MEC6905 iT-CDT Group Mini-Project:

"Instrumenting an Auto Engine to Measure Tribological Components"

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Abstract

Viscosity is the most important property of a lubricating oil. In an internal combustion engine, oil stocked in the oil pan is pumped in sections where sliding and reciprocating motion occur, such as gears, bearings, journal bearings and the piston liner. Because of the high pressure and shear rate in thin layers, the oil viscosity is likely to be very different from that in the bulk, where it is strongly dependent on the temperature of the oil. In addition, further temperature variations around a component like a journal bearing can lead to a change in viscosity [1]. The paper refers to viscosity measurements done on an electrical generator's 4 stroke engine. The viscosity profile of the oil in the bulk is compared with that of the thin layer around the journal bearing. Two methods, "STAMINA (STAnding wave Measurements of INterfaces and lAyers)" and "The quarter wavelength matching layer technique" based on the reflection of ultrasonic shear waves at the solid-liquid boundary, are executed and compared. These are based on the principle that the portion of the wave reflected at the interface can be related to the viscosity of the oil.

Introduction

There has been relentless pressure in the second half of the 20th century to develop ever more fuel efficient engines with reduced environmental impact. From the view of point of the tribologist this means increasing specific loads, speeds and temperatures for the major frictional components of the engine, namely, the piston assembly, the valve train and the journal bearings, and lower viscosity engine oils with which to lubricate them. Inevitably, this leads to decreasing oil thickness between the interacting surfaces of these components and a more crucial role for the topography and surface profile of the two surfaces in determining tribological performance [2].

Around the 20% of energy losses of the energy from the fuel is lost in the friction of these parts and engine and lubricant manufacturers are continually try to improve lubrication to reduce these losses. The main tasks of lubricating oil in internal combustion engines are the reduction of friction and wear, the provision of cooling and the suspension of contaminants. The engine oil is exposed to operating conditions depending on the fuel quality, the ambient conditions and the operating parameters, that strongly affect its rate of deterioration [3].

The most important physical property for the characterisation of the engine oil is the viscosity. It is this that determines the thickness of any separating film that forms and hence the load carrying capacity, affects frictional losses and consequently affects the global efficiency of the engine. Furthermore monitoring the state of the oil allows the implementation of increased oil drain intervals, provides increased insight into the actual state of the engine which may enable the detection of possible approaching engine failures, and allows to evaluate the change in lubrication performance due to the utilization of engine oils of different quality [4].

The viscosity of mineral oil in the bulk is strongly temperature dependent whereas in thin layers of fluid, viscosity is also affected by high pressures and shear rates. Viscosity variation will have a direct effect on lubricant film formation and will hence the lubrication performance of the engine. Although the evaluation of the oil viscosity in the bulk could be done by using viscometer, in sections where oil is present in thin layers the use of viscometer is not possible [4]. A convenient non-invasive method for measuring the viscosity of the oil which was used in these tests, is based on the reflection of ultrasonic shear waves incident at the solid-liquid interface. The measured reflection coefficient was used to calculate the viscosity.

Because of the operating conditions, the viscosity of the oil in the bulk is expected to be different from that of the oil in the thin layer around the journal bearing.

As previously mentioned, viscosity values measured in the pan will be strongly dependent on the temperature of the oil. Tests were done with the scope of evaluating how the electrical load applied to the generator affected the temperature relationship of the oil and consequently its viscosity. The change in temperature of the oil occurs throughout the start-up phase, thus the generator has been turned on with different loads applied with the scope of evaluating the change in viscosity.

Whereas in the thin layer of oil around the journal bearing, viscosity is also affected from other parameters such as the pressure, the shear rate and additional changes in temperature due to the frictional heating of the journal bearing. For this purpose tests were done with the scope of evaluating how the electrical load applied to the generator affected the tribosystem and consequently the oil viscosity.

Final step is the validation of the measurements using an algorithm.

In the following paragraphs the two methods are introduced and a description of all apparatus will be provided.

Methodologies

This chapter provides background information on ultrasound techniques applicable to the objectives of this study.

The purpose of this chapter is to provide a simple introduction on the definitions of sound and of the ultrasound plane waves. Next, ultrasonic transducers are defined with an explanation of the piezoelectric effect and the possible applications of piezoelectric materials. Finally, are briefly analysed the two methodology used in this work for the measure of the oil viscosity in a running engine:

- The quarter wavelength matching layer technique
- STAMINA – STAnding wave Measurements of Interfaces and lAyers method.

Sound and ultrasound

The sound is a pressure wave that propagates throughout a medium by elastic deformation of its particles. In analogy to visible and ultraviolet light, the terms sound and ultrasound are used to describe the propagation of a vibration in different frequency ranges. We talk about ultrasounds when the vibration occurs at frequencies above the human audible limit (conventionally 10^4 Hz). Sound wave type, source and medium directly influence the ways ultrasound propagates. In this study plane wave propagation is analysed. Plane waves are defined as constant frequency waves with wave front propagating as a series of infinite parallel planes.

Ultrasound and sound propagate in fluids (gases and liquids) and solid. The mechanical perturbation provokes tiny disturbance of the medium particles from their resting position. These disturbance induce a displacement of these particles and are transmitted step by step to other parts of the medium. The interaction between the particles can be schematically described using a mechanical spring analogy. When a longitudinal or compressional wave interacts with the particles network the displacement of the particles is parallel to the wave propagation; on the other hand, when a shear or transversal wave interacts with the particles network the displacement of the particles is normal to the wave propagation.

As written above, the conditions of sound propagation in a medium are strictly linked to the material properties. The wave propagation velocity in a given material is called speed of sound. This is characteristic of every material and is given by the relation:

$$c = f\lambda$$

In the equation c is the speed of sound, f is the wave frequency and λ is the wavelength.

Another important acoustic property of materials is the acoustic impedance. This property measures how well a sound wave propagates through a material and is defined as the ratio of the acoustic pressure, the pressure imposed to the atoms when interacting with a sound wave, and the displacement velocity of the particles.

$$z = \frac{P}{\nu}$$

In the equation z is the acoustic impedance, P is the acoustic pressure and ν is the displacement velocity. The acoustic impedance can also be expressed in terms of material density and speed of sound.

$$z = \rho c$$

In the equation ρ is the material density. This equation states that the denser the medium the easier is for the sound to travel through it for longer distances.

As an ultrasonic wave passes through a material it will be attenuated as a function of the distance, eventually decaying to zero amplitude, due to the conversion of ultrasonic vibration energy into other forms such as thermal energy. A simple relation can be used to define the relationship between the initial amplitude, A_0, and the amplitude, A, after the wave has travelled through the material for a distance d.

$$A = A_0 e^{-\alpha d}$$

Where α is the material specific attenuation coefficient.

When a sound wave is incident to material boundaries part of the wave is reflected away from the original trajectory, the magnitude of which depend upon the conditions at the interface. It can be defined a reflection coefficient, R, as the amplitude of the reflected wave, A_R, divided by the amplitude of the incident wave, A_I.

When a sound wave is incident to a boundary between two media, part of the wave is reflected from the interface and the remainder is refracted at an angle given by Snell's law. The magnitude of the reflections depends upon the conditions at the interface. It can be defined a reflection coefficient, R, as the amplitude of the reflected wave, A_R, divided by the amplitude of the incident wave, A_I.

$$R = \frac{A_R}{A_I}$$

The magnitude of R depends on the nature of the interface. If at the interface there are two materials perfectly bonded together, R depends on the acoustic impedance, z, of the two media.

$$R = \frac{z_1 - z_2}{z_1 + z_2}$$

For a solid-air boundary, $z_2 << z_1$, $R \rightarrow 1$ and $A_R = A_I$.

At a boundary a change in the phase (ϕ) of the reflected wave may also occur, depending on the materials at the interface. If the wave is reflected at a boundary from a less dense to more dense material, the phase changes by $\phi = \pi$, if dense to less dense then the change is $\phi = 0$.

Ultrasonic transducers

Ultrasonic transducers are used to generate and receive sound waves; this is possible thanks to a property possessed by a class of materials, the piezoelectric materials, called the piezoelectric effect. When an electric potential is applied to a piezoelectric material a deformation or vibration occurs. Vice versa, when the material is mechanically deformed an electric charge is produced. This particular effect can be used for the production of ultrasonic transducers for non-destructive and non-invasive examinations of real components during manufacture or operation.

Thanks to the piezoelectric effect, ultrasonic transducers can be used as transmitter or receiver of the ultrasonic wave. Some systems use separate transmitters and receivers, while others combine both functions into a single piezoelectric transceiver, as the ones used in this project. In this case, the transducers generates an ultrasound wave which propagates through the medium and is reflected due to a material discontinuity. The transducer acquires the reflected wave, which carries important information about the material properties or the condition at the material boundaries.

Ultrasonic transducers can be used for a wide range of applications, as well as in the field of the medicine or the industry. Focusing on the industry applications, ultrasonic sensors have a variety of uses such as detecting movement of targets and measure the distance to them (in automated factories), as parking sensors (in cars), to detect high-pressure gas or liquid leaks and to conduct non-destructive-testing. Ultrasonic transducers can be used also to determine several different properties and phenomena such as:

- The thickness of a film or coating
- The thickness of an oil film between components
- The viscosity of a layer of fluid
- Presence or absence of a contacting element
- The removal or loss of material from a surface
- Very accurate measurement of length, deflection or thermal expansion.

Methods

Conventional viscometers cannot reproduce the conditions of pressure and temperature that occur in real engine oil films. In this work, shear ultrasound reflectance is used to overcome this limitation as it allows measurements to be realized in-situ, thanks also to the fact that ultrasonic transducers have got small dimensions which allow access to complicated geometries, not accessible in other ways. In the following sections, two novel techniques, developed at the University of Sheffield, are introduced.

The quarter wavelength matching layer technique

A pulse of ultrasound, typically around 5 wavelengths long, is applied via a piezoelectric transducer. The pulse rebounds from the interface and a series of decaying echoes is received by the transducer as the pulse travels back and forth across the component. The amplitude of the measured echo can be compared to a reference measurement, made when there is no other medium in contact with the interface, to calculate the reflection coefficient.

The differences in acoustical properties between materials in lubricated contact lead to reduced transmission of ultrasound across the interface. This leads to very similar values of A_R and A_I causing low signal to noise ratios (SNR). The addition of a matching layer at the interface causes a greater amount of the ultrasound wave to be transmitted at the frequency whereby the matching layer is an odd integer amount of quarter wavelengths thick.

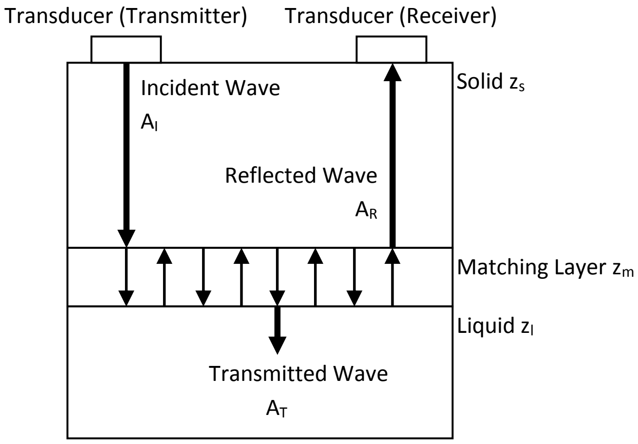

Figure 1: Schematic of the matching layer technique.

This matching layer technique is reliant on the destructive and constructive interference between the incident and the reflected waves interacting at the solid-matching layer interface. The ultrasound waves produced by the transducer are incident upon the matching layer. The reflected waves from the second interface destructively interfere with waves reflected from the first interface as shown in Figure 2. By conservation of energy, the waves transmitted into the liquid will be increased by the same amount. This increase in AT and reduction of AR allows for higher sensitivity to changes in the lubricant properties. The acoustic impedance of the matching layer, z_m, is chosen to be:

$$z_m = \sqrt{z_s z_l}$$

The thickness of the layer is chosen as an odd integer multiple of quarter wavelengths:

$$t = \frac{(2n+1)c}{4f}$$

In the equation *t* is the expected matching layer thickness, *c* is the shear speed of sound in the matching layer, *f* is the frequency and n is a natural integer.

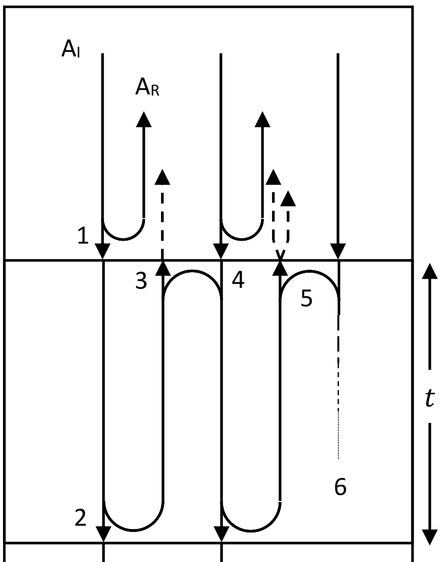

Figure 2: Wave interference in the Quarter Wavelength Matching Layer Technique

Figure 2 shows the individual steps involved in the interference between the incident, transmitted and reflected waves within the matching layer.

1. A wave is incident upon the matching layer, proportion R_{ML} is reflected and (1-R_{ML}) transmitted.
2. The transmitted wave is incident upon the matching layer liquid boundary, $(1-R_{ML})^2$ is transmitted, R(1-R_{ML}) is reflected back into the layer.
3. The reflected wave is incident upon the initial interface, R_{ML} $(1-R_{ML})^2$ is transmitted, however due to the extra half wavelength travelled it is π out of phase with the initial reflection, causing destructive interference. The measured reflected wave is therefore R_{ML}- R_{ML} $(1-R_{ML})^2$.
4. The doubly reflected wave in the matching layer undergoes an additional phase change of π as it has reflected from a less dense to more dense interface. This causes constructive interference with the new transmitted wave, which is now $(1-R_{ML})(1+R_{ML}^2)$
5. The constructively reflected wave reflects upon the matching layer liquid boundary and is incident upon the matching layer solid boundary. The transmitted portion of the wave is R_{ML} $(1-R_{ML})^2+R_{ML}^3(1-R_{ML})^2$ which again causes destructive interference with the reflected wave from the transducer.
6. This process repeats for as many wavelengths as there are in the signal pulse. The reflected wave can be calculated by:

$$A_R = A_I\left(R_{ML} - (1 - R_{ML})^2 \sum_{n=1}^{i} R_{ML}^{2n-1}\right)$$

   where i is the number of wavelengths in the pulse.

The increase in sensitivity due to this process is shown in Figure 3 for an ultrasound pulse 5 wavelengths long. For normal interfaces when $\frac{z_1}{z_2}$ is over 50 it becomes increasingly difficult to detect any change in R, however for the quarter wavelength matching technique $\frac{z_1}{z_2}$ can be over a magnitude larger before this becomes an issue.

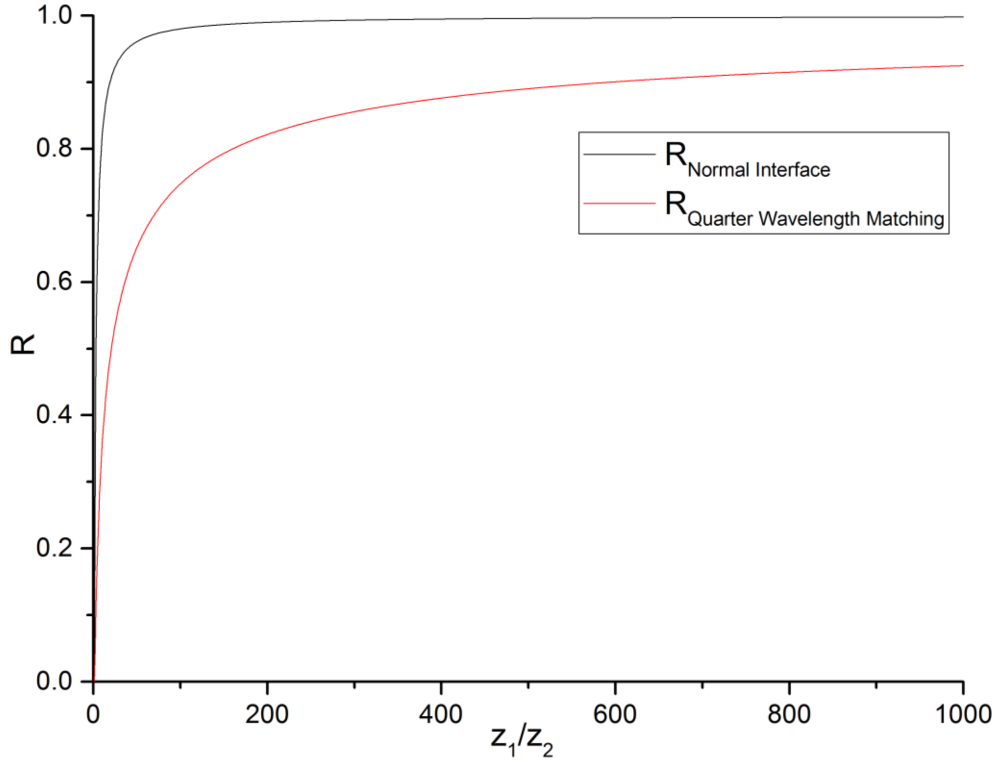

Figure 3: The effective reflection coefficients for a normal interface and one with a quarter wavelength matching layer.

For matching layers that are close to a quarter wavelength thickness, the reflected wave can be calculated by:

$$A_R(\phi) = A_I(\phi)R_{ML} + (1 - R_{ML})^2 \sum_{n=1}^{i} A_I\left(\phi + \frac{4n\pi t}{\lambda} + (n-1)\pi\right) R_{ML}^{2n-1}$$

The value of $A_R(\phi)$ is periodic in t with a wavelength of $\frac{\lambda}{2}$. One cycle of $A_R(\phi)$ for a $\frac{z_1}{z_2}$ value of 100 and $A_I(\phi) = \sin(\phi)$ is shown in Figure 4. The maximum transmitted pulse occurs at an odd integer multiples of quarter wavelengths. Both equations give an effective reflection coefficient of 0.75 for a perfectly matched layer.

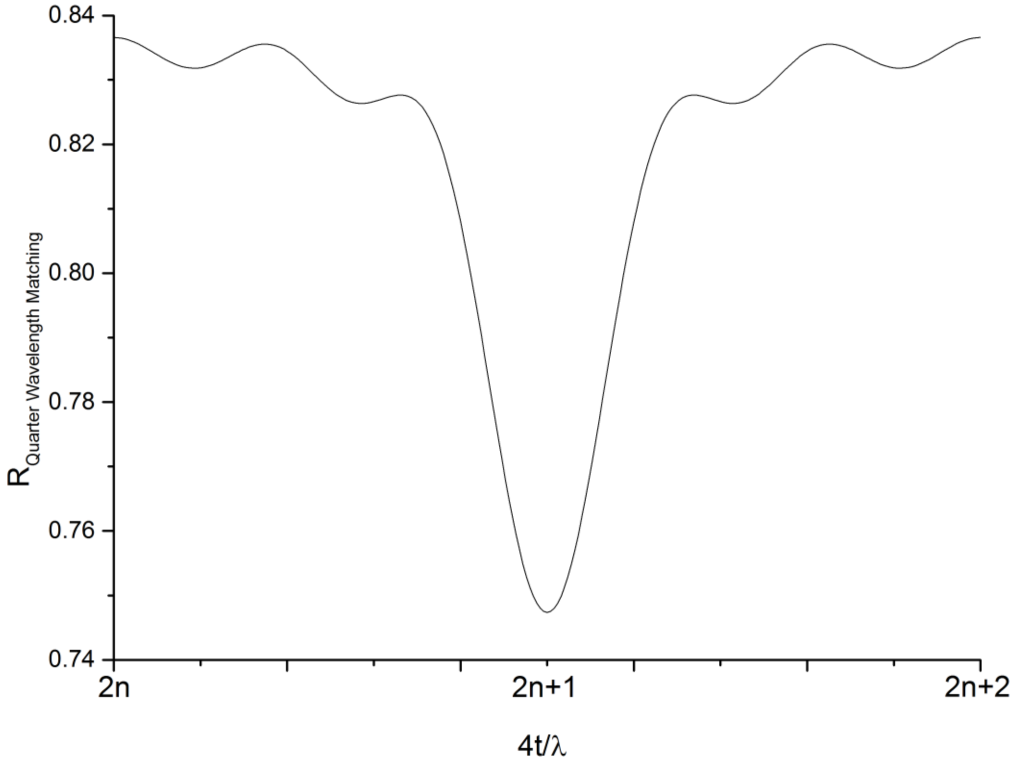

Figure 4: The effective reflection coefficient of an ultrasound wave incident upon a matching layer with varying thickness.

The oil viscosity can be evaluated using a logarithmic relation function of the reflection coefficient, which is obtained dividing a reference signal, $A_r(f)$, acquired when there is no oil present in the system, and the subsequent measurements from solid-liquid interfaces, $A_m(f)$.

STAMINA method

The STAMINA method, (STAnding wave Measurements of INterfaces and lAyers) relies on standing waves being set up in the component being measured. As the wave travels through the material it will attenuate according to an exponential relationship:

$$|A|(x) = |A|_0 e^{x\alpha}$$

where $|A|_0$ is the initial amplitude, x is the distance travelled and α is a material specific attenuation coefficient. Assuming the generated signal is a simple sine wave, the signal detected by the transducer will be a superposition of all waves present in the component given by:

$$A_R = A_0 \sum_{n=1}^{\infty} sin\left(\frac{\omega nL}{c} + n\theta + (n-1)\theta'\right) e^{2nL\alpha} R^n R'^{n-1}$$

where ω is the angular frequency of the wave, n is the amount of times the wave has travelled back and forth from the transducer, θ and R are the phase change and effective reflection coefficient at the solid fluid interface and θ' and R' are the phase change and reflection coefficient at the solid transducer interface. It should be noted that R is dependent on the resonant frequency of any matching layer present.

The amplitude of the wave can be compared to a reference signal measured when there is no fluid present at the fluid solid boundary to calculate the reflection coefficient. The amplitude can be used to measure boundary conditions, in this specific case to evaluate the viscosity of the oil, or to measure any changes in dimensions, as the amplitude of a standing wave is very susceptible to how close the length is to an integer number of wavelengths.

Experimental set up

Experiments were carried out to perform real-time and in-situ measurements of the lubricant properties in an internal combustion engine, by exploiting the ultrasound techniques previously described. A Honda GX630 electric-generator set was chosen due to the relative simple accessibility of the parts to be fitted with sensors. In order to provide a variable load for the tests the generator was connected to three electric heaters that offered an adjustable load of up to 8 kW. Although the ultimate purpose of the study was to monitor the oil film properties in the main journal bearing and in the cylinder-piston interface, the oil sump was first instrumented. This allowed to assess the feasibly of the experiment and the capability of performing the measurements within the restricted timeframe.

A sump-plug was modified to fit a measurement nut and to assure direct contact of this component with the oil (Figure 5). The nut was machined from aluminium and had a thin polyamide layer applied onto the measurement surface, whereas the opposite side was equipped with two piezoelectric transducers, one to generate signals and one to receive. A thermocouple was also included in the nut for calibration purposes. The other sump-plug of the engine was instrumented with a second thermocouple in order to monitor the temperature of the oil.

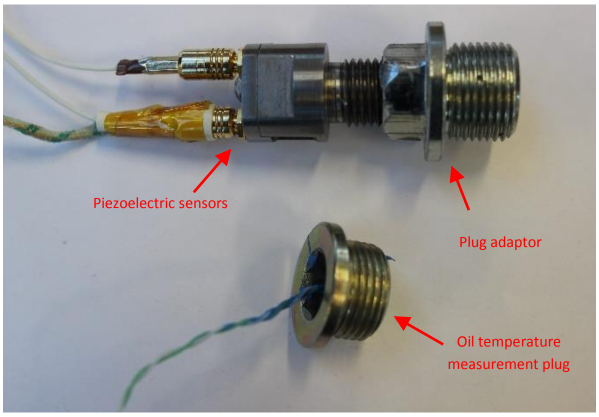

Figure 5: Instrumented sump-plugs.

The piezoelectric sensors were connected to a PicoScope 5000 series device, which functions as both signal generator and oscilloscope. The system was controlled by a computer via a LabView program developed in-house.

Data acquisition

Prior to each test the sump plug was calibrated by recording its response to ultrasound over a temperature range that the engine would operate at. For an unloaded test this was 20°C to 60°C and for a loaded test 20°C to 110°C. The plug was calibrated with both pulses of ultrasound, known as chirps, and continuous ultrasound at a linearly increasing frequency, known as sweeps.

For the chirp mode, chirps from 3MHz to 5MHz were performed with 200mV applied to the transducer. For the continuous ultrasound the frequency started at 0.7MHz and linearly increased to 8.7MHz, with 200mV again applied to the transducer.

The sump plug was screwed into an M14 to M20 adaptor and heated to specific temperatures in a miniature oven. The measured reflected wave was recorded for later use.

For in-situ tests the engine was instrumented and run from start up until the oil temperature had stabilised. Whilst the engine was running alternating chirps and sweeps were applied to the sump plug at the same frequencies and voltages as the calibration. The response to these were recorded.

For the chirp method, multiple echos of decaying amplitude were recorded in both the calibration and in-situ recordings. Fourier transforms were performed on the first echo present in each case and the magnitude of the complex results taken as the amplitude. The in-situ spectrum was divided by the calibration spectrum to acquire the reflection coefficient across different wavelengths. This should result in a spectrum similar to that shown in Figure 4.

For the STAMINA method, the portion of the spectrum with the lowest response in the calibration was studied. This is due to the low values of A_R indicating larger values of A_T and more sensitivity. The magnitude of the in-situ spectrum was divided by the magnitude of the calibration spectrum to acquire the reflection coefficient across different wavelengths.

The viscosity of the oil was calculated using two equations. The first equation is derived from the Greenwood model:

$$\eta = \frac{2\rho_S^2 c_S^2}{\omega\rho_l}\left(\frac{1-R}{1+R}\right)^2$$

where ρ_S is the density of the solid, ρ_l the density of the liquid, c_S the speed of sound in the solid, ω the angular frequency and $R = \frac{A_R}{A_I}$. This was used for the STAMINA method.

The second equation is an empirical fit independent of angular frequency and material properties developed at the University of Sheffield. This was used for the chirp method.

$$\eta = a_2 e^{-a_3\sqrt{\frac{\ln(a_0-R)}{a_1}}}$$

The coefficients are given in table 1.

Coefficient	Value
a_0	0.98305
a_1	-0.92349
a_2	21.198
a_3	4.9335

Table 1: Coefficients for empirical logarithmic equation.

Results

The generator was run for several minutes to allow for the oil temperature to stabilise. For the initial test a load of 8% was applied to the generator until the oil temperature stabilised again. This procedure was repeated with loads of 25%, 50% and 75% of maximum power, with the temperature stabilising between each load change. The following results show the reflection coefficient against time, (Figure 6), along with the temperature change over time.

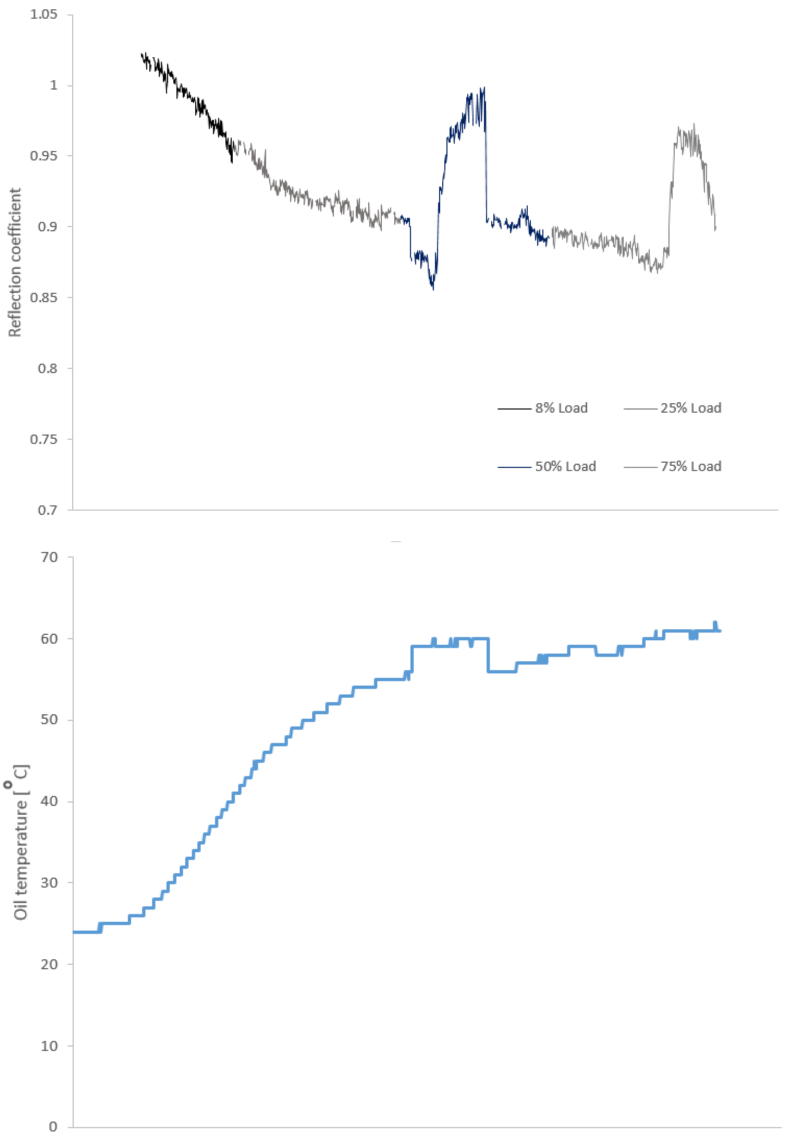

Figure 6: The calculated reflection coefficient, chirp method, for different temperatures and engine loads.

The trend of the reflection coefficient presented in the results is inverse to that of the oil temperature, which increases with time due to application of the load. This result is not consistent with the theoretical behaviour of the system and with the experimental results obtained by Schirru et al. [5] in other application of the technique. The viscosity reduction associated to rising temperature is expected to lead to smaller reflection coefficients.

It should be noted that the expected reflection coefficient when a suitable matching layer is used is at most 0.8 and in most cases between 0.5 and 0.7. In this test the lowest recorded was 0.85 during a very noisy section of data.

For the second test the engine was started from cool and a load of 75% immediately applied. However, all reflection coefficients calculated using the chirp method for this test were within statistical error from 1.

The STAMINA results are not presented for several reasons. For the first test the signal to noise ratio is not satisfactory, with reflection coefficients from 0.7 to 5 being recorded. The calibration signals are also visibly different to the signals captured during the test. For the second test the calculated coefficients are, as the chirp results were, within statistical error of 1. The calibration signals are indistinguishable to the signals captured during the test. As such the authors do not have confidence in the results.

A third test was conducted with the instrumented plug in contact with oil heated to specific temperatures outside of an engine, again the STAMINA and chirp methods both gave reflection coefficients of 1.

Discussion and conclusion

An ICE was instrumented to monitor the oil viscosity in the sump using continuous, non-invasive ultrasound methods. The quarter length wave matching layer method data showed that the variation of the oil temperature influenced the reflection coefficient, however, the relationship was not as expected. Tests immediately after did not show any frequencies in resonance with the matching layer, despite sampling from 0.7MHz to 8.7MHz allowing for matching layers from 10^{-4}m to 10^{-3}m. This implies progressive damage to the adhesion between plug and matching layer which may have affected the measurements. The inconsistency between experimental results and theory may also be related to data misanalysis or to an incorrect calibration process.

One encouraging sign is that the data from the third and second tests were near identical. Whether the plug was in a running engine or not did not appear to have an impact upon the recorded signals, indicating that vibrations and noise from the engine will have a minimal impact upon the data.

Further work

Further work is needed to investigate the causes that have affected the measurements performed. Once these has been resolved, the plug should be again tested in an ICE and viscosities calculated.

The next step of this project will consist in attempting to measure the oil viscosity and film thickness in one of the engine main journal bearings (Journal bearing 1), the location of which can be identified in Figure 7. This was chosen as it offers easier accessibility for instrumentation. The crankcase cover shown in Figure 8 will be bored in order to fit an instrumented bush in which the crankshaft will sit.

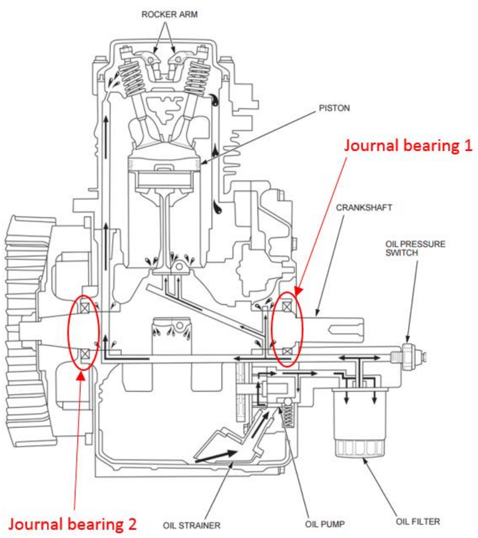

Figure 7 Engine schematic.

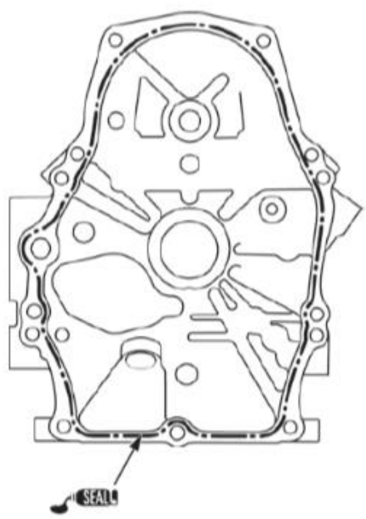

Figure 8 Crackcase cover.

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