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Measurement of circumferential viscosity profile in stationary journal bearing by shear ultrasonic reflection ☆

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ABSTRACT

Viscosity is the most important property of a lubricant that can affect bearing performance. It controls the film thickness that is established during an operation. In this study, the ultrasonic method was used to measure the static viscosity profile around a journal bearing by using shear reflection coefficients at several locations around the journal bearing. This enables the viscosity profile to be established. The technique introduced was found to be successful and acceptable results were obtained from certain regions of the journal bearing flow. This study serves as a preliminary work for developing viscosity measurement in a rotating journal bearing.

1. Introduction

Fluid viscosity in bulk is easily measured by using different types of viscometers. However, inside a journal bearing where the lubricant exists in a thin layer, the use of viscometer is not feasible; hence, an alternative means is required. The use of an ultrasonic approach to measure viscosity in bulk fluid has been reported [1,2] but the approach has not been extended to measure the viscosity in thin films fluid especially in bearing lubricants.

Earlier work that measures viscosity in thin layers between parallel plates by using shear reflection coefficient [3,4] concluded that the phase method was more appropriate for thinner layers with lower Sommerfeld numbers. This method has been validated and an agreement was achieved via independent means of measurement.

In this study, an ultrasonic means was used to measure shear reflection coefficients at different locations around a journal bearing in static conditions (i.e. no circumferential temperature change and hence constant viscosity). The reflection coefficient data were then converted to viscosity values and compared against the predicted values using both the Bulk model and the Spring model.

The Bulk model and the Spring model are used for thick and thin layers, respectively. Judgment on the layer thickness can be approximated by the ultrasonic wavelength.

2. Literature review

2.1. Correlating reflection coefficient to viscosity by the Bulk model

The acoustic impedance of the fluid medium [5], can be expressed as a complex number as follows:

$$z_{\text{liq}} = \left(\frac{\omega\rho\eta}{2}\right)^{0.5}(1+i) \quad (1)$$

Eq. (1) expresses the acoustic impedance of the fluid in terms of the frequency of the propagating shear wave, fluid density and fluid viscosity.

The acoustic impedance may be expressed as a function of reflection coefficient of the shear wave as discussed [1]. If the acoustic impedance of the liquid and solid are known, the reflection coefficient R can be computed [1,6]. The equation can simplified as

$$z_{\text{liq}} = z_s\frac{(1-R^2)}{(1+R)^2} + iz_s\frac{(2R\sin\theta)}{(1+R)^2} \quad (2)$$

Eq. (2) expresses the acoustic impedance of the fluid as a function of the acoustic impedance of a solid and the reflection of a shear wave. Equating the real part of both equations produces a mathematical relation that relates fluid viscosity and the reflection

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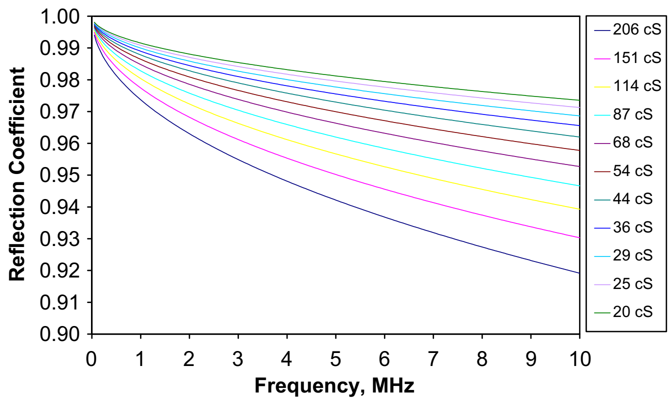

Fig. 1. Predicted shear reflection coefficient from Perspex–oil interface at different viscosity values.

Table 1
Acoustic properties of materials.

Material	Density (kg/m^3)	Shear Velocity (m/s)
Perspex	1180	1430
Oil	884	31
Brass	8560	2300

coefficient. This relation can be arranged to give the density–viscosity product so that

$$(\rho\eta)^{0.5} = \rho_s c_s \left(\frac{2}{\omega}\right)^{0.5} \left(\frac{1-R}{1+R}\right) \quad (3)$$

Alternatively, Eq. (3) can be rearranged to give the reflection coefficient, R as

$$R = \frac{1-X}{1+X}; \quad X = \frac{(\rho\eta)^{0.5}}{\rho_s c_s (2/\omega)^{0.5}} \quad (4)$$

where ρ_s and c_s are the density–viscosity product in the solid (load material). The viscosity of the fluid may be computed from the measurement of the reflection coefficient if other properties of Eq. (3) are known. Graphically, Eq. (4) can be shown as in Fig. 1 for the reflection from a Perspex–oil interface so that the relation can be explored and anticipated (acoustic properties given in Table 1). It is clear that the reflection coefficient spectra for shear waves have a negative slope, indicating that the reflection coefficient decreases with increasing frequency. It is also noted that at low viscosity the reflection coefficient is larger.

2.2. *Correlating reflection coefficient to viscosity by Spring model*

Thin fluid layer between two solids was considered (Fig. 2). The layer stiffness, K can be determined from the reflection coefficient measurement [4,7,8]. The mathematical expression that relates reflection coefficient, R to K is given as

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

where z is defined as acoustic impedance of the media.

Reflection coefficient from Eq. (5) shows as a complex quantity containing amplitude and phase information. It can be used for both longitudinal and shear waves. For a longitudinal wave, the longitudinal velocity and the longitudinal interfacial stiffness must be used. In the case of shear wave, the shear velocity and the shear interfacial stiffness are appropriate. For thin viscous

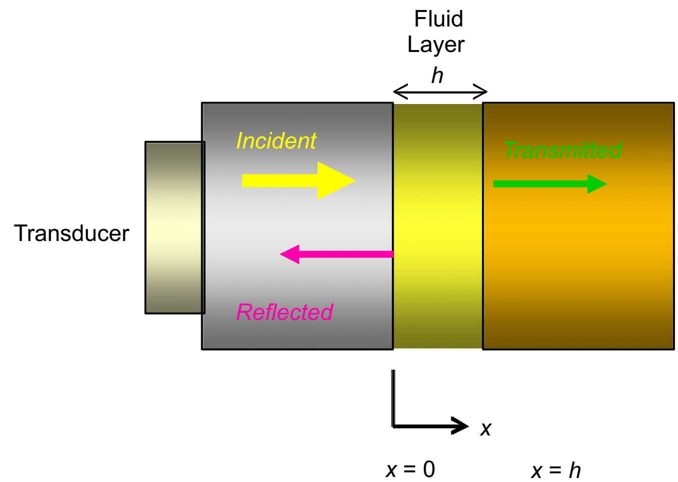

Fig. 2. Schematic diagram of an ultrasonic wave traveling through a thin layer.

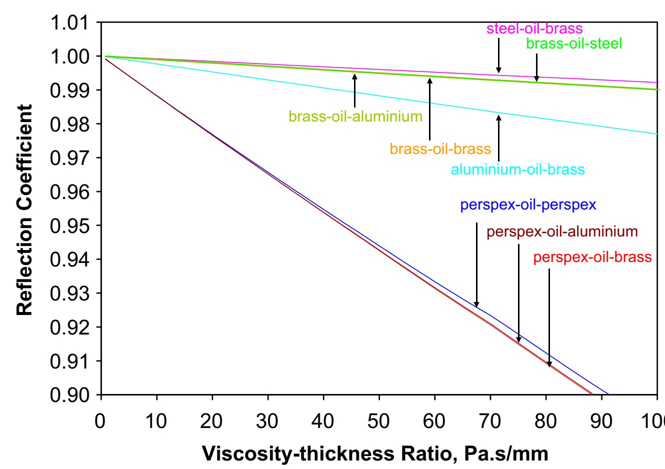

Fig. 3. Predicted reflection coefficient from oil layer for different materials.

liquid, the interfacial shear stiffness K is given by [9] as

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

By putting Eq. (6) into Eq. (5), it gives

$$R = \frac{(z_1 - z_2) + (h/\eta)(z_1 z_2 - z_0^2)}{(z_1 + z_2) + (h/\eta)(z_1 z_2 + z_0^2)} \quad (7)$$

Further simplified for similar materials on either side of the fluid layer $z_1 = z_2$ (acoustic impedance of solid), Eq. (7) can be rewritten as

$$R = \frac{(h/\eta)(z_s^2 - z_0^2)}{2z_s + (h/\eta)(z_s^2 - z_0^2)} \quad (8)$$

Rearranging Eq. (8) to give the ratio of viscosity to thickness, it becomes

$$\frac{\eta}{h} = \frac{(z_s^2 - z_0^2)(R-1)}{-2Rz_s} \quad (9)$$

The equation shows the correlation between viscosity and reflection coefficient. In Fig. 3, Eq. (7) is plotted for various combinations of materials on either side of the oil film. The reflection coefficient amplitude is plotted as a function of the viscosity–thickness ratio for each combination.