VISCOSITY MEASUREMENT IN THIN LUBRICANT FILMS USING SHEAR ULTRASONIC REFLECTION

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Keywords

viscosity measurement; ultrasound; shear wave, ultrasonic reflection; oil film measurement

Abstract

When a shear ultrasonic wave is incident on a solid and liquid boundary, the proportion that is reflected depends on the liquid viscosity. This is the basis for some instruments for on-line measurement of bulk liquid viscosity. In machine elements, the lubricant is usually present in a thin layer between two rubbing solid surfaces. The thin film has a different response to an ultrasonic shear wave than liquid in bulk. In this work, this response is investigated with the aim of measuring viscosity in-situ in a lubricating film. The proportion of the wave reflected at a thin layer depends on the layer stiffness. A shear wave is reflected by the shear stiffness of the thin layer. For a thin viscous liquid layer, the stiffness is a complex quantity dependent on the viscosity, wave frequency, and film thickness. This stiffness is incorporated into a quasi-static spring model of ultrasonic reflection. In this way, the viscosity can be determined from shear wave reflection if the oil film thickness is known. The approach has been experimentally evaluated on some static oil film between Perspex plates. Predictions of the spring model gave good measurement up to layer thicknesses of around 15 μm. For thicker layers, the shear stiffness reduces to such an extent that almost all the wave is reflected and the difference associated with he layer response is hard to distinguish from background noise.

1. Introduction

Fluid viscosity is an important physical property in machine element lubrication. It is this that determines the thickness of any separating film that forms and hence the load carrying capacity. The reflection of shear wave at a solid-liquid boundary is a convenient non-contact method of measuring oil viscosity in bulk samples [1,2]. This has found particular application in the measurement of the viscosity of dirty or contaminated fluids in pipelines and storage vessels.

However, the viscosity of a thin layer of fluid under high pressure and shear rate is likely to be very different from that in the bulk. In addition, temperature variation around a component, like a journal bearing, can lead to a changing viscosity profile. This variation in viscosity will have a direct effect on lubricant film formation and hence the machine performance.

In this paper, an ultrasonic approach for the measurement of viscosity in a thin film is investigated. Longitudinal ultrasonic waves have been used for extensively to study tribological contacts. The reflection of a longitudinal wave depends on the stiffness of the interface [3] whether it consists of a thin liquid layer or an array of asperity contacts. The determination of contact stiffness in this way has allowed the

measurement of oil film thickness in machine components [4-6] and the study of roughness effects in dry contacts [7-11]. Shear ultrasonic waves have also been used to study contacts. The reflection of the wave depends on the shear stiffness of the interface. Researchers have used shear waves to study dry rough surface contacts to compare shear and normal stiffness [12-13] and also shear waves have been used to monitor whether contact occurs in a lubricated face seal [14].

In these previous studies a quasi-static spring model is used to predict the response of the interface to an ultrasonic wave. The layer is thus expressed simply in terms of its stiffness; for thin layers mass and damping terms have no effect on the reflection [15]. Here we extend this approach to consider a shear wave reflected from a thin liquid layer.

2. Ultrasonic Reflection at Solid-liquid Interface

Shear Wave Reflection from a Solid-liquid Boundary

When an ultrasonic wave strikes a solid-liquid boundary a proportion of the wave amplitude is reflected. This proportion is known as the reflection coefficient, *R* and depends on the acoustic impedance mismatch according to [16]:

$$R = \frac{(z_1 - z_0)}{(z_1 + z_0)} \qquad (1)$$

where z_0 and z_1 are the acoustic impedance of the liquid and solid respectively. For a solid the impedance is the product of the density and the speed of sound in the material. For an entirely viscous fluid (i.e. no visco-elastic effects) the acoustic impedance is a complex term given by the expression [1, 17]:

$$z_0 = \left(\frac{\omega\rho\eta}{2}\right)^{0.5}(1+i) \qquad (2)$$

where ρ and η are the density and viscosity of the fluid, and ω is the angular frequency of the ultrasonic wave. Combining equation 1 and 2 and expressing the reflection coefficient in terms of its magnitude:

$$(\rho\eta)^{0.5} = \rho_1 c_1 \left(\frac{2}{\omega}\right)^{0.5}\left(\frac{1-|R|}{1+|R|}\right) \qquad (3)$$

where ρ_1 and c_1 are the density and speed of sound of the solid. This can be rearranged to give:

$$|R| = \frac{1-\dfrac{\sqrt{\omega\rho\eta}}{\rho_1 c_1\sqrt{2}}}{1+\dfrac{\sqrt{\omega\rho\eta}}{\rho_1 c_1\sqrt{2}}} \qquad (4)$$

Equation (4) is shown graphically in Figure 1 for the reflection from a Perspex-oil interface for a range of fluid viscosities. The reflection coefficient is clearly dependent on the frequency of the incident wave.

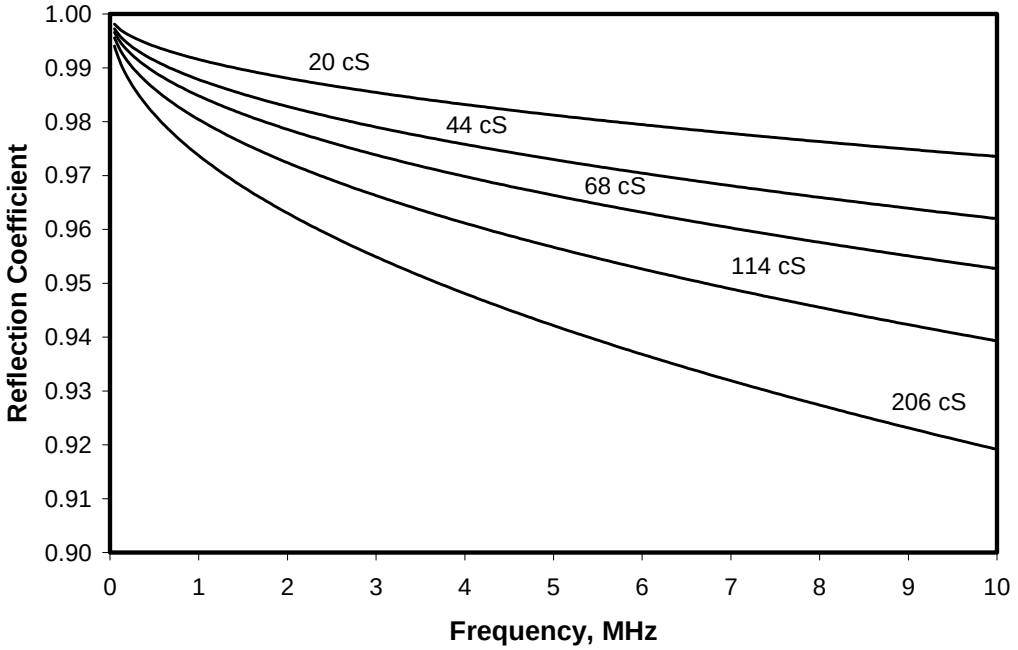

Figure 1. Predicted shear reflection coefficient spectra from a Perspex-oil interface for as range of oil viscosities (equation 4).

Shear Wave Reflection from a Thin Liquid Film

The response of a thin layer of liquid bounded by two solid materials must be treated using a different approach. For a three layer system, where the wavelength of the ultrasonic wave is large compared with the thickness of the middle layer then the quasi-static spring model is applicable [3] and the reflection depends on the stiffness of the interface according to:

$$R = \frac{\left(z_1 - z_2\right) + \frac{i\omega}{K}\left(z_1 z_2 - z_0^2\right)}{\left(z_1 + z_2\right) + \frac{i\omega}{K}\left(z_1 z_2 + z_0^2\right)} \qquad (5)$$

where z_1 and z_2 are the acoustic impedance of the materials either side of the fluid layer and z_o is the acoustic impedance of the thin fluid layer. Equation (5) is applicable to both longitudinal and shear mode ultrasonic waves, provided the shear impedances and the layer shear stiffness are used.

For viscous liquid, the interfacial shear stiffness K of a layer of thickness, h, is a complex number given by [1, 3, 17, 18]:

$$K = \frac{i\omega\eta}{h} \qquad (6)$$

The shear stiffness of the fluid depends on the fluid viscosity and thickness, as well as the ultrasonic frequency. Combining equation (5) and (6) gives a relationship for the reflection coefficient in terms of the fluid film thickness and viscosity:

$$R = \frac{\left(z_1 - z_2\right) + \frac{h}{\eta}\left(z_1 z_2 - z_0^2\right)}{\left(z_1 + z_2\right) + \frac{h}{\eta}\left(z_1 z_2 + z_0^2\right)} \qquad (7)$$

The acoustic impedance of the liquid z_0 is a complex term and is also frequency dependant (equation 2), so it follows that theoretically R is also both complex and frequency dependent. However the term $z_0^2 = \omega\rho\eta i$ is several orders of magnitude smaller than the term $z_1 z_2 = \rho_1 c_1 \rho_2 c_2$ for all conventional solid/lubricant combinations. Thus equation (7) reduces to:

$$R = |R| = \frac{\left(z_1 - z_2\right) + \frac{h}{\eta}\left(z_1 z_2\right)}{\left(z_1 + z_2\right) + \frac{h}{\eta}\left(z_1 z_2\right)} \qquad (8)$$

So whilst both the stiffness and impedance of a thin liquid layer are complex and frequency dependent the reflection coefficient is both real and frequency independent.

In Figure 2, equation (8) is plotted for a mineral oil layer (using η= 0.163 Pas) bounded by various combinations of materials either side. The reflection coefficient amplitude is plotted as a function of the thickness of the liquid film. The measurement range used in these tests (4 to 22 μm) is also shown on the plot.

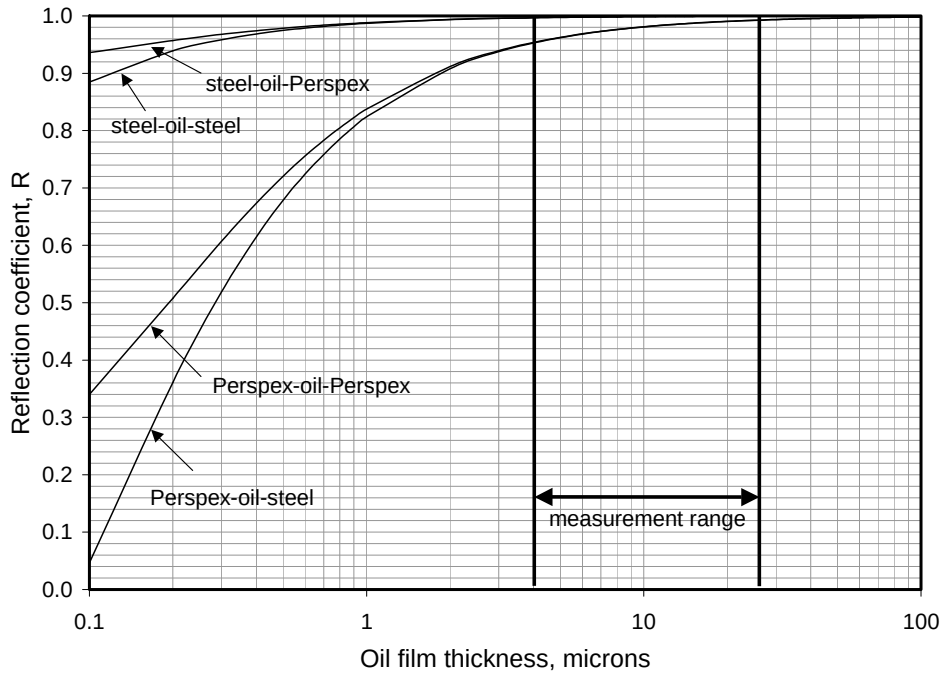

Figure 2. A plot of reflection coefficient versus film thickness for the given condition (using η= 0.163 Pas)

For sub-micron oil films there is a strong dependence of reflection coefficient on film thickness. As the oil film increases the reflection increases rapidly and tends to unity. As expected, the liquid layer transmits very little of the sound wave. The plot also demonstrates that the acoustic impedance of the first material has a much greater influence on the reflection coefficient than that of the second medium. The liquid is such a poor transmitter of ultrasound that the second medium has little effect.

Sub-micron films are difficult to generate over a suitably large area in the laboratory. This test work has been limited to oil films of the order of a few microns formed between flat blocks. Over this region the reflection coefficients are close to one. Clearly for an effective measurement it is preferable that there is a wide as possible range of reflection coefficient variation with viscosity or film thickness. The cases where the first medium is Perspex (acoustically closer to oil than steel) provides a greater change in the reflection coefficient with viscosity and hence easier to detect experimentally. In this work a Perspex-oil-Perspex layered system was used for the experiments.

Where the materials either side of the oil film are identical ($z_1=z_2=z$) equation (8) reduces to:

$$\frac{\eta}{h}=\frac{(1-R)z}{2R} \qquad (9)$$

3. Apparatus

Ultrasonic Signal Processing Equipment

The ultrasonic equipment used in this investigation is shown in Figure 3. The main components are a computer, an ultrasonic pulser receiver (UPR), a digitiser (oscilloscope), and a transducer. The UPR generates short duration voltage pulses. The voltage pulses excite the transducer causing it to resonate, thus sending the required ultrasonic pulse to the medium.

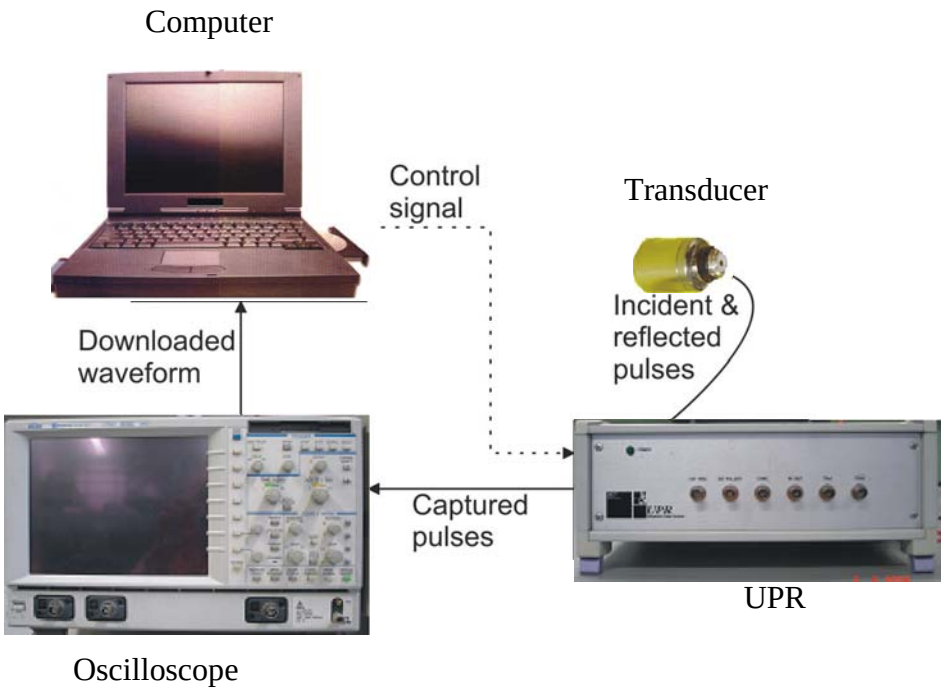

Figure 3. Schematic diagram of ultrasonic measurement apparatus.

The transducer operates in pulse-echo mode as shown in Figure 4. The transducer converts electrical signals supplied by the UPR into a mechanical vibration. When the pulse encounters a boundary, it is partially reflected and received by the same transducer. The reflected pulse is converted to a voltage by the transducer, amplified by the UPR, digitised by the oscilloscope and passed to the computer for processing. A series of LabView routines control the operation of the hardware and the subsequent processing of the received signals.

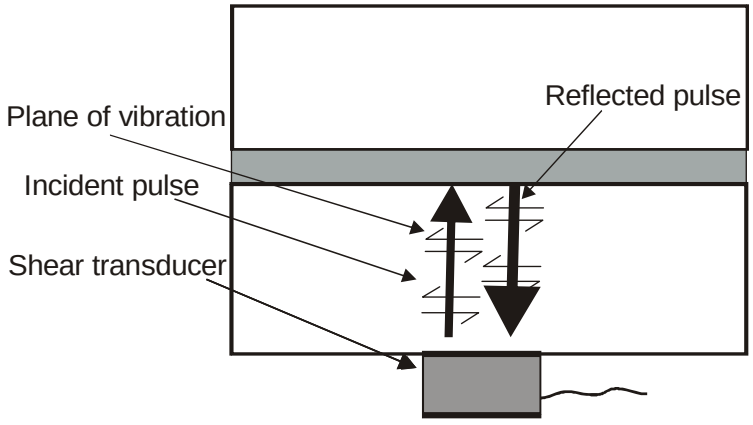

Figure 4. Schematic diagram of the reflection of a shear wave from a thin layer.

Transducer and Coupling

A commercial (Panametrics SN-V156) shear polarised piezo-ceramic transducer was used. The bandwidth of the transducer (measured to a 6dB reduction in amplitude) was between 2 and 3MHz with a centre frequency, where the amplitude was

maximum, of 2.5 MHz. The polarisation causes vibration in a plane parallel to the direction of propagation of the wave.

A thin layer of highly viscous molasses based gel was used to couple the transducer to the underside of the Perspex specimen. Figure 6 shows the view of the transducer through the clear Perspex and oil film assembly. In practice it proved necessary to hold the transducer in place with fixing screws and ensure the experiments were done at constant temperature. Any variation in the thickness of properties of the coupling layer caused a significant change in the amplitude of the signal propagated into the Perspex block.

Model Oil Film Generation

A static oil film was created by sandwiching a drop of Shell T68 mineral oil between two flat Perspex plates. The mass of the oil drop was first measured using an accurate electronic balance. The oil drop was then pressed between the plates as shown in Figure 5. Given the mass, density and diameter of the oil circle, the film thickness could be determined.

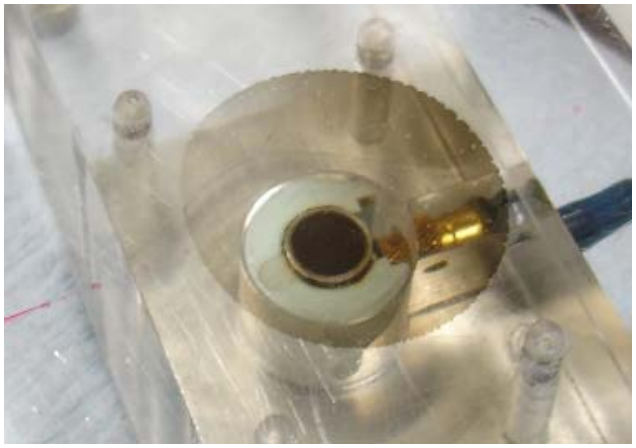

Figure 5. Photograph of the model oil film apparatus. The circle of oil is visible as is the transducer through the transparent blocks.

The oil film thickness was varied either by changing the quantity of oil measured out or by varying the pressure applied to the Perspex plates. A few experiments demonstrated that repeatable oil film thicknesses in the range 4 μm to 22 μm could be generated in this way. Thinner oil films could not be achieved without direct contact occurring between the Perspex sheets at some places. Thicker oil films tended to be harder to maintain constant as the plates start to drift with time.

Signal Processing

The required parameter for measurement was the reflection coefficient. This was obtained by dividing the amplitude of the reflected signal by that of the incident signal. The simplest way to determine the incident signal was to record a reflection when the upper Perspex specimen is removed and there was no oil present. The wave thus reflects from a Perspex-air interface. In this case the pulse was virtually fully reflected (according to equation 1) and so the incident signal equalled the reflected signal. This reflected pulse was stored as a reference pulse.

The upper Perspex block and oil film were then reassembled and pulses recorded from the internal layer. Both the reference signal and the reflected signals were recorded in the time domain. A Fast Fourier Transform (FFT) was performed on each to obtain amplitude spectra. Each oil film reflection spectra was divided by the reference spectra to obtain a series of reflection coefficient spectra, $R(\omega)$. For each frequency the reflection coefficient was transformed to the oil viscosity using equation (9) using the measured oil film thickness from the oil circle diameter. The measured viscosity should then be constant at whichever frequency it is determined.

The signal processing used here is analogous to that for measuring oil film thickness using longitudinal ultrasonic waves. In that method a frequency dependant longitudinal wave reflection coefficient spectra is transformed into film thickness measurements that are frequency independent. More details of this procedure for longitudinal wave reflection can be found in reference [4].

4. Results

Reflection Coefficient Spectra

Figure 6 shows a series of shear reflection coefficients recorded for five different oil film thicknesses. As expected, reflection coefficient values were lower for thin films and higher for thick films. This is because thin film is stiffer than thick films as modelled by equations (5 and 6) and demonstrated in Figure 2.

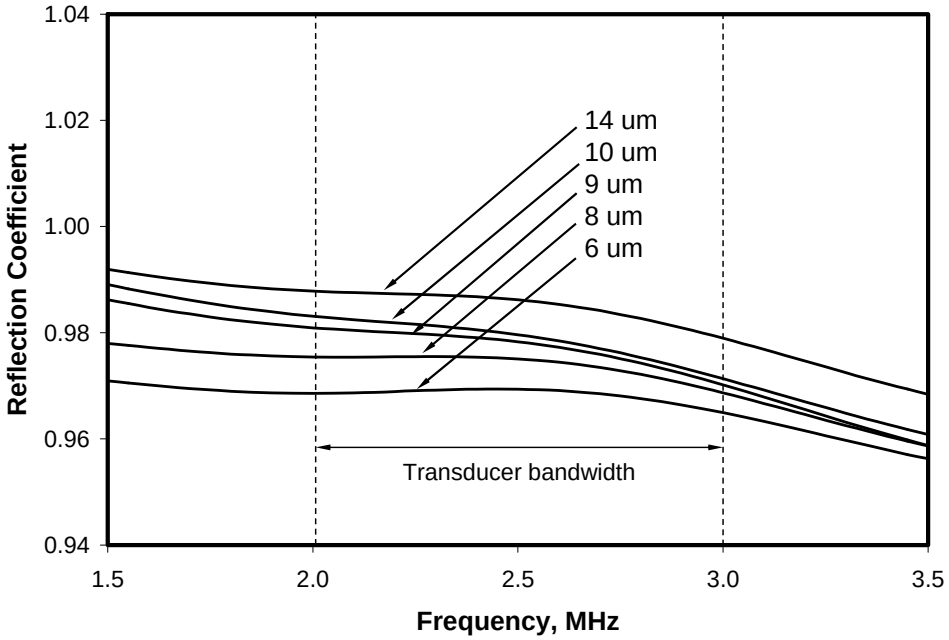

Figure 6. Reflection coefficient spectra from a series of different thickness oil films between Perspex plates.

The reflection coefficient (equation 8) should strictly be frequency independent and therefore horizontal lines would be expected on figure 6. This is approximately the case when the frequency is within the transducer bandwidth (2 to 3 MHz as shown on the figure). There is some slight tendency to the reflection decreasing at higher frequency. To ensure the reasoning described in section 2 above was correct the full equation (5) was plotted. The result was, as expected, frequency independent and so

the assumption that the oil film impedance is negligible is correct. The source of the slight negative slope in figure 6 is not clear at this stage. At higher frequencies the wavelength starts to become comparable with the oil film thickness. This violates the spring model assumption and is a possible source of the observed frequency dependence (discussed further in section 4).

Variation of Reflection Coefficient with η/h ratio

For each measured reflection coefficient spectrum, (including those shown in figure 6) the ratio of η/h was determined; using the datasheet value of the oil viscosity (0.163 Pas) and the film thickness from the oil patch diameter. The mean value of the measured reflection coefficient over the transducer bandwidth was calculated for each test case. Figure 7 shows the experimental data points plotted alongside the theoretical prediction of equation (8).

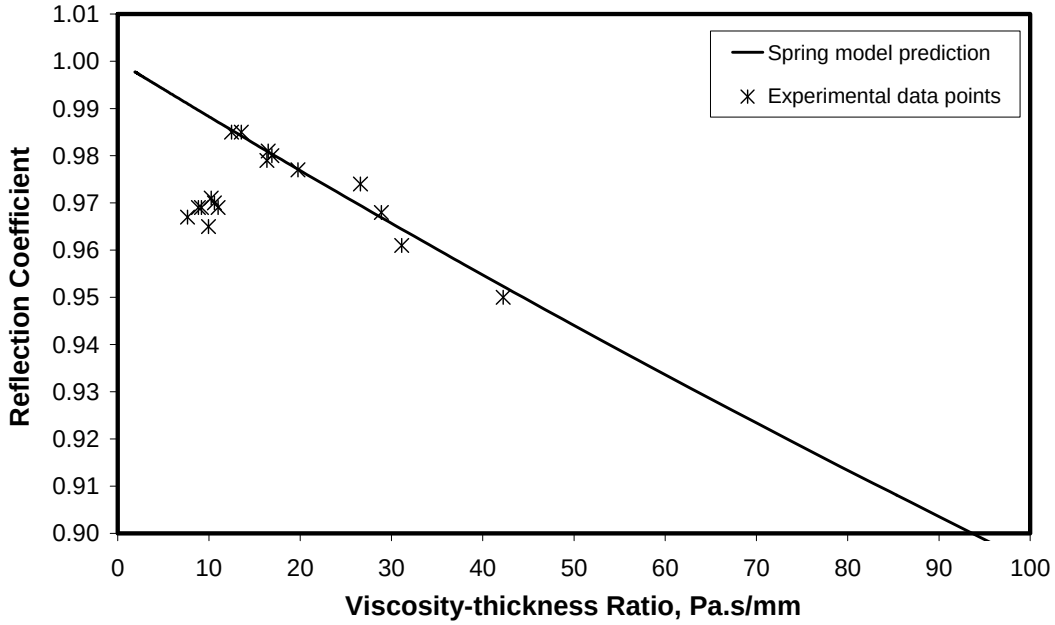

Figure 7. The relationship between η/h and R from experimental data compared with the predictions of equation (8).

The data clusters into two groups. At high values of η/h the data fits the spring model relationship very closely; whilst at low values it clearly does not. The transition value of η/h is approximately 11 Pas/mm which corresponds to measurements recorded from a film of thickness of 15 µm. For oil films below 15 µm the spring model appears to describe the oil film response adequately.

The quasi-static spring model (equation 5) is only valid when the ultrasonic wavelength is large compared with the thickness of the intermediate layer. It is possible that this assumption does not hold at the larger film thicknesses. At this stage it is not possible to accurately determine the shear wave speed in the oil layer, and hence the wavelength.

However, a first approximation for the wave speed was obtained by assuming purely elastic behaviour for the fluid. If this is the case then the acoustic impedance is given

by the product of the density and the wave speed, $z_0=\rho_o c_o$ (in contrast to the fully viscous assumption given by equation 2). A reflection coefficient was measured from a Perspex-oil interface, where the oil was in bulk form and not a thin layer. The measured value was 0.968; this was used to find the acoustic impedance of the oil using equation (1) and hence the wave speed was determined as c_0=31 m/s. For an ultrasonic frequency of 2.5 MHz this corresponds to a wavelength of 15.5 μm. This suggests that the large wavelength is the reason for the discrepancy between the spring model and the observed results for thicker film response.

When an intermediate layer is no longer thin compared to the sound wavelength it must be modelled as a continuum rather than a single spring element [19]. Such modelling is beyond the scope of this work but suffice to say, as the layer gets thicker resonant frequencies are observed and the reflection coefficient reduces as a resonance is approached.

It should be noted that the *longitudinal* wave speed in oil is considerably higher (~1400 m/s) and so the spring model assumption for longitudinal wave reflection holds for much larger oil film thicknesses.

Determination of Viscosity from Ultrasonic Reflection

In Figure 8 the measured reflection coefficient data has been used to compute the oil viscosity (from equation 9); using the oil film thickness measured from the oil patch diameter. Again a mean *R* has been determined over the transducer bandwidth. The predicted viscosity is compared with the datasheet value on the figure.

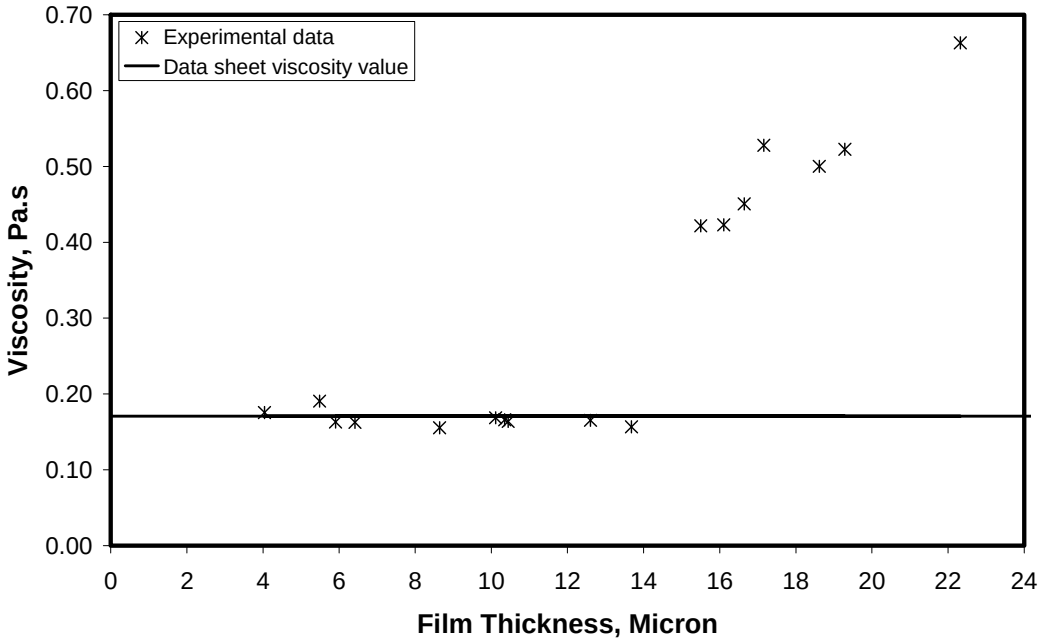

Figure 8. Viscosity determined from reflection coefficients measured from different thickness oil layers.

For oil films lower than around 15 μm, the measurement technique gives results close to the expected value. The viscosity measured from thicker oil films is a considerable over predicted. This means that the measured reflection coefficient lower than expected (also demonstrated in figure 7). If the ultrasonic frequency is approaching a

resonance of the oil film then more transmission and a lower reflection coefficient would indeed be expected.

Determination of Film Thickness from Experimental R

In early work [13, 14], the reflection coefficient amplitude of a longitudinal wave has been used to measure oil film thickness. The same spring model approach was used (equation 8) but the longitudinal wave impedances were substituted. In the same way, if the fluid viscosity is known, the film thickness can in priciple be determined from the shear wave reflection (equation 13).

Experimental reflection coefficient values were used with the corresponding viscosity values from the data sheet to compute the oil film thickness. Figure 9 shows the film thickness determined in this way compared against those obtained from the diameter of the oil patch. The results are shown in Figure 9. Again good agreement is observed for the lower oil film thickness values.

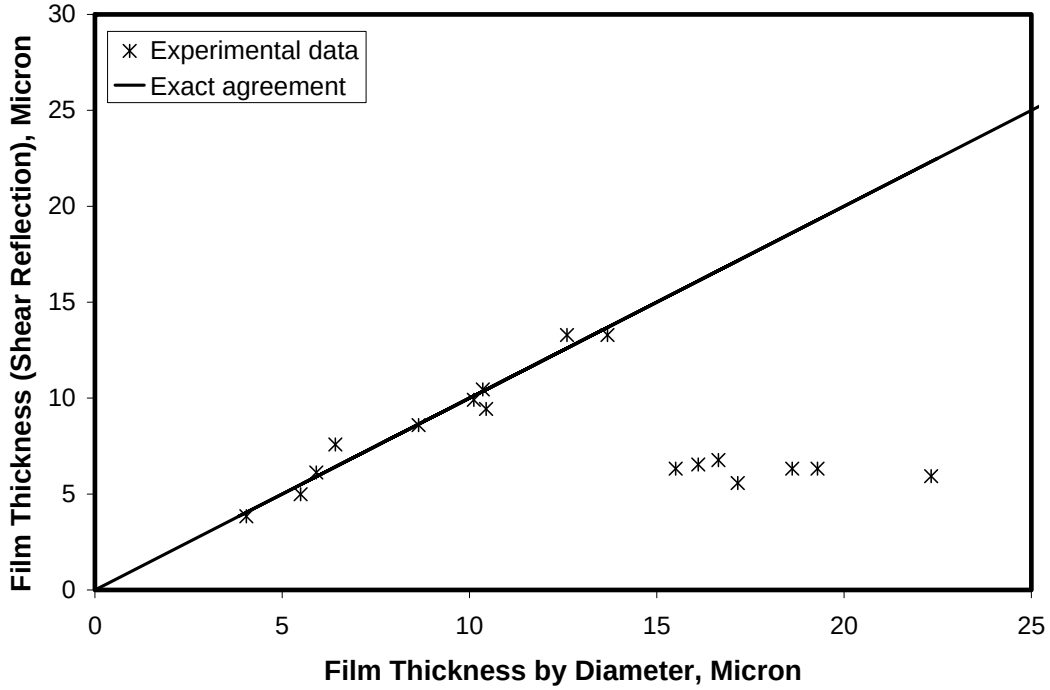

Figure 9. Oil film thickness determined from shear wave reflection compared against measurement from the diameter of the oil patch.

So, provided the oil film is thin (below around 15 μm), and the viscosity is known, this would appear to be a viable technique for measuring oil film thickness. However in this thickness range, the measured reflection coefficients are very close to unity and there is not a large variation with changing film thickness. The approach would be much more robust for sub-micron oil films were the shear wave reflection changes considerably with changing film thickness as demonstrated in figure 2.

5. Conclusion

The reflection of an ultrasonic shear wave at a thin liquid layer can be described by a quasi-static spring model. This is in common with longitudinal waves but in the shear

case, the reflection is independent of ultrasonic frequency. The use of this relationship has been investigated as a method to measure viscosity in thin liquid layers.

Experiments were carried out to record the shear wave reflections from a static oil film between two Perspex plates. An independent measurement of the oil film thickness was obtained by pressing a drop of oil of known mass between the plates. Oil films in the range 4 to 22 μm could be quantified in this way.

The measured shear wave reflection was close to being frequency independent as expected. The data fitted the predictions of the spring model but only up to film thicknesses of approximately 15 μm. Above this value the acoustic wavelength is no longer large compared with the film thickness and the spring modelling assumption is no longer valid.

The reflection data was used in two ways; firstly to determine the viscosity if the film thickness is known; and secondly to determine the film thickness if the data sheet value of viscosity is used. In both cases, good agreement was achieved for thin oil films (less than 15 μm). This approach could be a viable method for measuring viscosity in a lubricating film but best results are achieved for the thinnest layers.

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