensors and recording reflections from the lubricated contact as the piston passes. It has thus proved possible to monitor the lubricant film, without requiring cylinder penetration and with minimal modification to the external surface of the cylinder. The method is fully capable of running externally to a test cell environment and has the potential to be used during the 'field test' of a production vehicle. The use of ultrasound for measurement of tribological films has been successfully applied to cases both in laboratory conditions [6], [8], [21] and machine elements [2], [14] and highlights the versatility of the technique.

Table 1: Briggs and Stratton *Quantum* engine information

No. Cylinders	1
Capacity	190cc
Stroke	52mm
Bore	68mm
Compression Ring Width	1.54mm
Fuel Mixing	Carburetor

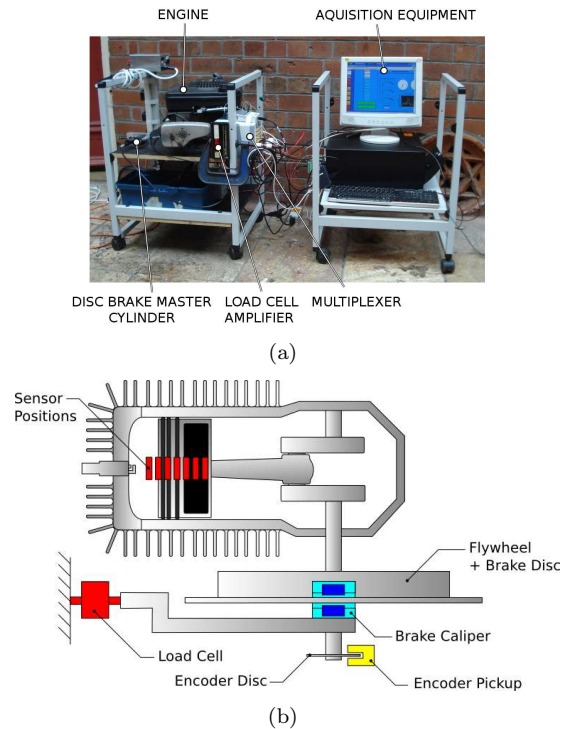


Figure 1: (a) Photograph of engine unit and acquisition apparatus, (b) Schematic showing engine instrumentation

Measurement system and methodology

The Engine Unit

The engine used during this work was a 5hp, single cylinder, four-stroke Briggs and Stratton *Quantum* unit. The benefits of this engine included its small size and portability as well as its air-cooled design, enabling simple sensor application to the external surface of the cylinder. The engine was mounted on a wheeled platform and operated outside the lab, highlighting the freedom of the technique from the constraints of a test cell (see figure 1a and table 1).

Mechanical Instrumentation

A simple loading mechanism consisting of a hydraulic disc brake coupled through a load cell was constructed. A rotary encoder was mounted to the end of the crank shaft to provide shaft speed. This system was able to function as a rudimentary dynamometer, applying a measurable resistive torque as well as recording engine speed thus giving an approximate measure of developed shaft power (see figure 1b).

The Sensor Array

Originally, the engine was used to power a rotary lawnmower and as such, was configured with a vertically oriented crank-shaft. Side-valve aspiration meant that only the anti-thrust side of the engine was accessible. To prepare the cylinder for the ultrasonic instrumentation, a small section of the cooling fins was removed and a flat machined on the external surface of the combustion chamber

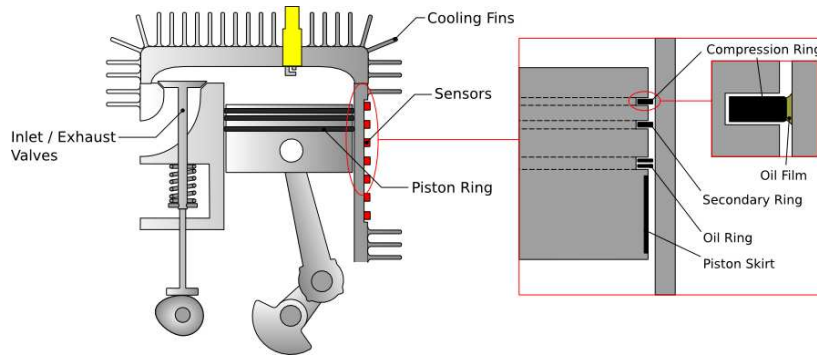


Figure 2: Engine section depicting contacts being investigated

(see figure 2) however this was the only structural modification that had to be performed.

Principally, the technique uses a piezoelectric element bonded to the exterior surface of the contact to generate an ultrasonic pulse when excited with a short duration voltage signal. This sound wave propagates through to the interface where some of the energy is lost through the contact before being reflected back to the element. This energy loss depends partly on the thickness of the fluid film, changing the condition of the reflection and it is this effect that is exploited in these measurements. The particular piezoelectric transducer configuration used in this work is often referred to as the 'pulse-echo' method, whereby the same transducer acts as the emitter (sending the pulse) and receiver (sensing the reflection). The transducers used for this system were made from low cost, off the shelf 10MHz piezoelectric discs formed from high sensitivity Lead Zirconate Titanate (PZT). The nominal diameter and thickness of the piezo-elements was 7.1mm and 0.2mm respectively and came pre-sputtered with wrap around electrodes of silver. The spatial resolution of the measurements depends partially on the geometry of the sensors. If used in the disc form, the sensing area would have been approximately 5 times that of the thickness of the ring. As a consequence, the disc elements were modified to form strips, 7.1mm long and 1.5mm wide, comparable to the width of the compression ring, providing a much narrower sensing area.

To obtain measurements at a series of locations down the axis of the cylinder, an array of 7 sensors was bonded to the modified region of the cylinder; shown in figure 3, using a high temperature adhesive (*Vishay M-bond 610*). Unfortunately, due to the arrangement of the head clamping bolts, it was not possible to place a sensor at the TDC position of the compression ring where the minimum film might be expected.

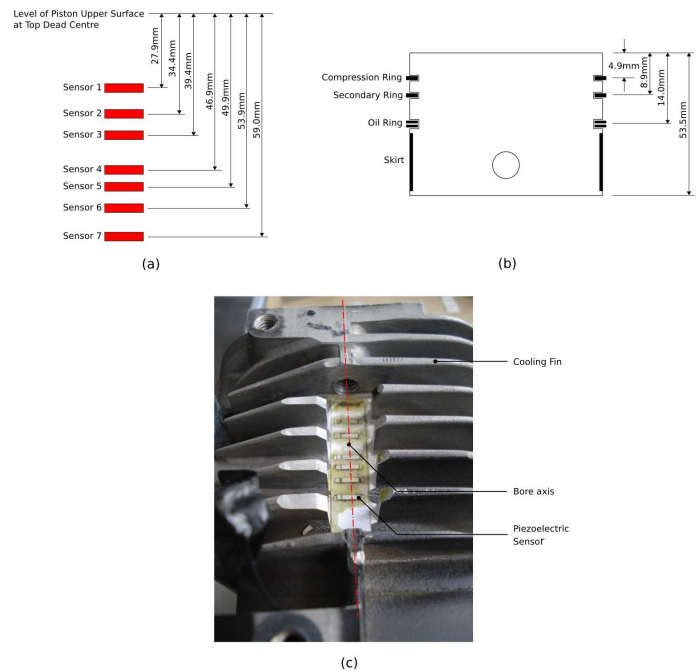


Figure 3: schematic showing (a) sensor position on bore, (b) ring position on piston and (c), photo of sensor array

The Acquisition Equipment

To generate and receive the ultrasonic signals, a PC fitted with a pulser-receiver card generating short duration voltage pulses was used. To excite the 10MHz central frequency of the PZT elements, a -25V 'top-hat' signal of 100ns duration was employed at a repetition rate of 40K pulses per second. At this rate it was only possible to monitor a single sensor at any one time so a remotely operable multiplexer was used to sequentially switch between different sensors during test runs. Each reflection was digitised with 12 bit precision at 100M samples per second and streamed directly to the hard disc for storage. Due to the high capture rate, all analysis was performed in a post-processing routine. To provide a measure of oil temperature, a thermocouple was placed in the oil sump. A schematic showing all sensor instrumentation on the engine is given in figure 4.

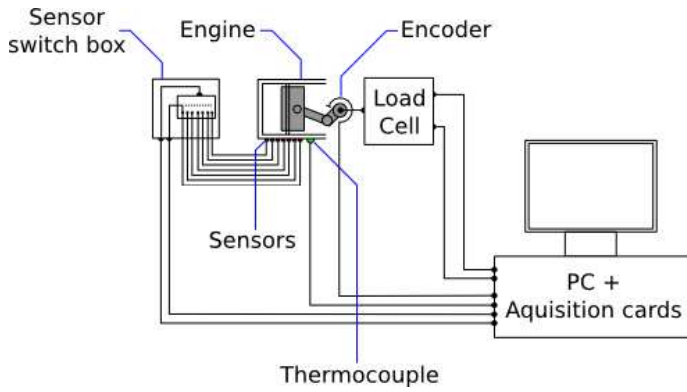


Figure 4: Schematic overview of system

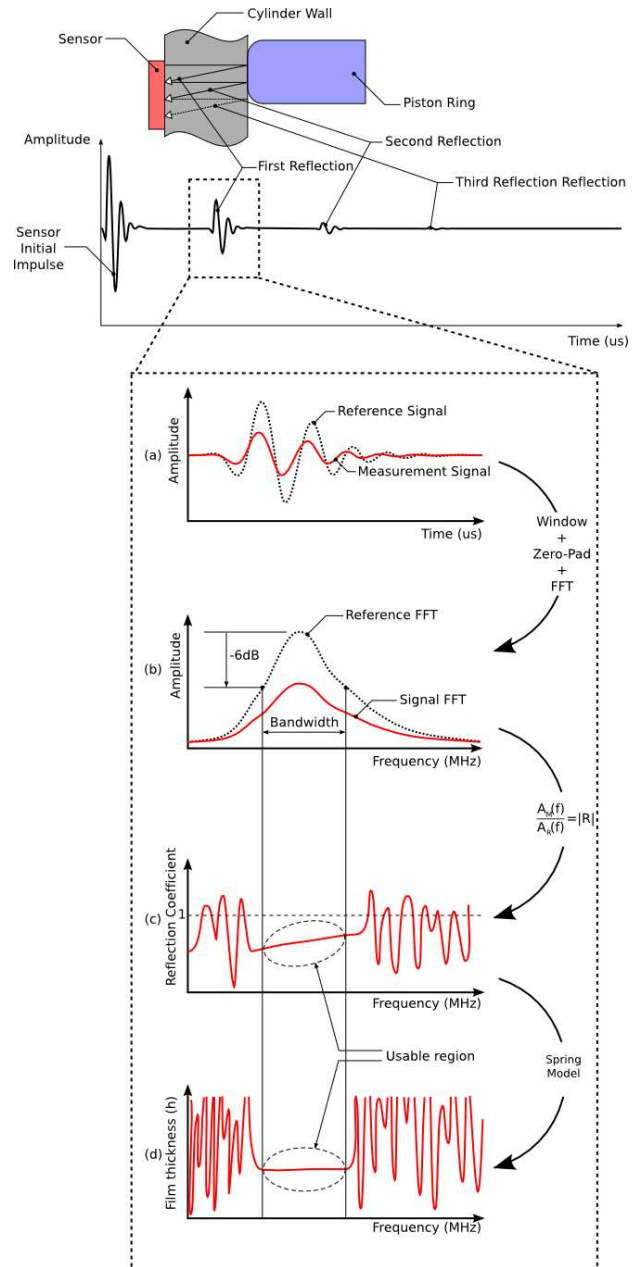


Figure 5: Signal processing sequence showing a schematic of the A-scan produced from an interface. (a) Time domain signal for an air interface (reference) and oil film, (b) Time signals transformed into the frequency domain, (c) Reflection coefficient obtained by the division of film FFT by reference FFT.

Ultrasonic Signal Generation and Acquisition

To recap, the ultrasonic wave generated by the PZT elements propagates towards the internal surface of the bore at which point a portion of the wave is reflected back to the transducer. The amplitude and frequency content of the reflected portion of the signal, in part, is governed by the conditions of the contact. However this ultrasonic wave will undergo a series of additional reflections as it bounces between the internal and external cylinder surface (shown schematically in figure 5) and the PZT element will sense these multiple 'echoes'. While the wave propagates, energy is lost through three main mechanisms; the degree of acoustic coupling at the interface surfaces (governed by the conditions of the oil film), the geometric dispersion of the wave and attenuation within the carrying media (in this case the cylinder wall). As a consequence the first reflection was captured (corresponding to the cylinder-ring contact) to maximise the signal-to-noise ratio, being extracted from the rest of the signal using a simple rectangular window. This method had the additional benefit of reducing the rate of data being stored enabling the pulse rate to be maximised (see figure 5).

Analysis Procedure

In having the piezo elements at a fixed locations and having the piston moving past each sensing region, the acquired reflections consisted of certain portions of the cycle where the piston was 'visible' and others where it was not. During the period of absence, a reference signal was obtained by averaging a set of reflections from the aluminium-gas interface. For the purposes of this measurement process, this reference reflection could consid-

ered a total internal reflection of the sound wave as approximately 99.99% of the incident acoustic energy is reflected under such conditions. By generating local references for each engine cycle, any drift in sensor response (due to temperature changes etc.) could be removed.

Mathematically processing the data to obtain oil film thickness is now well documented in many articles, [7], [5] and is explained only briefly here. This ultrasonic technique is inherently based on physical principles of the system meaning that a calibration as such is not required. Instead, experiments to determine the validity of the process steps have been carried out [21]. Excellent agreement was documented for the quasi-static spring model technique.

Initially, the reflected signals (reference and measurement) are processed using the fast Fourier transform and a frequency-wise division is performed to give a frequency dependent reflection coefficient. The frequency range within the -6dB bandwidth of the sensor was then processed using the quasi-static spring model proposed in [12] with the mean film calculated from the frequencies contained within the specified bandwidth. As an overview, the reflection coefficient $|R|(\omega)$ can be related to the stiffness of the lubricant layer by equation 1.

$$R = \frac{(z_1 - z_2) + i\omega(z_1 z_2)/K}{(z_1 + z_2) + i\omega(z_1 z_2)/K} \quad (1)$$

z_1 and z_2 are the acoustic impedance values of the cylinder wall and piston component, formed from the the product of the speed of sound, c and the density, ρ . ω is the specific angular frequency of the ultrasound under consideration (within the bandwidth of the sensor). To obtain the acoustic properties of the cylinder and piston components, a small piece of the cylinder (removed from part of a cooling fin) and the compression ring were analysed. The density of each was found and speed of sound measured using the 'time of flight' method, whereby the time required for an ultrasonic wave to pass through a section of known thickness was recorded. The product of these two quantities give the materials' acoustic impedance and are given in table 2.

The stiffness, K , can be related to the properties of the lubricant layer by equation 2.

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

Where B is the bulk modulus of the lubricant and h is the thickness of the lubricant layer. Measuring bulk modulus poses a challenge, however it can be related to the speed of sound and density of the fluid as in equation 3.

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

The bulk modulus of oil (and correspondingly speed of sound) is highly dependant on temperature. To characterise the oil, the same 'time of flight' principle was employed by passing a pulse through a channel of oil with a known separating gap at different temperatures (22 to 100°C) and characterised by linear regression, the fit of which is given in table 2. It is prudent to highlight that the bulk modulus is also dependant upon pressure, but poses a more significant challenge to measure, particularly in the contact. For the content of this paper, the properties of the fluid within the contacts was assumed to be equivalent to those at ambient pressure. Various computational simulations have been performed to estimate maximum hydrodynamic pressures within the ring-liner contact, with results ranging from 8MPa to 50MPa [1], [13]. If such higher pressures are assumed to exist (probably unlikely in engine used within this work and even if so, only over a very localised region of the ring), equation 3 suggests that the film may be under-measured as an increased bulk modulus for a constant film thickness will increase the propensity for the ultrasound pulse to be transmitted through the contact and will lower the observed reflection coefficient. An error of the order of 10-15% in film measurement (estimated from data within [6]) could be possible, given such film pressures. This clearly highlights implications of the assumption the validity of which is the subject of current work.

By combining and rearranging equations 1 and 3, the oil film thickness as a function of reflection coefficient is given by 4.

$$h = \frac{\rho c^2}{\omega z_1 z_2} \sqrt{\frac{|R|^2(z_1 + z_2)^2 - (z_1 - z_2)^2}{1 - |R|^2}} \quad (4)$$

Table 2: Engine structure and lubricant acoustic properties

Engine components	Acoustic impedance (MRayl)	Bulk modulus (GPa)
Aluminium Cylinder and Piston	17.3	76
Cast Iron Piston Ring	34.7	169
Lubricant	Density (Kg/m ³)	Speed of sound (m/s)
15W40 motor oil	890	$c = -3.238T + 1519$

The difference in acoustic properties of the piston rings and skirt meant the relevant conditions had to be applied according to which part of the piston was present

at any given measurement. For situations where the film at the piston skirt was being measured, resulting in an aluminium-oil-aluminium system, equation 4 could be simplified to equation 5 as z_1 and z_2 were equal.

$$h = \frac{2\rho c^2}{\omega z} \sqrt{\frac{|R|^2}{1 - |R|^2}} \quad (5)$$

Cycle sequence analysis

Under the described set up it was not possible to obtain an absolute measure of crank angle for each ultrasonic pulse, but there were sufficient differences in signal structure over the four strokes to identify individual cycles. To separate and extract cycle sets from the film data, an algorithm was written to take a 'master' cycle; identified by the user, and cross-correlate it with the entire data set to identify similar matching sub-sequences. To overcome the lack of absolute crank position and locally varying speed of the engine, the 'master' sequence was stretched and cross correlated iteratively to respond more robustly to locally faster and slower cycles (resulting from the fluctuating engine speed). The array of identified cycle sets was then analysed to extract the average minimum oil film thickness (MOFT) at the different sensor positions for the compression ring and skirt. During this process, the appropriate material boundary conditions were applied according to the piston position and the local temperature of the oil was accounted for.

Results and Discussion

A set of test runs were performed involving idle and loaded conditions. The throttle of the engine was set manually, but the shaft speed was metered by an inertial governor and meant that specific load/speed combinations could not be set.

Visualisation of oil film

The engine throttle was set to approximately 90 percent of its range and allowed to stabilise for a short period. A load was applied to the brake disc and manually controlled to maintain a torque of 7Nm however, due to brake heating and subsequent fluid expansion, fluctuations of ± 1 Nm were observed. This loading produced a mean engine speed of 2,230 rpm corresponding to a measured shaft power of approximately 1.6kW. Data was captured over a period of 5 seconds for each sensor and contained approximately 90 full engine power strokes.

Figure 6 shows shows the measured film from a set of four full cycles of the engine at sensor position 6, with each of the data sets plotted in a different colour. Of note is the

degree of repeatability between the cycle sets, particularly at each of the rings. The lower portion of figure 6 shows how the measurements relate to the movement of the piston with the highlighted line passing through sensor 6 on the barrel.

Figure 7 focuses on the expansion stroke. Each of the rings is well defined including the twin rails of the oil scraper ring despite each rail having a width of 0.8mm. The lands of the piston were not visible as the diameter was approximately 500 microns smaller than the bore (at room temperature), meaning that the thickness of the oil film would have been outside the functional range of the spring model. It should be noted that the measured profile of the ring observed in the film thickness data does not directly correspond to the true geometric shape of the ring. The observed curvature is the result of the ring passing the observation window of the sensor which is 2/3 the width of the compression ring. In the current form, it is only the minimum point of the dip that provides a meaningful measure of film thickness as away from this point, the processed data applies to a partial overlap of the ring and observation window, appearing as a thicker film.

Film thickness at the compression ring

MOFT data has been plotted in figure 8 and for clarity, the individual strokes of the cycle have been isolated with each data point formed from the mean of a series of cycle sets. The standard deviation is plotted to indicate the degree of variation between cycle sets. The local piston speed has been inferred from the local rotational speed of the engine, relative position of the sensor and geometry of the piston.

During loaded conditions (figure 8a), all strokes show that the MOFT increases with piston speed typically from 3.2 microns at 2.2m/s to 5.8 microns at 7m/s. This suggests that a hydrodynamic wedge is forming at the interface, increasing surface separation with increasing lubricant entrainment speed. The data shows good consistency between cycle sets, with the standard deviation generally being below 0.3 microns, though some fluctuation occurred at BDC following the combustion stroke. Little variation between strokes suggests that the compression ring is not supporting a greatly varying load from combustion pressure. Comparing measurements with work by other authors ([17], [18]) gives measurements of similar magnitude erring on the lower side, however it should be noted that the work in both these papers was performed using large diesel engines rather than a small, single cylinder gasoline unit.

Measurements taken during idling (figure 8b) show much thicker films (up to 11 microns) being generated and with greater variation from cycle to cycle. It is possible that this variation was due to the rotational instability inherent of a single cylinder engine and it was noted during oper-

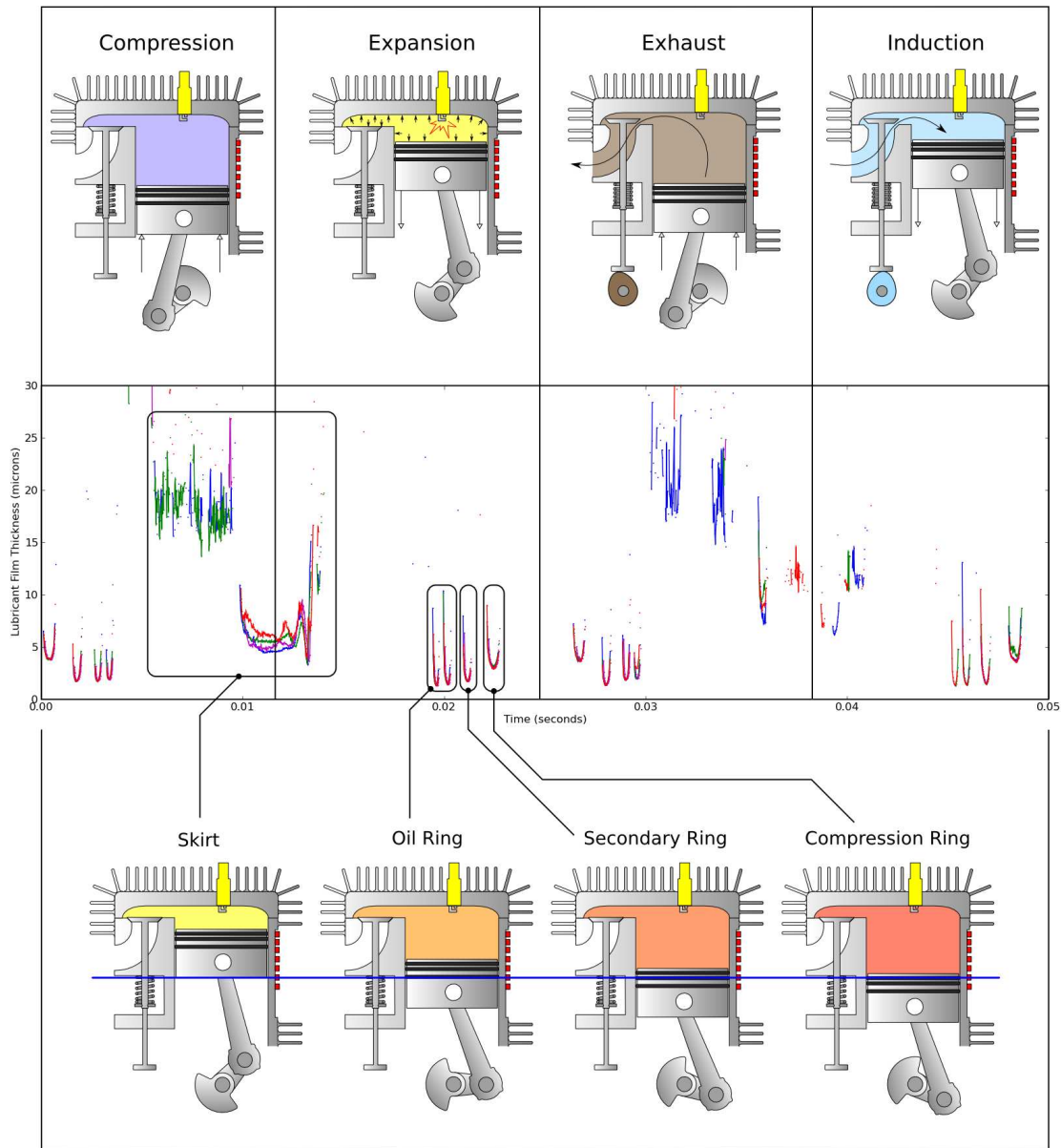


Figure 6: Superimposed oil film traces from sensor 6 as the piston moves through the four strokes of a cycle, with passage of the piston highlighted

ation that the engine would 'hunt' erratically during idle conditions due to the feedback from the speed dependent throttle governor. Only measurements from sensors 2, 3 and 6 only are plotted as those from 4 and 5 were troublesome to pin-point. Future simultaneous measurements of ultrasonic data with crank position would provide a means of geometrically isolating the position at which the compression ring should be visible.

Film thickness at the skirt

By the nature of the experimental set up, the crank position during each sensor's measurement period was different for each of the rings and the skirt. Consequently,

the speed of the piston at each measurement position was different for the skirt and compression ring (as shown in figure 9). In addition to this, the relative length of the skirt meant that it was 'visible' to the sensor over a large portion of the stroke during which time there would have been a significant change in piston speed. Consequently the MOFT data has been plotted against the mean speed of the skirt within the measurement region, given the rotational speed of the engine.

A greater variation in MOFT between cycles is observed when compared to the compression ring, particularly between power and pumping strokes. The minimum film during the power stroke is significantly lower than for the other strokes, between 4 and 7 microns for all sensors, whereas the pumping strokes show a film varying between

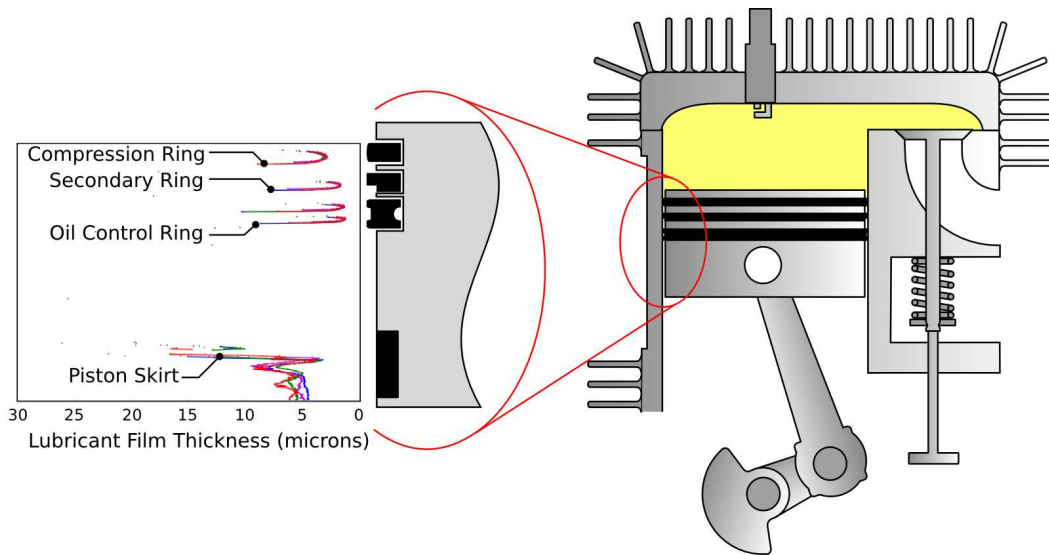


Figure 7: Plot showing expansion stroke from sensor 6

7 and 22.5 microns (at the very extremity of the thickness that can be measured). This result correlates reasonably well with the findings documented in [11] where canting of the piston during the power stroke was observed. The pumping strokes suggest that the film is thicker when the piston is slower, an effect that may be the result of secondary motions of the piston which is also suggested by the large variance at each data point. The compression stroke shows an interesting arched MOFT which may be the result of the pressure building within the cylinder, affecting the local orientation of the piston, though further investigation is warranted to substantiate this hypothesis.

Evaluation of the applicability of the ultrasonic technique

The findings contained within this paper suggest that the ultrasonic technique has the potential to provide a minimally invasive route to obtain oil film thickness information at the piston-cylinder interface. However the authors think it prudent to outline current limitations of the method.

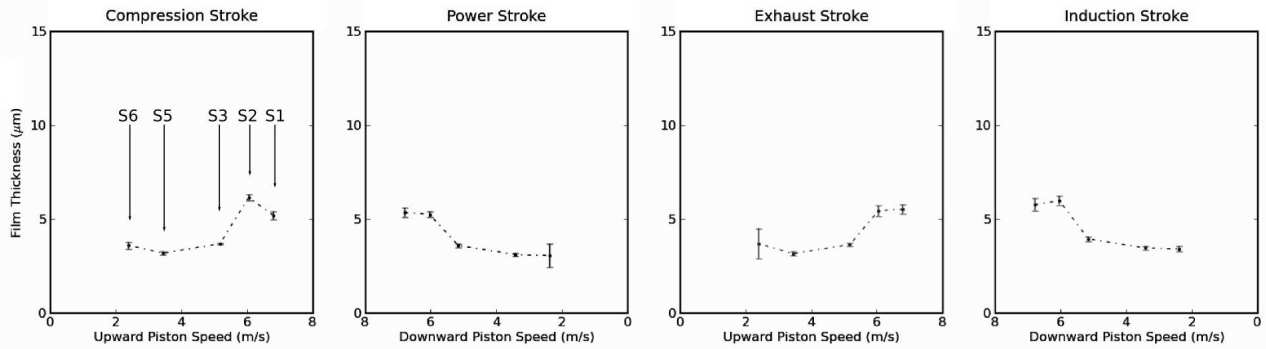
- The bulk modulus of the oil: A key assumption, eluded to previously in the text, is that the pressures within the contact are low enough not to have an effect on the bulk modulus of the oil. Simulations of ring-cylinder contacts however, suggest this may not be the case and so the validity of this assumption is the focus of ongoing research. In addition to the effect of pressure, the presence of contaminants (such as soot) and dissolved air is of interest.
- Spatial resolution of sensors: The size of the sensor in relation to the contact will limit the ability to resolve the true minimum film, particularly at

the ring contact. This issue is also present in other techniques, however improvements are being made to miniaturise the sensors and improve signal processing techniques.

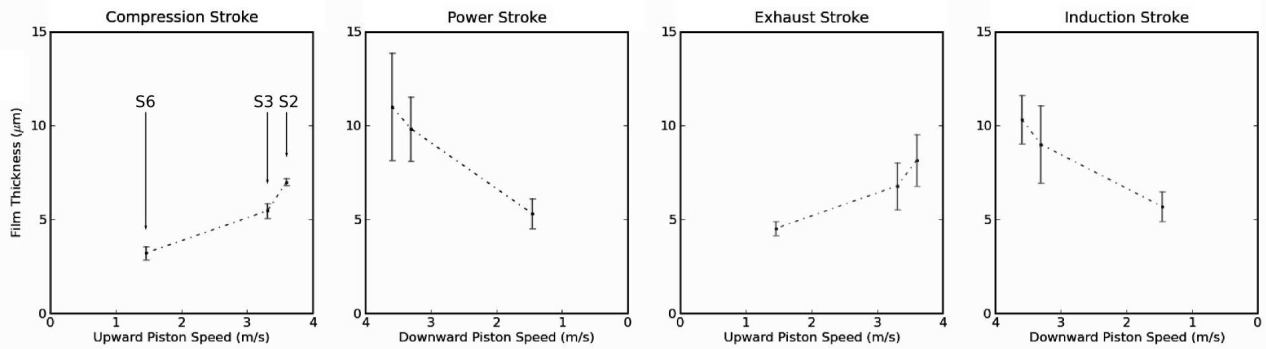
- Data acquisition: The equipment used in this test limits the acquisition rate to between 80K and 100K measurements per second which is lower than that of other techniques such as capacitive measurements where 200K measurements per second are being acquired [17]. Hardware improvements are always being made and would have the potential to increase this limit thus improving resolution particularly at higher engine speeds. However a physical limit (with the current methodology) will exist due to the finite speed of sound of the cylinder material, whereby the echo sequence from a pulse will not have decayed sufficiently before a subsequent pulse is initiated, however this limit is unlikely to be a problem for the speed range of most engines.
- Sensor robustness: This set of experiments has shown that the piezoelectric elements can operate at elevated temperatures, having been placed on the exterior surface of an air-cooled engine and subjected to temperatures in excess of 100°C.

Conclusions

The ultrasonic technique for the measurement of film thickness has been applied to fired, piston-cylinder oil film thickness measurements with minimal modifications to the base engine. The technique shows significant promise as a viable method and future work aims to build confidence and improve on the current capability.



(a)



(b)

Figure 8: Mean film thickness occurring at compression ring during (a) loaded conditions, (b) idle conditions

1. A highly flexible system has been constructed to monitor MOFT within the piston-cylinder contact during combustion with minimal modification to the base engine. The approach has demonstrated the ability to operate without the constraints of dedicated test cell conditions and highlights the potential for installation within road going vehicles.
2. The intermittent nature of the signal observed at each sensor enable compensation routines to be applied, ensuring any response drift due to thermal effects or otherwise can be accurately removed on a cycle to cycle basis.
3. It has been shown that the rings and skirt can be imaged with a high degree of clarity.
4. The high capture rate of the sensors has shown an interesting oscillation at the skirt of the piston during the expansion stroke. This may be the result of 'piston-slap' though more work is required to verify this idea.
5. Results show that MOFT can be measured at the ring-pack and skirt with low data variance when the piston is loaded. An increase in MOFT with speed was observed at the compression ring (though little difference between strokes) varying between

3.2 and 5.8 microns during loaded conditions. The skirt MOFT was much smaller during the expansion stroke (4 to 7 microns) though during pumping strokes the film reduced with increasing speed. The large variance in data however, suggests that secondary piston motions may be the cause.

Acknowledgements

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References

- [1] O. Akalin and G.M. Newaz. Piston ring-cylinder bore friction modeling in mixed lubrication regime: part i - analytical results. *Journal of tribology*, 123:211, 2001.
- [2] C.L. Brockett, P. Harper, S. Williams, G.H. Isaac, R.S. Dwyer-Joyce, Z. Jin, and J. Fisher. The influence

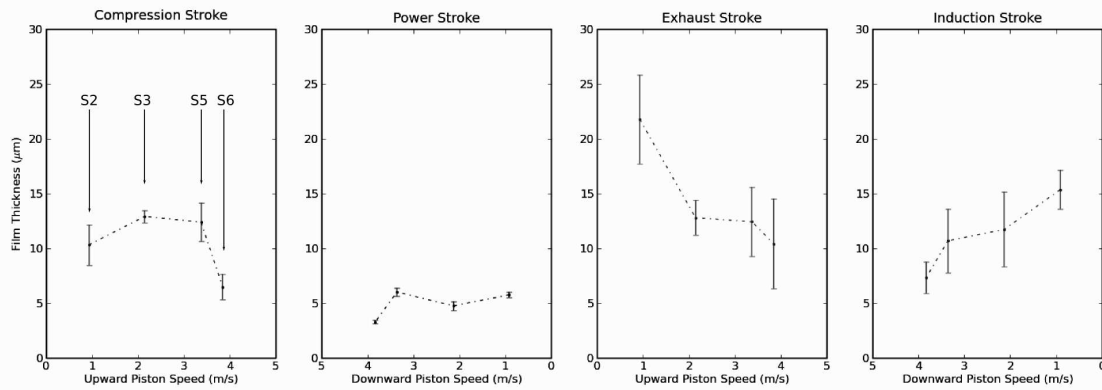


Figure 9: Mean film thickness occurring at skirt during loaded conditions

of clearance on friction, lubrication and squeaking in large diameter metal-on-metal hip replacements. *Journal of Materials Science: Materials in Medicine*, 19(4):1575–1579, 2008.

- [3] JS Courtney-Pratt and GK Tudor. An analysis of the lubrication between the piston rings and cylinder wall of a running engine. *ARCHIVE: Proceedings of the Institution of Mechanical Engineers 1847-1982 (vols 1-196)*, 155(1946):293–299, 1946.
- [4] TA Dow, CA Schiele, and RD Stockwell. Technique for experimental evaluation of piston ring-cylinder film thickness. *Journal of lubrication technology*, 105(3):353–360, 1983.
- [5] RS Dwyer-Joyce. The application of ultrasonic NDT techniques in tribology. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 219(5):347–366, 2005.
- [6] RS Dwyer-Joyce, BW Drinkwater, and CJ Donohoe. The measurement of lubricant-film thickness using ultrasound. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 459(2032):957, 2003.
- [7] R.S. Dwyer-Joyce, D. Green, S. Balakrishnan, P. Harper, R. Lewis, P. King, and H. Rahnejat. The measurement of liner-piston skirt oil film thickness by an ultrasonic means. 2006.
- [8] RS Dwyer-Joyce, P. Harper, and BW Drinkwater. A method for the measurement of hydrodynamic oil films using ultrasonic reflection. *Tribology Letters*, 17(2):337–348, 2004.
- [9] S. Furuhashi and T. Sumi. A dynamic theory of piston-ring lubrication: 3rd report, measurement of oil film thickness. *Bulletin of JSME*, 4(16):744–752, 1961.
- [10] GM Hamilton and SL Moore. Comparison between measured and calculated thicknesses of the oil-film lubricating piston rings. *ARCHIVE: Proceedings of the Institution of Mechanical Engineers 1847-1982 (vols 1-196)*, 188(1974):262–268, 1974.
- [11] M. Kamiya, T. Kobayashi, Y. Mihara, and T. Someya. Measurement of Piston Skirt Oil-film Pressure under Piston Slap. 2007.
- [12] J. Krautkramer and H. Krautkramer. Ultrasonic testing of materials. *Springer- Verlag New York, Inc. 1977*, 667 p(Book)., 1977.
- [13] M. Priest, D. Dowson, and CM Taylor. Theoretical modelling of cavitation in piston ring lubrication. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 214(3):435–447, 2000.
- [14] T. Reddyhoff, R. Dwyer-Joyce, and P. Harper. Ultrasonic measurement of film thickness in mechanical seals. *Sealing Technology*, 2006(7):7–11, 2006.
- [15] T. Seki, K. Nakayama, T. Yamada, A. Yoshida, and M. Takiguchi. A study on variation in oil film thickness of a piston ring package: variation of oil film thickness in piston sliding direction. *JSAE Review*, 21(3):315–320, 2000.
- [16] I. Sherrington and EH Smith. Experimental methods for measuring the oil-film thickness between the piston-rings and cylinder-wall of internal combustion engines. *Tribology international*, 18(6):315–320, 1985.
- [17] S.J. Söchting and I. Sherrington. The effect of load and viscosity on the minimum operating oil film thickness of piston-rings in internal combustion engines. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 223(3):383, 2009.
- [18] M. Takiguchi, R. Sasaki, I. Takahashi, F. Ishibashi, S. Furuhashi, R. Kai, and M. Sato. Oil film thickness measurement and analysis of a three ring pack in an operating diesel engine. 2000.

- [19] LL Ting. Development of a laser fluorescence technique for measuring piston ring oil film thickness. *J. Lubr. Technol.*, 102:165–171, 1980.
- [20] RD Wing and O. Saunders. Oil film temperature and thickness measurements on the piston rings of a diesel engine. *ARCHIVE: Proceedings of the Institution of Mechanical Engineers 1847-1982 (vols 1-196)*, 186(1972):1–9, 1972.
- [21] J. Zhang, B.W. Drinkwater, and R.S. Dwyer-Joyce. Calibration of the ultrasonic lubricant-film thickness measurement technique. *Measurement Science and Technology*, 16:1784, 2005.