Auto-Calibration of Ultrasonic Lubricant-Film Thickness Measurements

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Abstract

The measurement of oil film thickness in a lubricated component can provide information for performance monitoring and design. Lubricant films can be measured by reflecting an ultrasonic pulse from the oil layer. The thickness of the oil film is then readily related to the proportion of the pulse amplitude reflected, known as the reflection coefficient. However, this method requires that the amplitude of the incident wave is known. This is usually determined by measuring a reference reflection when the component faces are separated. The reflection from the component–air interface is then equivalent to the incident signal.

This paper presents a novel approach in which reflection coefficient values are obtained without the requirement for recording a reference. The method involves simultaneously measuring both the amplitude and phase of an ultrasonic pulse reflected from a layer. Then, providing the acoustic properties of the substrate are known, a theoretical relationship between the two can be fitted in order to yield reflection coefficient amplitude and phase for an infinitely thick layer. This is equivalent to measuring a reference signal directly but importantly, does not require that the surfaces either side of the layer are separated.

A further, valuable aspect of this approach, which is demonstrated experimentally, is the ability to be used as a self-calibrating routine, inherently compensating for temperature effects. This is due to the relationship between amplitude and phase being unaffected by changes in temperature that result in erroneous changes to the incident pulse.

Finally error analysis is performed showing how the accuracy of the results can be optimised. A finding of particular significance is the strong dependence of the accuracy of the technique on the amplitude of reflection coefficient input data used. This places some limitations on the applicability of the technique.

Introduction

The thickness of the oil film in tribological components, such as bearings and seals, is a key parameter. If the film is too thin, then surface contact can occur, resulting in high friction and wear. If the film is too thick, energy is expended needlessly in overcoming churning loses. The film is usually so thin that it is small compared to elastic distortions of the bearing elements. For this reason measurement of the bulk separation of the bearing components is not usually sensitive enough to deduce the oil film thickness. Electrical resistance and capacitance have proved useful methods, as

have optical methods. However, all these approaches require modifications to the bearing machinery that frequently preclude their application outside of the laboratory [1-5].

One method that shows potential for non-invasive oil film measurement is the use of ultrasonic reflection. An ultrasonic transducer can be coupled to the outside of a bearing and a wave transmitted through the bearing shell. The wave is partially reflected when it strikes an oil film. The proportion of the wave reflected, known as the reflection coefficient, depends on, amongst other parameters, the thickness of the oil film.

The response of a thin intermediate layer between two solid bodies to an ultrasonic wave can be conveniently determined using a quasi-static spring model [6]. In the context of such thin layers (thin with respect to the ultrasonic wavelength), the reflection is dominated by the stiffness of the layer and it is assumed that mass and damping have insignificant contribution to the reflection coefficient.

For the purposes of the analysis, the layer can be a film of elastic homogenous material (liquid or solid) between two solid bodies, or a region of reduced stiffness, for example a rough surface contact. This spring model method has been successfully used to study adhesive bonds [7, 8], cracks under compressive loading [9, 10], and rough surface contact phenomenon [11, 12, 13]. In the latter case measurements of phase shift have also been used to verify tribological parameters such as percentage contact [14].

Oil films in engineering bearing components are typically very thin (and of lower acoustic impedance than the bearing materials), here the spring model approach provides a suitable method for interpreting their ultrasonic response. In Dwyer-Joyce et al. [15] the approach was evaluated for hydrodynamic and elastohydrodynamic oil film thickness measurement. The validity of the approach has been assessed in laboratory calibration experiments [16] and used to measure the oil film in rolling element bearings [17] and hydrodynamic journal bearings [18].

Typically, ultrasonic measurements of reflection coefficient rely on a reference measurement from a known interface. Often this is most easily achieved from a solid-air interface, and so it is required to separate the component surfaces. For example, in a journal bearing this entails disassembling the bearing and removal of the journal from the bush.

The through-thickness resonance method is a particularly robust approach [19], for ultrasonic film thickness measurement, which requires only the amplitude spectrum of the reflected wave. A typical plot showing minima in the reflection coefficient spectrum resulting from a 1μm oil film is shown in figure 1. If in this way, layer resonant frequencies are measured, film thickness can be obtained with no prior knowledge of the reference signal. This method is however limited to films above 30 μm as thinner films require high frequencies which are prone to attenuation.

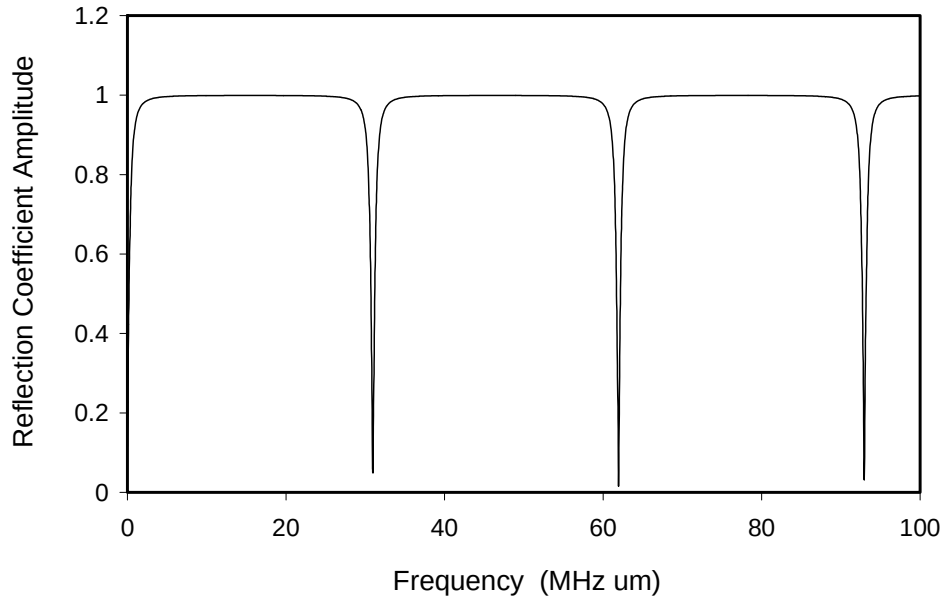

Figure 1. Reflection coefficient amplitude vs. frequency for a 1μm oil film

It is often overlooked that a reflected wave experiences a phase change as well as a reduction in amplitude; the reflection coefficient is therefore a complex quantity having both amplitude and phase. A simple relationship exists between reflection coefficient amplitude and phase [20].

Following the approach suggested by Offterdinger et al. [21], the relationship between amplitude and phase is used to reconstruct a reference reflection coefficient. In doing this, a reference is acquired without separating the interfaces. The validity of this method is proven in a series of experiments where the reference signal is obtained by both the established and accurate separation method, and the new reference-free approach.

Background

Ultrasonic Reflection from a Thin Liquid Layer

When an ultrasonic wave (defined in terms of its displacement amplitude) is normally incident on a boundary between two perfectly bonded media, the proportion of the incident signal reflected (known as the reflection coefficient, R) is given by:

$$R = \frac{z_1 - z_2}{z_1 + z_2} \tag{1}$$

where z is the acoustic impedance of the media (given by the product of density and speed of sound) and the subscripts refer to the two media. Equation 1 shows the reflection coefficient R as having no imaginary parts; this is due to there being no phase difference between the incident and reflected wave (there is simply a reduction in amplitude).

If ultrasound is incident on a three layer system then part of the wave will be reflected at the front face of the layer and part at the back face. For thin layers, the reflected pulses overlap and it becomes impossible to distinguish the discrete reflections. If the lubricant film thickness is very thin with respect to the ultrasonic wavelength then the

layer behaves like a spring and the reflection of the wave depends on the spring stiffness [22].

By considering the equilibrium of forces and compatibility at the boundaries of the layer during the passage of the wave, Tattersall [6] demonstrated that the reflection coefficient of a spring layer was given by the expression:

$$R = \frac{z_1 - z_2 + i\omega(z_1 z_2 / K)}{z_1 + z_2 + i\omega(z_1 z_2 / K)} \tag{2}$$

where K is the stiffness per unit area of the layer and ω is the angular frequency ($\omega=2\pi f$) of the incident wave.

It should be noted that the reflection coefficient for a perfectly bonded interface (R in equation (1)), is a real quantity showing the reflected wave is reduced in amplitude. The reflection coefficient for a layer (R in equation (2)) on the other hand is complex quantity showing that, in addition a phase lag is present between incident and reflected waves.

The stiffness of the oil film is a function of its bulk modulus, B and film thickness, h according to:

$$K = \frac{B}{h} \tag{3}$$

Or in terms of the oil's acoustic properties (Hosten [23]):

$$K = \frac{\rho c^2}{h} \tag{4}$$

where ρ is the oil density, and c is the speed of sound through the oil. Thus, if the oil film stiffness can be measured, then the thickness can be deduced easily from the oil acoustic properties.

Assuming identical materials either side of the lubricant film ($z_1=z_2=z$) the reflection coefficient (equation (2)) can be split up into amplitude $|R|$ and phase Φ_R:

$$|R| = \frac{1}{\sqrt{1+\left(K/\pi f z\right)^2}} \tag{5}$$

$$\Phi_R = \arctan\left(\frac{2K}{\omega z}\right) \tag{6}$$

Combining equation (3) with (5) and (6) leads to two relationships for the oil film thickness, both of which can potentially be used to measure layer thickness:

$$h = \frac{B}{\pi f z}\sqrt{\frac{|R|^2}{1-|R|^2}} \tag{10}$$

$$h = \frac{B}{\pi f z \tan\Phi_R} \tag{11}$$

Combining equations (10) and (11) gives a simple relationship between reflection coefficient amplitude and phase.

$$R = \cos \Phi_R \tag{12}$$

It will be shown that, by fitting this relationship to a set of reflected amplitude and phase data (recorded as the film varies), it is possible to deduce a reference reflection and hence auto calibrate the measurements.

For reasons of brevity in the above modelling, it is assumed that the materials either side of the interface are identical. A complete derivation, without this simplification can be found in [20].

Measurement of Reflection Coefficient

In order to measure film thickness in a bearing, an ultrasonic transducer is coupled onto the bearing back face, such that a pulse is emitted normal to the oil film. The transducer acts as both a transmitter and receiver, and the reflected wave is captured and digitised.

The reflection coefficient amplitude, required for equation (10), is obtained by comparing the signal reflected from the oil film to that from a known reference interface:

$$R(f) = \frac{A(f)}{A_0(f)} R_0 \tag{13}$$

where, $A(f)$ is the amplitude of the signal reflected from the oil film, $A_0(f)$ is the amplitude of the reference signal, and R_0 is the reflection coefficient of the reference interface. The reference interface can be achieved by removing the lower bearing specimen and the oil film. Then the reflection coefficient amplitude, (from a steel-air interface) is very close to unity (R_0=0.9999820).

The reflection coefficient phase, required for equation (11), is defined as the difference between the phase of the reflected wave and the phase of the incident wave. Assuming that the phase of the incident signal remains constant throughout, reflection coefficient phase is obtained by comparing the signal reflected from the interface of interest to that from a known reference interface:

$$\Phi_R(f) = \phi(f) - \phi_0(f) \tag{14}$$

where, $\phi(f)$ is the phase of the signal reflected from the lubricant film, and $\phi_0(f)$ is the phase of the reference signal.

The amplitude and phase of the displacement of a reflected pulse from a thin oil film is shown schematically in figure 2a. The reflection from a typical metal-air reference interface is shown in figure 2b, here the amplitude and phase of the reflected pulse effectively equal that of the incident pulse.

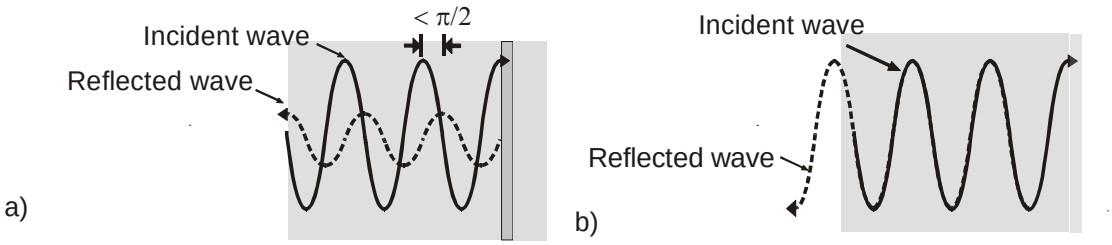

Figure 2. Schematic diagram of pulses from (a) an oil film and (b) a metal-air interface.

Reference Signal and Calibration

Consider an ultrasonic transducer bonded to a bearing shell in order to measure lubricant film thickness. If the temperature of the bearing shell and transducer increases while properties of the film (namely thickness) remain constant, the amplitude of a reflected signal is seen to decrease. This is due to the temperature dependence of the following parameters: the piezoelectric element itself, the properties of the adhesive layer securing the transducer, and properties and dimensions of material.

These temperature effects are detrimental to the operation of an oil film monitoring system, as an increase in temperature would indicate an erroneous reduction in oil film thickness. One solution to this problem is to heat the measuring system in a temperature controlled oven prior to testing, record the variation in response with temperature, and use this to compensate for temperature effects.

The method of auto-calibration described in this paper has important implications for calibration, due to the relationship between reflection coefficient amplitude and phase (equation (12)) remaining constant throughout testing. As conditions change, a new reference can be deduced that takes into account changes to the reflected signal caused by temperature. This negates the need for either updating the reference, or for a thermal pre-calibration of the transducer and pulser-receiver system. However, it should be noted that in order to apply equation (10) to obtain the film thickness, the bulk modulus of the film must be known. The method will be outlined in the following section.

Prediction of Reference Amplitude

If the definitions of reflection coefficient amplitude and phase, equations (13) and (14), are substituted into (12), the resulting expression relates the amplitude and phase of a pulse reflected from an oil film (A and ϕ), to the amplitude and phase the reference pulse (A_0 and ϕ_0).

$$A = A_0 \cos(\phi - \phi_0) \tag{16}$$

This relationship is the basis of the auto-calibration technique. In practical terms, reflected amplitude and phase (A and ϕ) are measured simultaneously, while A_0 and ϕ_0 are the reference amplitude and phase that need to be found. Measured amplitude and phase data for a varying oil film are plotted against each other and equation 15 is fitted to the data using a least mean squared (LMS) algorithm. This is possible because equation (12) applies for all film thicknesses, while the reference amplitude

and phase remain constant. Figure 3 shows an example of the curve fitting approach to obtain values of reference amplitude and phase from the measured data.

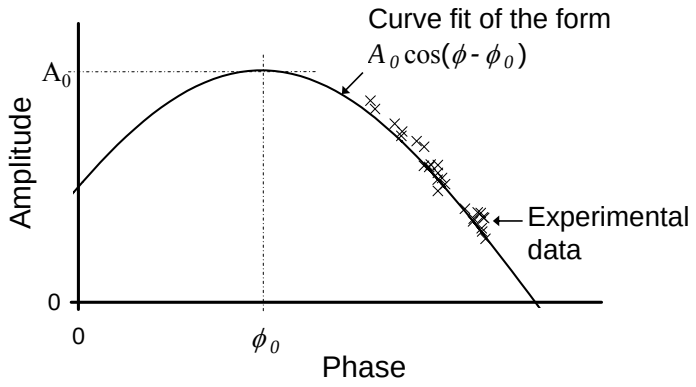

Figure 3. Example plot of amplitude verses phase of pulses reflected from oil films of varying thickness. Also shown on the plot is the curve fit of equation (12), giving constants A_0 and ϕ_0.

Measurement Apparatus

An oil film was produced by sandwiching a drop of oil between two sheets of glass. The mass of the drop was measured accurately. When the drop was pressed between the glass sheets the diameter of the resulting film was measured. The oil film thickness was determined by dividing the droplet mass by the product of the density and the spread-out film area.

A longitudinal wave ultrasonic transducer with a centre frequency of 2 MHz and bandwidth of 1.45-2.50 MHZ (defined at the –6 dB points) was located such that it would send and receive pulses perpendicular to the oil film. The transducer was coupled to the specimen with a permanent adhesive bond.

The transducer was driven by an ultrasonic pulser receiver (UPR). The transducer operated in pulse echo mode and so received reflections back from the oil film. Reflected pulses were digitised (at 500 Ms/s) using a PCI digitising card and stored on the PC for post processing. Bespoke LabVIEW routines were written top control the UPR, digitizer, and perform the required signal processing. A diagram of the experimental setup used is shown in figure 4.

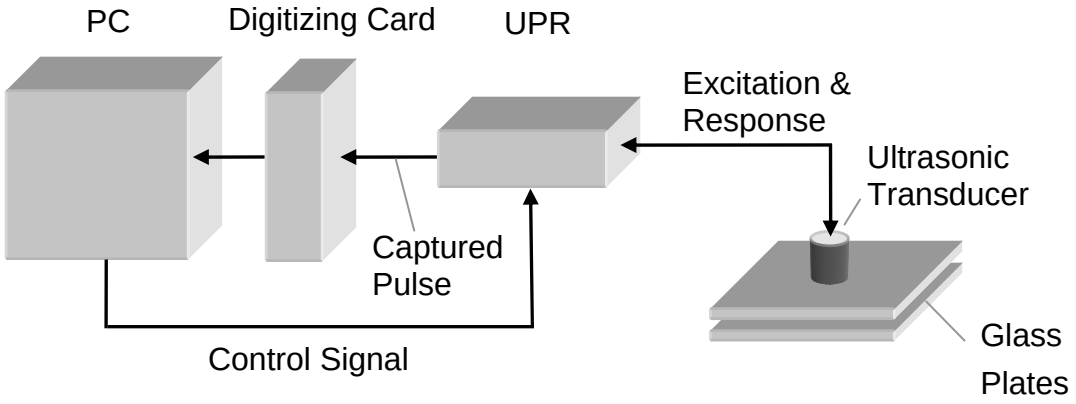

Figure 4: Schematic diagram of ultrasonic apparatus

Results

The first step in the signal processing was to record a reference signal. To achieve this, the glass plates were separated and a measurement of the reflection was then made from the interface between the glass and air. Since the reflection coefficient from this interface is close to unity then the reflected signal will be equal to the incident signal.

The glass plates were then reassembled and drops of oil were sandwiched between the two in order to produce film thicknesses ranging from 5μm to 27μm. The resulting pulses are shown in figure 5. As the oil film thickness decreases, the amplitude of the pulse reduces and the phase shift increases. Each reflected pulse was converted to the frequency domain using an FFT. The reflection coefficient was then calculated via equations (13) and (14), and the lubricant film thickness via equations (10) and (11).

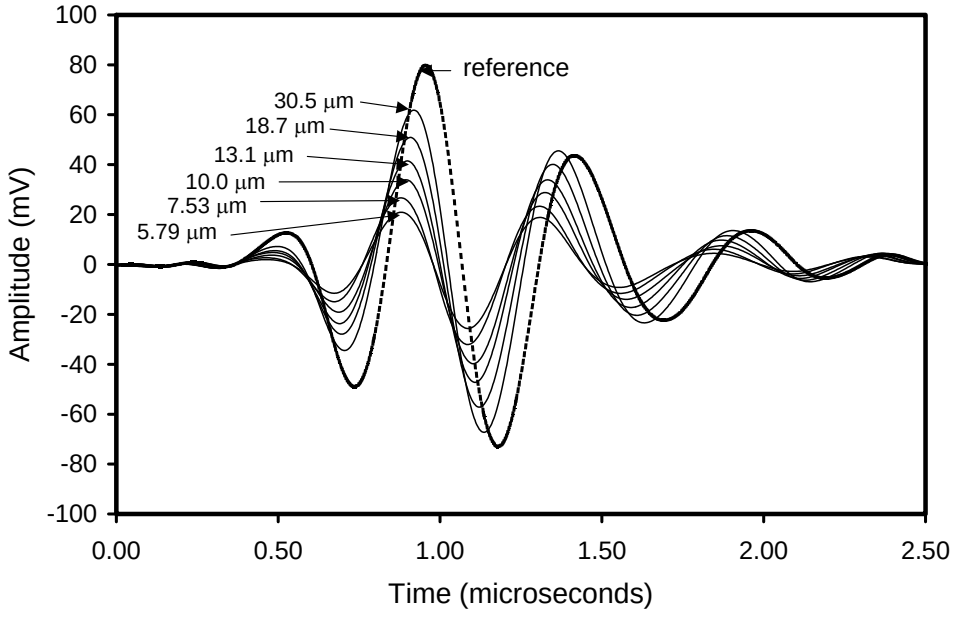

Figure 5. Pulses recorded for a series of oil films of varying thickness.

The amplitude and phase at the centre frequency of the waves reflected from the oil films are shown in figure 6 along with the LMS curve.

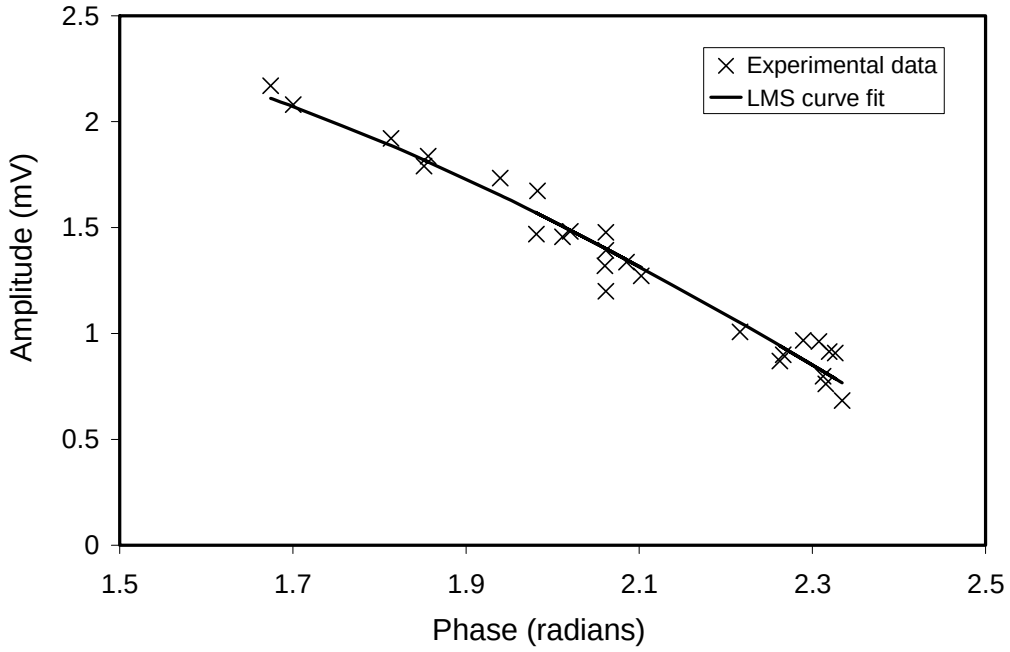

Figure 6. Plot of amplitude against phase at the centre frequency of the wave reflected from the oil film, with LMS curve-fit line.

The auto-calibration technique was then used at 2MHz. Table 1 shows the reference amplitude and phase (A_0 and Φ_0) deduced from the curve fit, alongside values found directly by experiment. There is good agreement between the two methods. It should be noted that the error values are not simply the errors in the LMS (reference free) prediction they are also generated by inaccuracies in the experimental values.

	Experimental value	LMS Prediction	Percentage error
A_0 (V)	2.496	2.570	2.9
ϕ_0 (radians)	1.049	1.067	1.7

Table 1. Comparison of reference amplitude and phase found experimentally with those found using the LMS prediction.

The auto-calibration approach can also be applied over the whole useable bandwidth of the transducer. For each frequency, the amplitude and phase of the reflected signal were plotted against each other and equation (15) was fitted. This yielded a frequency spectrum for A_0 and ϕ_0 that is equivalent to the reference spectrum obtained by taking a FFT of the reference signal. Figure 7 shows the resulting deduced spectrum compared to the measured reference; excellent agreement is seen between the two.

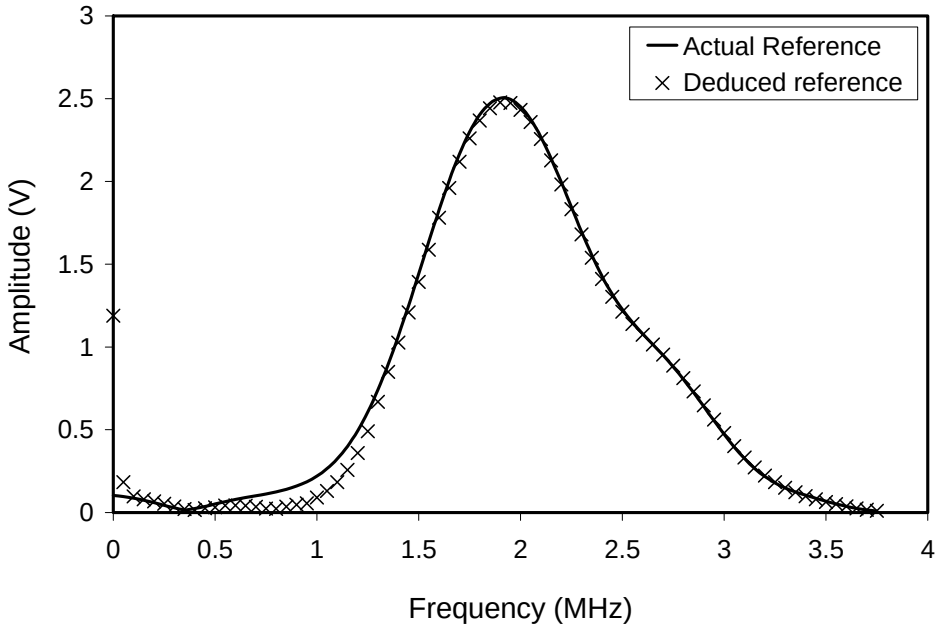

Figure 7. Measured reference spectrum compared to that deduced by the auto-calibration approach.

Analysis of Errors

In the auto-calibration approach described in this paper, the precision of the lubricant-film thickness is governed by the precision of the estimated reference amplitude (A_0 in equation (15)). How to best extract the reference amplitude from a group of signals reflected from lubricant-layers (input data) is therefore the key issue determining the effectiveness of the approach.

Experimental Study

The accuracy of the predicted values depends on several characteristics of the input data, namely the range, mean, and number of data pairs. For the previous tests carried out using the glass plates, the 26 amplitude and phase pairs of input data from films ranging between 5μm and 27μm, corresponded to a reflection coefficient range of 0.60 about a mean value of 0.53.

Here is should be noted that it is the reflection coefficient range that is important in establishing the accuracy of the technique, rather than the film thickness range. The reason for this is that the required film thickness range is specific to frequency of ultrasound used, while the corresponding reflection coefficient range can be used to demonstrate the accuracy of the technique over all applications.

In order to study the effect on accuracy of variations in input data, the following steps were taken. The curve fitting technique was applied as the range of input data was increased. The range was increased in three ways: with an increasing mean, with a constant mean and with a decreasing mean. The three input data cases are described in Table 2, and the resulting LMS predictions are compared to the actual amplitudes in figure 8.

	R_{mean}	R_{min}	R_{max}	ΔR	Number of A, ϕ pairs
case 1	0.27→0.53	0.27	0.27→0.86	0→0.60	1→26
case 2	0.53	0.53→0.27	0.53→0.87	0→0.60	1→26
case 3	0.87→0.53	0.87→0.28	0.87	0→0.60	1→26

Table 2. Input data characteristics; case 1 increasing mean; case 2 constant mean; case 3 decreasing mean.

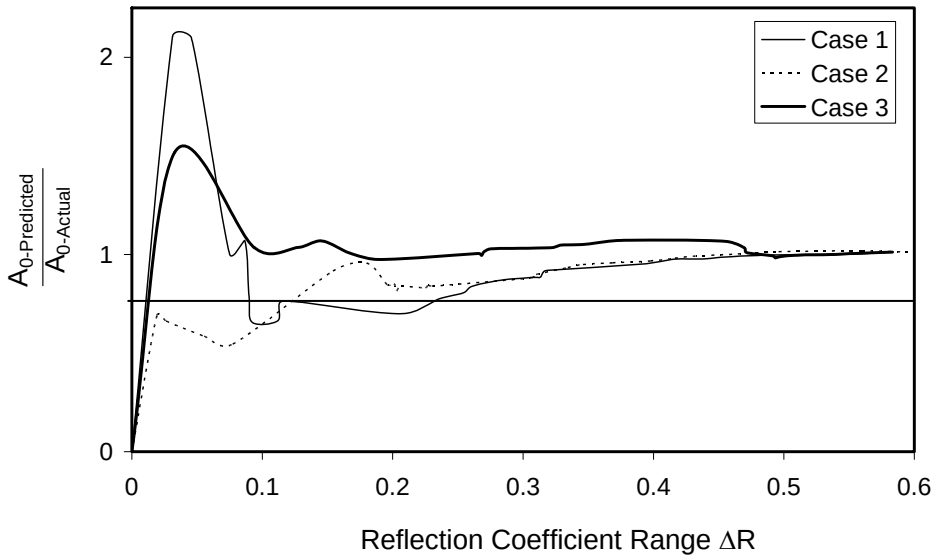

Figure 8. Amplitude of the deduced reference signal plotted against range of reflection coefficient available in the input data.

Figure 8 shows that it is not only the range of input reflection coefficient, but more critically the mean about which the range is located, which affects the accuracy of the deduced amplitude. Best results are achieved as $R_{mean} \rightarrow 1$.

In order to validate the results shown in figure 8, the test on case three was repeated but with a larger set of input data. The results from this test are shown in figure 9. It can be seen that the same trends are present with the large data set, that satisfactory results (error < 3%) are only obtained with a range of R above ~0.35.

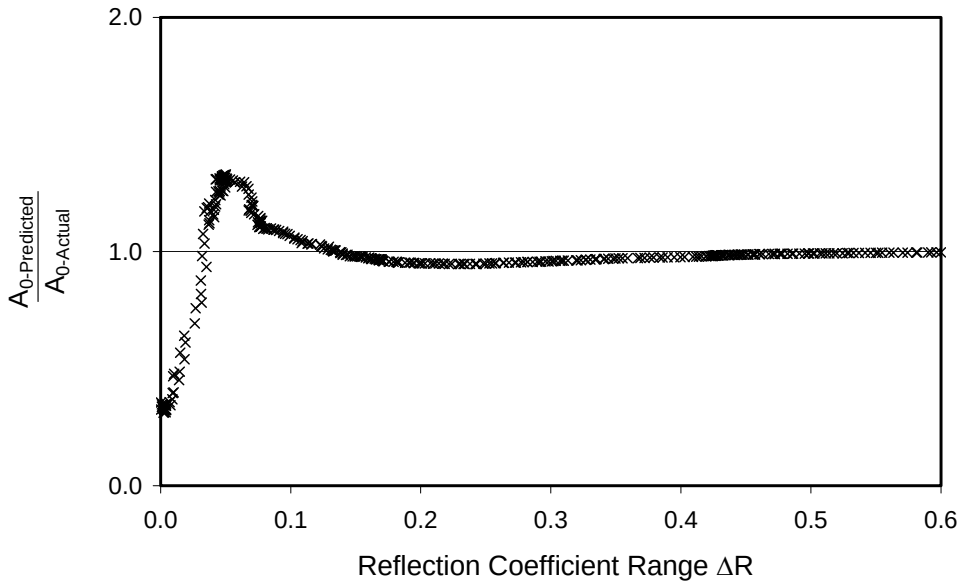

Figure 9. Amplitude of deduced reference signal vs. range of reflection coefficient input for large data set (400 A_0 ϕ_0 pairs).

The results shown in figure 8 and 9 demonstrate that the accuracy of the technique depends strongly on the range of amplitude and phase data used. This has some practical implications for the technique. If the technique was implemented in a journal bearing for example, the bearing may have to be run at and a range of speeds in order to achieve different film thicknesses and hence a sufficient range of input reflection data.

If insufficient input data is given, the curve fitting either under or over predicts the amplitude of the reference. Figure 10 demonstrates how this can occur; in the case shown, errors in the experimental data cause the curve fit peak (and therefore A_0) to be greater than its true value. It should be noted from figure 10 how input data that is close to reference (thick film data i.e. $R \rightarrow 1$, $A/A_0 \rightarrow 1$) is most beneficial to the accuracy of the curve fit; for instance points close to B are of more use than points close to C.

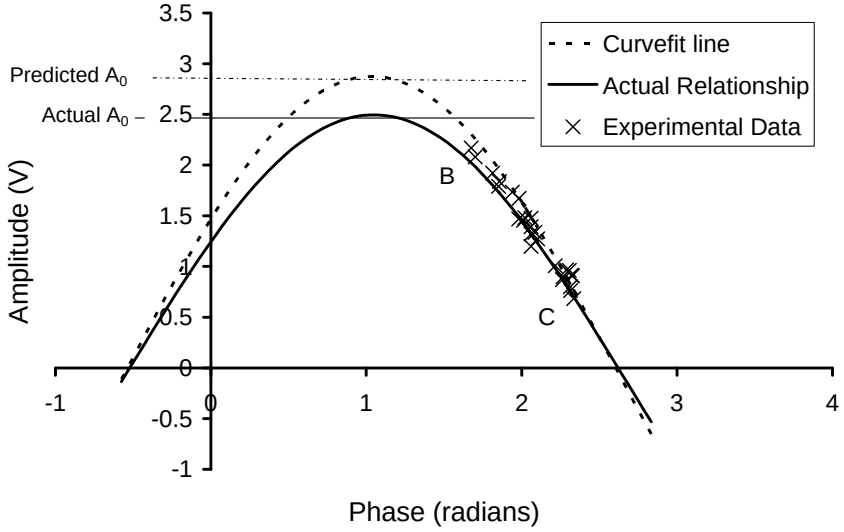

Figure 10. Plot of amplitude against phase showing how errors occur in the curve fitting leading to an over-predicted reference amplitude.

The scatter in the experimental data shown in figure 10, i.e. the deviation from the actual relationship line has several possible causes. The most substantial cause is errors in the measured refection coefficient. These errors are likely to be due to deviation in the excitation pulses from the UPR and also due to electrical noise interfering with the measured signal. For the equipment used, this reflection coefficient variation has been measured and found to be less than 5%. The second source of error is that due to the plates not being completely parallel. This lack of parallelism would result in amplitude and phase pairs (A and ϕ), which do not obey the relationship shown in figure 16. This is thought to be a secondary effect, and requires further modelling to be properly understood.

Theoretical Treatment

The influence of reference errors on lubricant film thickness

Once a reference signal has been estimated, it is useful to assess the effect of any errors on the resultant predicted lubricant film thickness. The equation relating the calculated thickness, h', to the measured reflected amplitude (equation 10) can now be rewritten with the addition of an error term as:

$$h' = \frac{B}{\pi f z}\sqrt{\frac{A^2}{\left(A_0 + 2r\sigma_{A_0}\right)^2 - A^2}} \tag{17}$$

where, σ_{A_0} is the standard deviation of the reference about its true value and r is a random Gaussian variable between -1 and 1. That is, the measured value of reflected amplitude is assumed to be taken from a Gaussian distribution of values about the true value A_0. It follows from Gaussian theory that 95% of measured amplitude values will fall within two standard deviations from true value. It is for this reason that the number two is present in the denominator of equation (17). Using a Taylor series to expand the square root term to the second order gives:

$$h' = \frac{BA}{\pi f z}\left[\frac{1}{\sqrt{A_0^2 - A^2}} - \left(4r\sigma_{A_0}A_0 + 2\left(r\sigma_{A_0}\right)^2\right)\frac{1}{\sqrt{\left(A_0^2 - A^2\right)^3}} + 6\left(r\sigma_{A_0}A_0\right)^2\frac{1}{\sqrt{\left(A_0^2 - A^2\right)^5}}\right] \tag{18}$$

As it is known that the expectation, $E(r)$=0 and $E(r^2)$=1 and if it is assumed that A_0=1 the relative bias error can be written as:

$$\varepsilon_h = \frac{E\left(h' - h\right)}{h} = 2\sigma^2{}_{A_0}\left(\frac{2 + R^2}{\left(1 - R^2\right)^2}\right) \tag{19}$$

Figure 11 shows relative bias error of the calculated thickness versus standard deviation error of the predicted reference amplitude.

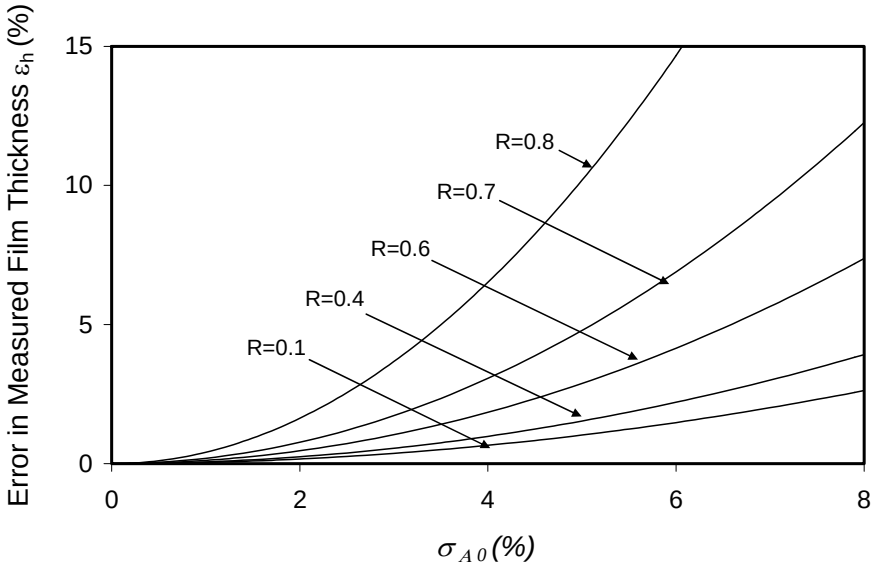

Figure 11. Relative bias error of the measured thickness plotted against the standard deviation of the estimated reference amplitude for different reflection coefficients.

Results are shown for a number of different reflection coefficients from which it can be seen that, as expected, the thickness error increases with the error in the reference (A_0) obtained from the least squares fit. It can also be seen that, for a given reference error, the thickness error decreases with decreasing reflection coefficient. Although not modelled, this trend would be limited by the effect of the signal-to-noise ratio at very low reflection coefficients.

Practical Implementation of the Auto-Calibration Procedure

It has been demonstrated that, given sufficient input data (a sufficient number of A, ϕ pairs), the auto-calibration technique is capable of deducing a reference with sufficient accuracy for film thickness measurement. All analysis of the method so far

has been carried out in post processing. The procedure is now implemented in real time to investigate whether it is capable of compensating for changes in temperature and sensor/pulser output.

Auto-calibration should occur as follows. If the transducer output changes during the test (for example because the temperature changes) then the auto-calibration procedure will be used to update the reference signal. Practically implementing this procedure online entails saving a set of A, ϕ pairs and applying the auto-calibration procedure to deduce a new reference, as the temperature fluctuates. The auto-calibration routine was incorporated into the LabVIEW software used for measuring film thickness.

To demonstrate temperature compensation, a known oil film thickness was produced, and a comparison was made between the compensated and uncompensated measurements, as temperature varied. The aim of this was to show fluctuations in temperature and/or sensor output causing the uncompensated technique to give erroneous measurements, while the compensated measurement remains unaffected.

An oil film of known thickness was produced by sandwiching a drop of oil between two blocks of metal separated by shims. Due to variation in material properties with temperature it was difficult to produce a constant oil film in this way. As the temperature increased, the metal specimens expanded and the viscosity of the oil decreased. These two factors resulted in a fluctuating film thickness when a constant one was required. A further problem was the difficulty in keeping a constant temperature while adjusting the oil film thickness. To overcome these problems, the signal variation with temperature was simulated by varying the gain of the excitation signal (from the UPR to the transducer). Varying the gain of the excitation signal results in the sensor output changing, this is a more severe effect than that caused by temperature, but has the advantage of not altering the actual film thickness. It should be noted however that if temperature varies then the bulk modulus value in equation (10) must be updated.

Figure 12 shows the results from this test, with an oil film produced between two 13μm shims. After 10 seconds, the auto-calibration technique was run and a reference was deduced; this reference was then used to calculate film thickness. At this point, both compensated and uncompensated methods agreed and gave the correct thickness. After 20 seconds the gain of the excitation signal was reduced; this had the effect of reducing the transducer output and suggesting erroneously a thinner film.

The oil film was then varied (at the 38 second point by physically moving the blocks apart slightly) so that sufficient input data was obtained for the auto-calibration routine. Both methods agreed (erroneously) until the reference was deduced for a second time, removing the effect of the altered gain on the compensated signal and the technique measures 13μm again. The uncompensated technique obviously continued giving an erroneous thickness measurement. The results shown in figure 12 demonstrate that the auto-calibration technique can successfully be used to compensate for unwanted variations in the signal. It should be noted that the use of the shims to produce a known film thickness is only necessary for this demonstration. When implemented to measure film thickness in a bearing or seal, it can now be assumed that the technique functions correctly.

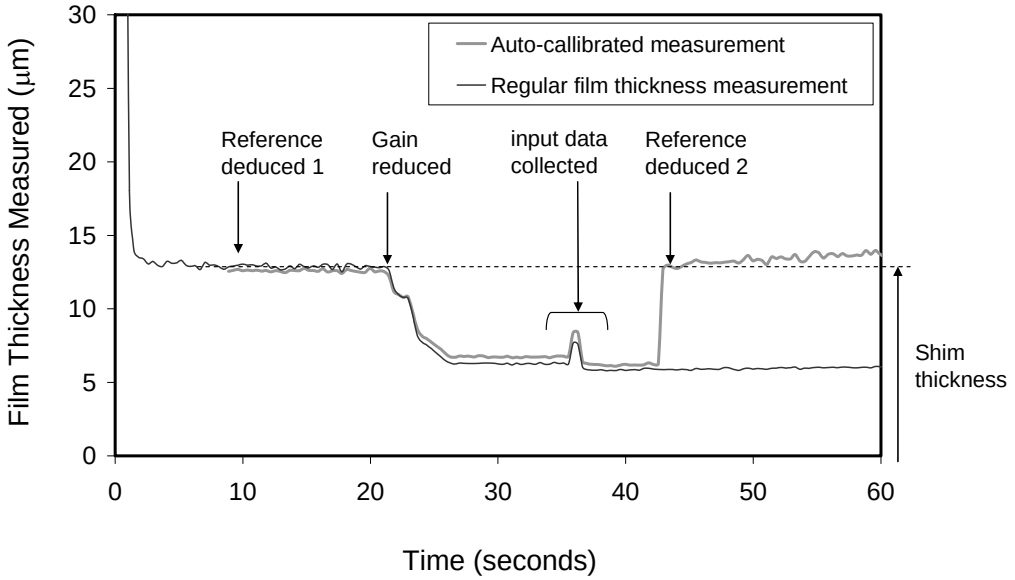

Figure 12. Compensated and uncompensated measurements of film thickness verses time as the excitation gain is altered to simulate a change in temperature.

Due to the reliance of bearings and seals on a fluid film to reduce friction and prevent wear, ultrasonic film thickness measurement is ideally suited to the condition monitoring of such tribological components. In these situations, the auto-calibration outlined in this paper would prove valuable in increasing the robustness of the measurement technique. In this case, several decisions need to be made regarding the algorithm used for the reference deduction procedure. The frequency with which the reference is updated, for instance needs to be set, and will depend on the rate at which the temperature is fluctuating. Secondly, the number of A, ϕ pairs that are saved as input data, from which the reference is deduced, will depend on the required accuracy of the technique and the processing time. Furthermore, as the temperature varies, A, ϕ pairs corresponding to previous temperatures used as input data will lead to inaccurate reference deduction. For this reason, the set of input data should be refreshed from time to time; or alternatively, a weighting approach should be implemented, where recent inputs are favoured over older ones. In short, the online procedure should be adapted to meet the requirements of the situation, be that temperature compensation, improved accuracy or processing time. This should be the focus of further investigation from a control engineering standpoint.

Conclusions

In previous work on ultrasonic oil film measurement, a pre-requisite is the recording of a reference signal. In practice this involves separating the surfaces either side of the interface. In this paper it has been shown that the reference can be deduced automatically without separation. This is of practical importance as it negates the costly requirement to dismantle the component prior to testing. The method has been demonstrated practically in a series of tests showing that the deduced reference spectrum agrees well with that measured directly.

Error analysis has been carried out showing that, providing sufficient input data is available (a range of R greater than 0.3), the error in the predicted reference amplitude can be reduced to <5%. The strong dependence of the accuracy of the technique on

the amplitude of reflection coefficient input data available places some limitations on the applicability of the technique.

The ability of the auto-calibration technique to compensate for unwanted temperature effects has been demonstrated experimentally. An experimental difficulty here was producing a constant film as temperature varied. This was overcome by mimicking the effect of temperature variation through varying characteristics of the incident ultrasonic wave.

Further work should be carried out devising a procedure for online implementation of the technique. This will be done from a control engineering standpoint in order to optimally reduce effects of temperature variation.

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