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Ultrasonic Reflection from Mixed Liquid-Solid Contacts and the Determination of Interface Stiffness

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In thin film or boundary lubricated contacts there is a possibility of potentially damaging asperity contact occurring. Whilst there are many models of this contact mechanism, experimental verification of the proportion of solid contact is difficult to achieve. Electrical methods will only indicate that contact has occurred. Whereas, optical methods can be used to determine the proportion of contact, but only when one surface is transparent. In this work the use of ultrasonic reflection is investigated as a means to analyse these types of mixed solid-liquid contacts.

A pulse of ultrasound is partially reflected at the contact between two rough surfaces. The proportion of the wave reflected can be readily used to determine the stiffness of the interface. Experimental data has been obtained from grit-blasted surfaces pressed together, both with and without liquid at the interface. The interface stiffness can be modelled by two springs in series, one of them representing the solid contact stiffness, K_{solid} and the other the stiffness of the liquid fluid, K_{liquid}. The variation of these stiffness values with contact pressure has been investigated.

At this stage it is not possible to directly determine the proportion of liquid or solid contact from the stiffness. The results however, give qualitative comparisons and information about the approach of the surfaces and hence the mean thickness of the liquid layer at the interface.

1. INTRODUCTION

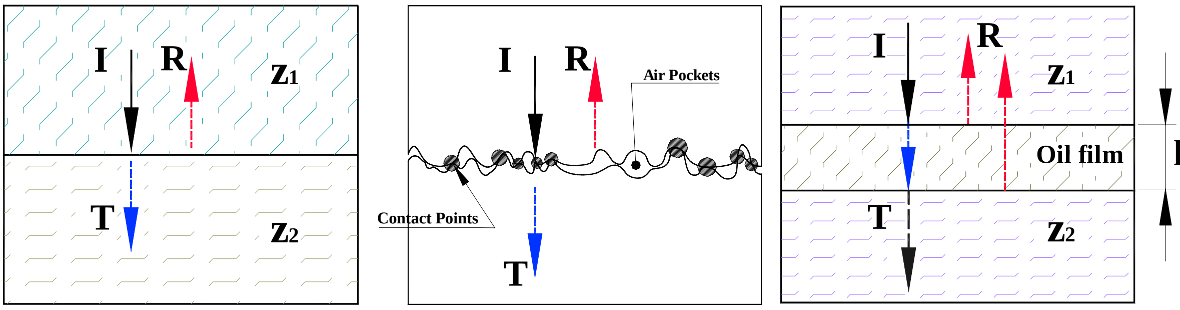
Many machine elements are designed so that surfaces involved in mechanical contact are properly separated by generating a protecting film of lubricant. However, in some situations, when either the load is very high or sliding speed very low, surfaces contact in the presence of lubricant. This phenomenon is known as *boundary* or *mixed lubrication*. In such conditions, load will be partially supported by asperities of the rough surfaces and the film of lubricant between them.

The proportion of solid contact controls the friction and influences the wear experienced by the machine elements. In this work, ultrasound is used to examine the nature of the mixed liquid-solid contacts under pressure.

2. BACKGROUND

Ultrasound has proved to be a useful method to study the in-situ characterisation of dry surfaces in contact [1,2,3,4]. The principle is based on the fact that, reflection of the ultrasound occurs when an elastic wave strikes a complete boundary between two different media. As a result, the original wave is split between one wave propagating into the next medium and another reflected wave returning back through the first medium (fig. 1a). Magnitudes of both waves are dependent on the acoustic impedances z_1 and z_2, of the two media. The acoustic impedance is calculated by the product of the density, ρ, and the speed of the sound, c, in the material. Reflection *(R)* and transmission *(T)* coefficients are determined using equations 1 and 2, respectively [5].

$$R = \frac{z_2 - z_1}{z_2 + z_1} \text{ and } T = \frac{2z_2}{z_2 + z_1} \tag{1,2}$$



a) b) c)

Figure 1. Reflection of ultrasound, from a) a complete interface, b) an incomplete rough interface and c) an oil film between two surfaces.

2.1. Ultrasound reflection from an incomplete interface

With real engineering surfaces, contact occurs at the asperities of the surfaces and contacts are seldom completely bonded. By increasing the normal pressure, more asperities contact, which causes both contact surfaces to approach and the real contact area to increase. In such conditions an incident ultrasonic wave is transmitted where asperities contact and is reflected from the air pockets (fig. 1b). Equation 1 is no longer valid. In this case, it has been shown that the reflection coefficient is influenced by the stiffness of the interface [1, 5]. The reflection coefficient is described by the so-called spring model:

$$R = \frac{z_1 - z_2 + i\omega(z_1 z_2 / K)}{z_1 + z_2 + i\omega(z_1 z_2 / K)} \qquad (3)$$

where K is interfacial stiffness and ω is the angular frequency of the ultrasonic wave ($\omega=2\pi f$). It can be seen that if the springs are infinitely rigid ($K=\infty$), i.e. there is complete contact, equation (3) reduces to equation (1), in which the two materials are assumed to be rigidly connected at the boundary.

If the two materials either side of the interface are identical ($z_1=z_2=z$). Then, the modulus of the reflection coefficient becomes:

$$|R| = \frac{1}{\sqrt{1+\left(\frac{2K}{\omega z}\right)^2}} \qquad (4)$$

The stiffness of the interface is given by the pressure required to cause unit approach of the surfaces:

$$K = -\frac{\mathrm{d}p}{\mathrm{d}u} \qquad (5)$$

where u is the approach of the surfaces and p is nominal contact pressure. The measurement of the reflection coefficient from rough surfaces has been used to determine features of their contact conditions such as plasticity, adhesion and shakedown [6].

2.2. Ultrasound reflection from an oil film

A similar approach can be used when there is a thin film of oil or any other liquid between two surfaces (fig. 1c). Dwyer-Joyce et al. [7] showed that the spring model is also applicable in this case, provided the oil film is comparable with the ultrasonic wavelength. The stiffness of the oil film is given by the rate of change of the pressure with oil film thickness. The bulk modulus of an oil film B, is defined as:

$$B = \frac{dp}{dV/V} = \frac{dp}{d(Ah)/Ah} \qquad (6)$$

where V is the volume ($V = Ah$), A is the area and h is the film thickness (fig. 1c). If the area remains constant and only h varies, then:

$$K = \frac{B}{h} \quad (7)$$

Measurements of the reflection of ultrasound from oil films has been used to determine their thickness in ball bearings [8] and full film journal bearings [9].

The bulk modulus in terms of density of the material ρ, and speed of sound c, is given by $B = \rho c^2$, so that:

$$K = \frac{\rho c^2}{h} \quad (8)$$

2.3. Ultrasound reflection from mixed contacts

If the contact is mixed liquid and solid, then the stiffness of the interface is composed of both a liquid part and solid part (fig. 2).

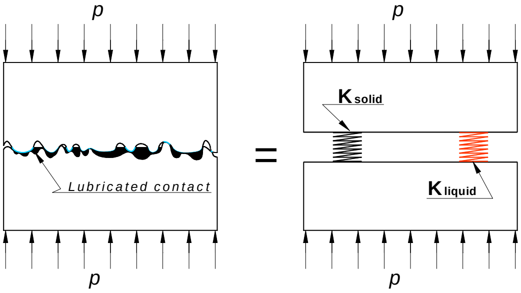


Figure 2. Modelling of a mixed contact by means of two springs.

Total stiffness has a contribution from both the solid and the liquid contacts. The ultrasound reflection will depend on the sum of these two stiffnesses in parallel:

$$K_{total} = K_{liquid} + K_{solid} \quad (9)$$

where, K_{solid} is interfacial stiffness of the dry interface and K_{liquid} is the stiffness of the liquid part.

In the experiments that follow the reflection from such a contact is measured and the relative size of the solid and liquid part investigated.

3. APPARATUS AND METHOD

Figure 3 shows a schematic diagram of the ultrasonic measuring apparatus and the loading rig. The loading rig is arranged so that there is a space between the transducer and bottom specimen of the interface filled with distilled water that allows a good signal transmission. The bottom specimens of steel (EN24) were ground, flat and polished. The contact faces of the upper specimens were grit-blasted. The rounded geometry of the specimen top was used to ensure alignment with the flat surface of the bottom specimen.

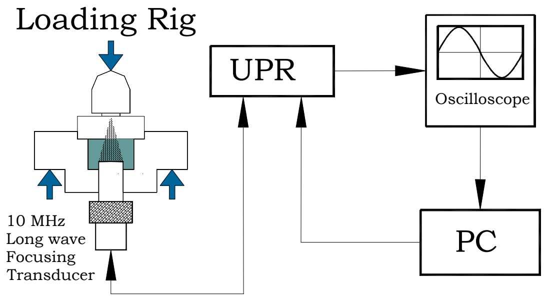


Figure 3. Schematic diagram of the specimen loading rig and ultrasonic measuring apparatus.

Before and after testing, the roughness of the surfaces of upper specimens (table 1) was recorded, bottom specimens were considered to have comparatively smooth surfaces.

Table 1. Roughness measurements (sample length 5mm, each result is an average of three profiles).

Specimen	CLA Roughness, R_a µm	
	Before Loading	After Loading
Steel (tested with oil)	4.84	3.90
Steel (tested with water)	4.94	4.16

The two specimens were pressed together in an electric Mayes loading machine. The load was gradually increased in steps from zero to 400 MPa and then unloaded in steps to 5 MPa. This was done to ensure non-separation of the interface; so that different asperities did not come into contact at each loading cycle. It was found that eleven loading-unloading cycles were enough to remove the plasticity at the interface and therefore achieve an elastic contact. After this, by using a syringe, water or oil was added at the start of the twelfth cycle. The effect of the liquid on the reflection coefficient and interfacial stiffness was recorded.

An ultrasonic pulser-receiver (UPR) was used to generate voltage pulses to actuate the piezo-electric transducer. The transducer, a longitudinal-wave 10 MHz in this case, is connected to the UPR. The voltage causes a short duration ultrasonic pulse of wide frequency band. This pulse reflects back from the interface and is received by the same transducer. The recorded voltage is then captured by the UPR and stored as a waveform on a digital oscilloscope. The first signal is recorded when the interface is still unloaded. In these conditions, no asperities are in contact, thus the reflected signal is maximum; this is used as a reference signal. Figure 4 shows the waveform of a reference signal. From here the waveform is passed to a PC for signal processing. This process is carried out for each load step.

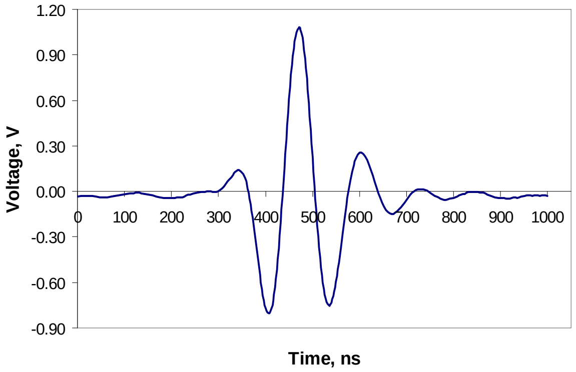


Figure 4. Reference signal recorded from an unloaded surface.

The captured waveform is passed to the PC and a Fast Fourier Transform (FFT) is performed. Figure 5 shows a frequency-amplitude plot from a series of contact loads. As the pressure is increased less of the signal is reflected. The reflection coefficient is directly obtained by dividing the amplitude of a given load by the amplitude of the reference signal. Figure 6 shows a frequency-reflection coefficient plot obtained from the data of figure 5.

Next, interfacial stiffness, in terms of the reflection coefficient, can be calculated by using the spring model (equation 4). The acoustic properties of steel are given in table 2.

Table 2. Acoustic properties of materials used in this study.

Material	**Density ρ, kg/m^3**	**Speed of sound, c m/s**
Steel**	7700	5900
Oil Turbo T68*	876	1450
Water at 20 ^{O}C**	1000	1483

* Obtained experimentally.

** Krautkramer and Krautkramer, 1990 [10].

Figure 7 shows the frequency-stiffness plot. The stiffness should be independent of frequency. The fact that this is reasonably the case suggests that it is appropriate to use the spring model. At the higher loads the reflection tends to unity and equation (4) becomes unstable (slight noise causes a big change in the calculated stiffness). This is the reason for the variations in the top curve of figure 7.

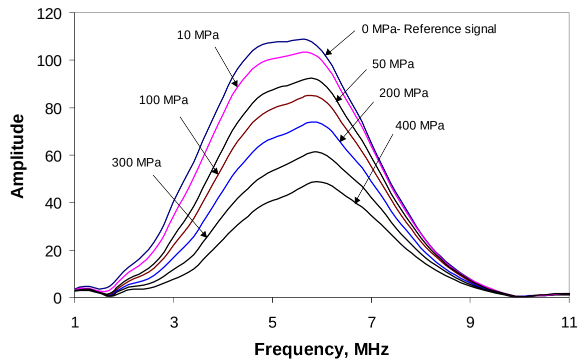


Figure 5. Time domain amplitude plots of the reflected signal for a series of contact loads.

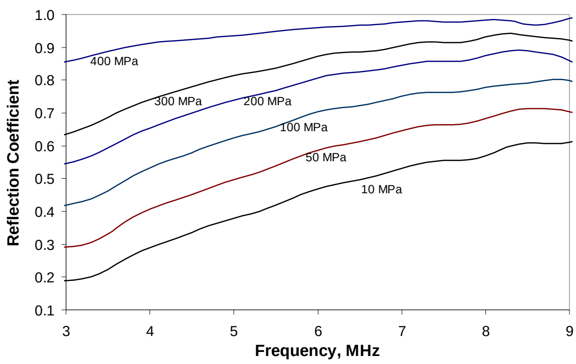


Figure 6. Reflection coefficient spectra for a series of contact loads.

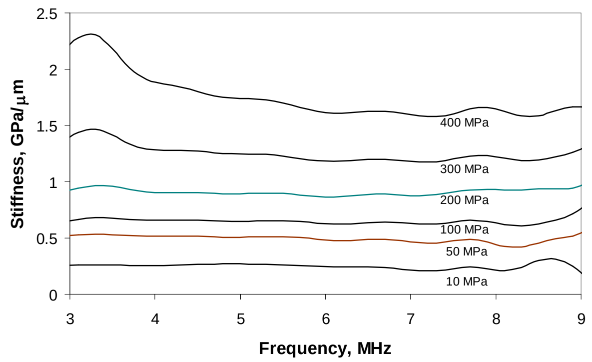


Figure 7. Stiffness – frequency plot for a series of contact pressures.

4. RESULTS

Figures 8 and 9 show the interfacial stiffness for two tests, one with oil at the interface and the other with water. The first loading cycle has a large proportion of plasticity. After the eleventh unloading this has virtually all gone. The unloading part of the eleventh cycle is close to first unloading.

After cycle 11, oil or water was injected into the interface and a further cycle was performed. Since the dry contact is practically elastic, the shift in stiffness during the 12th cycle is entirely due to the effect of the liquid.

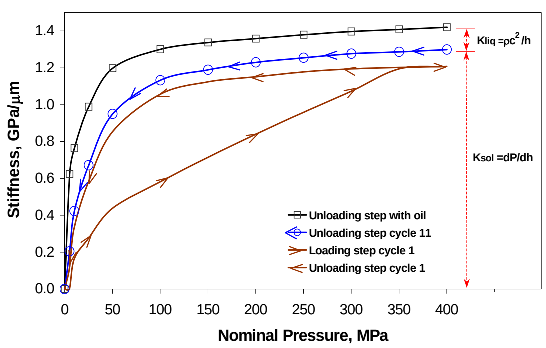


Figure 8. Stiffness against nominal pressure. Effect of oil at the interface.

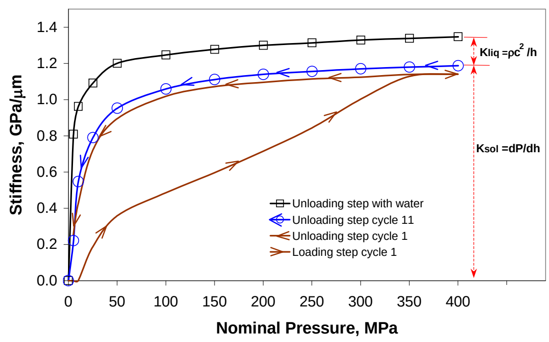


Figure 9. Stiffness against nominal pressure. Effect of water at the interface.

5. ANALYSIS

In figures 8 and 9, the addition of a liquid causes a corresponding decrease in reflection coefficient, which can physically be related to an increase in interfacial stiffness. The effect of the liquid on stiffness can be determined by considering the liquid as an extra spring in parallel with the spring modelling the solid part (fig. 2). Thus, total stiffness K_{total}, can be calculated by using equation (9). The stiffness of the dry contact alone can be obtained from the unloading step of cycle 11 (figs. 8 and 9).

The stiffness of the liquid layer is given by equation (8), when h is replaced by the separation of the surfaces mean line. In this analysis the dry contact stiffness is used to determine the separation which is then used to predict the liquid stiffness. This is then compared with the measured results.

The approach of the mean lines can be obtained by rearranging equation 5, so that:

$$u = \int \frac{\mathrm{d}\,p}{K_{solid}} + u_o \qquad (10)$$

The stiffness curves of figures 8 and 9 are integrated to give separation with nominal applied pressure. The constant u_0 is the approach at zero load. This is difficult to define, but one approach is to use the height of the maximum peak of the grit-blasted surfaces for the two tests with oil and water (see figure 10). The resulting curves for the approach variation with contact pressure (compliance curves) are shown as figure 11.

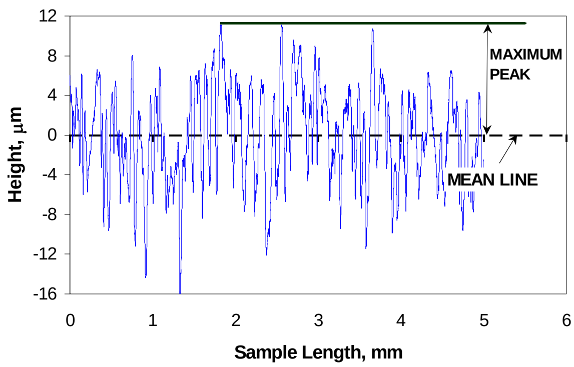


Figure 10. Profile showing maximum peak from the mean line.

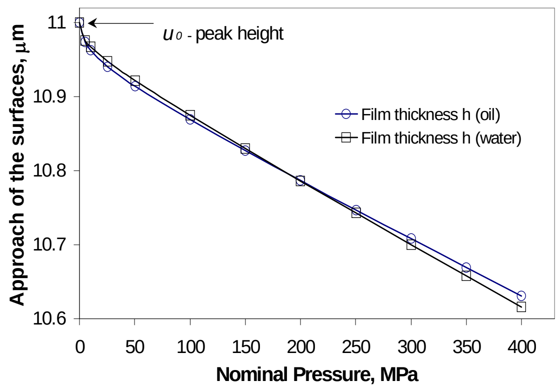


Figure 11. Surface approach against nominal pressure in specimens tested with oil and water.

The liquid stiffness is then obtained from this data by applying equation (8) since film thickness h, equals the approach of the mean lines u. Results are shown in figures 12 and 13. The liquid stiffness is then added to the measured dry solid stiffness to give the total stiffness. As can be seen, the measured total stiffness agrees well with the calculated total stiffness.

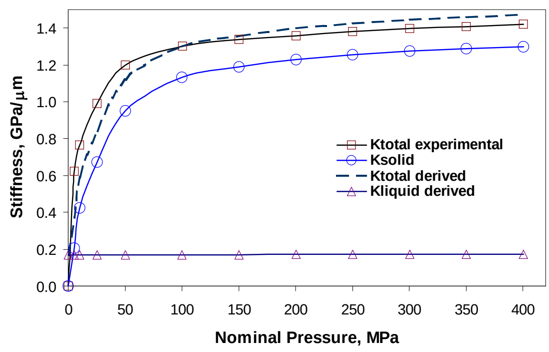


Figure 12. Comparison between experimental stiffness and calculated stiffness (K_{solid} + K_{liquid}). Specimen tested with oil.

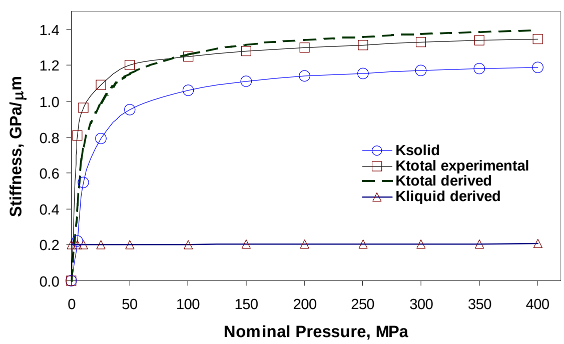


Figure 13. Comparison between experimental stiffness and calculated stiffness (K_{solid} + K_{liquid}). Specimen tested with water.

6. DISCUSSION

A method to measure the effect of a liquid film on interface stiffness in rough contact has been carried out. Calculation of the stiffness was based on the reflection coefficient of ultrasound. The found results show that adding liquid produces a decrease in reflection coefficient which in turn indicates an increase in interface stiffness according to a spring model.

In a practical lubrication case the stiffness will have contribution from both liquid and solid parts. It is not immediately obvious how to separate the two contributions. In this study, it was necessary to fully remove the plasticity in the contact interface by applying 11 loading-unloading cycles, after which the liquid was added. In these conditions, the decrease in reflection coefficient can then be assumed to be exclusively due to liquid.

An important aspect of this work is that it demonstrates that the liquid stiffness part can be deduced from the solid stiffness part, provided its ultrasonic properties are known (i.e. liquid and solid stiffness are dependent). This means that it is possible to separate the total stiffness into its two component parts and hence deduce the separation of the surfaces (oil film thickness).

However this relies on an integration of the solid stiffness which in turn means that a fixed load-approach point must be known (e.g. the initial approach at zero load, u_0). A practical approximation was to consider the maximum peak from the mean line of the profile after the test as the initial separation.

As can be seen in figure 11, for both specimens using water and oil, very little change in approach between surfaces was obtained (less than 0.4 microns) with increasing load. Rough surface contacts are very stiff. With this slight variation, the stiffness of the liquid film was found to be virtually constant (figures 12 and 13).

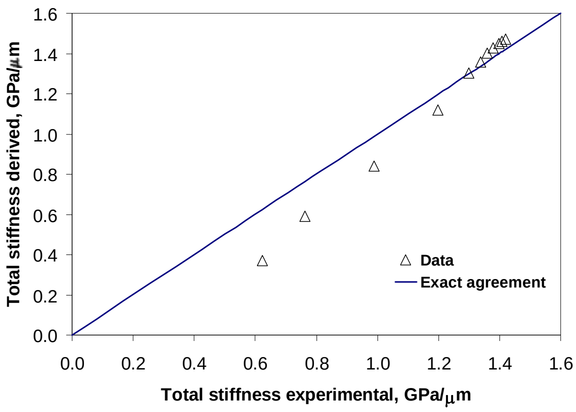


Figure 14. Experimental against calculated stiffness of the sample where oil was used.

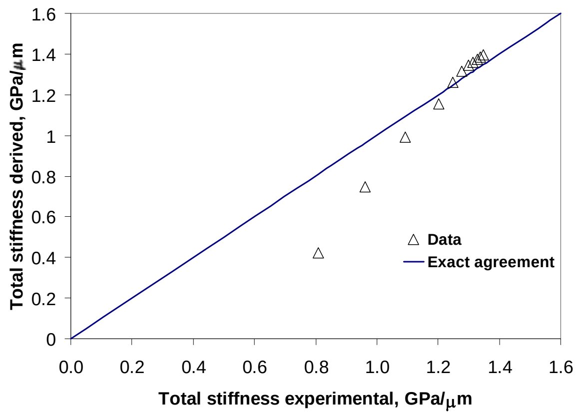


Figure 15. Experimental against calculated stiffness of the sample where water was used.

Is important to note that K_{solid} is much bigger than K_{liquid}, so the value of total stiffness in both cases is highly influenced by K_{solid}. The comparison between experimental and calculated stiffness in figures 12 and 13 showed that there is a good agreement between them. Comparison in figures 14 and 15 prove that both stiffnesses have a good correlation especially at the higher pressures (>50 MPa). The biggest difference is found at nominal pressures less than 50MPa.

The study demonstrates that it is possible to use ultrasound to measure the stiffness of mixed liquid-solid contacts. The combined stiffness can then be used to deduce the surface separation (i.e. film thickness). More work needs to be done to investigate the repeatability and accuracy of the approach. As yet the experiment has been static and with liquid at ambient pressures. A future development is to extend to dynamic pressurised contacts (elastohydrodynamic lubrication).

7. CONCLUSIONS

A method to determine the effect that a film of liquid has on the total stiffness of a conformal contact between two rough surfaces has been established. This method is based on the reflection coefficient of ultrasound, which was used to calculate stiffness by applying a spring model.

A decrease in reflection coefficient was found when a liquid was added to a dry interface. This implies a consequent increase in interfacial stiffness. This additional liquid stiffness can be used to determine the thickness of the film. The same information can be deduced from the stiffness of the dry contact alone, if an assumption is made about the initial separation of the surfaces.

A good agreement between the two measures of stiffness was found.

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