Development of a shear ultrasonic spectroscopy technique for the evaluation of viscoelastic fluid properties: theory and experimental validation.

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Nomenclature

A_m	Amplitude ultrasonic measurement (V)
A_r	Amplitude ultrasonic reference (V)
η	Shear viscosity (mPas)
k_m	Matching layer wavenumber (1/m)
t_m	Matching layer thickness (m)
z_l	Shear liquid impedance (Rayl)
z_m	Matching layer shear impedance (Rayl)
z_s	Shear solid impedance (Rayl)
ρ_l	Fluid density $(\mathrm{kg/m^3})$
f	Frequency (Hz)
f_0	STFT minimum detectable frequency (Hz)
f_s	Sampling frequency (Hz)
G'	Storage shear modulus (Pa)
G''	Loss shear modulus (Pa)
Im_{zl}	Imaginary part shear acoustic impedance (Rayl)
l	Slip length (nm)
Q	Quality factor
QCM	Quartz Crystal Microbalance
R	Reflection coefficient
Re_{zl}	Real part shear acoustic impedance (Rayl)
δ	Penetration depth (nm)
τ	Relaxation time (s)
W	STFT window size
ω	Rotational frequency (rad/s)

Abstract

In-situ measurement of viscosity advances the field of rheology, and aides the development of sensing systems for condition and performance monitoring of lubricated mechanisms. Many lubricated mechanisms, such as journal bearings or seals, are characterised by three-layer interfaces; an oil separating two solid (usually metallic) bodies. The viscoelastic study of the lubricating oil in layered systems is possible in-situ by means of ultrasonic reflection [1]. General solutions exist for the reflection of longitudinal plane waves from multi-layered solid-fluid systems. Similar solutions can be applied to plane shear waves. The use of a quarter-wavelength intermediate matching layer improves the sensitivity of the ultrasonic measurement and overcomes problems of acoustic mismatch. This opens the possibility of using reflectance methods to measure engineering (metal-oil) bearing applications that are acoustically mismatched. In this paper, a rigorous mathematical model for wave propagation in a three-layer system is solved for the reflection coefficient modulus and validated using a quarter wavelength ultrasonic viscometer. The model was tested against experimental data for two Newtonian reference fluids, water and hexadecane, and for one non-Newtonian reference fluid, squalene plus polyisoprene (SQL+PIP), measured ultrasonically at frequencies between 5 and 15 MHz. The results are in agreement with the expected viscosity values for the reference fluids. Further, the viscosity measurement is not limited to the resonance frequency, but it is performed over a broad band frequency range. This is important to improve