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To cite this version:
Nicolas Wilkie-Chancellier, Martinez Loïc, Serfaty Stéphane, Griesmar Pascal. Lamb wave sensor for viscous fluids characterization. IEEE Sensors Journal, Institute of Electrical and Electronics Engineers, 2009, 9 (9), pp.1142-1147. hal-00567973

HAL Id: hal-00567973
https://hal.archives-ouvertes.fr/hal-00567973
Submitted on 22 Feb 2011

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Lamb Wave Sensor For Viscous Fluids Characterization

Nicolas Wilkie-Chancellier, Loïc Martinez, Stéphane Serfaty, Member IEEE, and Pascal Griesmar

Abstract—This paper is a study of a new sensor for fluid characterization. This sensor is composed of a stainless steel plate in contact with a viscous material. The aim is to characterize the material viscosity by using reflected Lamb waves at the boundary interface. In order to identify the effects on the Lamb reflected modes by the viscous material, a complete study of the propagation wave in the alone plate is first presented. The propagation modes of the loaded plate are then investigated. By monitoring the mechanical impedance, the viscosity of the material in contact is extracted. In order to validate the experimental set-up, the mechanical impedance variation is measured for different water-glycerol mixtures. Results are in good agreement with those obtained by other techniques in the literature.

Index Terms—Lamb waves, Reflection, Viscosity, Viscous fluids.

I. INTRODUCTION

A wide range of commercial products have a great interest for their mechanical, electrical, optical and biocompatibility properties because of their colloidal structures. These include food products (such as milk, yogurt, mayonnaise), sprays and pharmaceutical products. These products exist either in sol phase or pass through a colloidal state. These include food products (such as milk, yogurt, mayonnaise), sprays and pharmaceutical products. These products exist either in sol phase or pass through a colloidal state during their manufacture. The monitoring of these complex fluids evolution is singularly crucial during the first step of their formation. Several techniques can be used to characterize the structure evolution [1]-[2]. To monitor the mechanical properties of these materials, low frequency rheometers are commonly used. They give access to the complex dynamic shear modulus [3]-[4] during the transition. More recently acoustic investigation have been carried out for the study of the sol-gel materials evolution [5]. Due to the frequency range used by these techniques, the first step of the microscopic evolution cannot be detected. Ultrasonic methods based on the measurement of either the propagation speed of acoustic waves or their attenuation by ultrasonic spectroscopy [6] can also be performed. Theoretical works have been performed to study the interaction of waves with a viscous fluid [7]-[8]. On the other hand, measurements of the viscosity [9] or the viscosity-density [10]-[11] product have been carried out using ultrasonic shear wave [12]-[13]. Ultrasonic guided waves have been used for viscosity measurements in melt using in a alumina buffer rod [14].

Works have been led on the study of viscoelastic anisotropic materials [15]-[16]. Recently, other studies based on the resonance of an AT cut quartz sensor have been developed. Indeed, the characterization of complex viscoelastic fluids is possible using shear wave propagation in the complex fluid [17]-[18]. Therefore a complete monitoring has been carried out from liquid to gel state. This experimental technique gives information from the microscopic to the macroscopic scale. For example, restructuration of yogurt (i.e. casein network) has been pointed out just before gelation [19]-[20]. Moreover, other works have clearly shown the interest of a new viscoelastic time (precursor to the gelation time) characteristic of sol-gel material evolution [21].

However, for all these techniques based on bulk waves propagation, the sensor has to be placed into the studied material. In order to deport the sensor, it seems to be interesting to use the properties of the surface wave propagation. Recently, applications have been studied by the mean of a microfluidic surface acoustic wave sensor platform based on Love wave propagation [22]. But up to now experimental techniques based on the Lamb wave propagation are not widespread in this subject. However, the reflection of a Lamb wave at the free edge of a straight cut plate has been theoretically [23]-[24], numerically [25]-[26] and experimentally [27] investigated.

The aim of this paper is to develop a sensor and an experimental technique based on the Lamb wave reflection phenomena in order to characterize viscoelastic materials. The great interest of this sensor is to assume a remote viscoelastic measurement. This presented work is a preliminary study on Newtonian liquid to validate the experimental device and the associated model.

In a first time, the reflection phenomena are experimentally investigated if a Lamb mode is incident on a free end. The propagation of the Lamb waves is followed using of a laser vibrometer. At the end of the plate, several refleted modes are qualitatively and quantitatively determined from a 2D Fast Fourier Transforms signal treatment.

In second step, an experimental study is carried out at the
end of the plate in contact with several water-glycerol mixtures. Referencing to the study at the free edge, the acoustic impedance of the viscous fluid is computed using the measured reflection coefficient at the plate-mixture interface. Experimental results are compared with the theoretical Newtonian liquid model. This model is suitable for the characterization of viscoelastic materials.

II. LAMB WAVE SENSOR INVESTIGATION

A. Sensor Description

Lamb waves are generated using a wedge transducer on a stainless steel plate (density $\rho=7800$ kg/m$^3$, longitudinal and transversal velocities respectively $c_L=5850$ m/s and $c_T=3150$ m/s). This plate is 150 mm long, 30 mm wide and 2 mm thick (thickness $E$). Its extremity is a normal free edge (Fig.1).

![Fig. 1. Description of the Lamb wave sensor.](image)

The transducer is made of a 1.5 mm thick piezoelectric plate (25x35 mm) and a plexiglass wedge to have a $\theta$ angle with the plate. The wedge is placed at $d=10$ cm from the plate end. This wedge transducer is chosen to generate a linear Lamb wave front (25 mm wide) at the resonant frequency $F=1.25$ MHz. The frequency-thickness product $FE$ is then equal to 2.5 MHz mm. At this frequency-thickness product, two different antisymmetric modes ($A_0$ and $A_1$) and one symmetric mode ($S_0$) are possible. In addition with the normal free edge, there is no change of symmetry modes at the reflection.

Taking into account the plexiglass properties, the wedge angle is chosen to 24 degrees to generate the $A_1$ Lamb mode because this mode is more sensitive to the conversion rate.

For our application, this sensor is used in reflectometry. Then, the reflected $A_1$ Lamb mode can only be received.

B. Lamb Wave Propagation in the Plate for Free Boundary

To characterize a fluid in contact at the end of the plate, the understanding of the unloaded sensor behavior is required. In fact, the knowledge of the reflection phenomena gives access to the interactions of surface waves with the fluid to characterize. To achieve this stage, the surface wave propagation is studied.

In order to study the propagation of Lamb waves in the plate, the experimental set-up shown in Fig.2 is implemented. Three units can be distinguished. The first one generates the $A_1$ Lamb mode using our transducer design. In order to generate this wave, a burst signal of twenty periods is applied to the transducer. A Polytec He-Ne laser vibrometer (OFV 505) coupling with a micro-positioning system scans by interferometry the normal surface plate displacements $U_2$ along the propagation. For each position of the vibrometer, its time response is acquired using a Lecroy digital scope (WS 424) and stored in a computer.

Along the last 5 cm of the plate the $U_2$ displacements are collected every 0.2 mm step. The Fig. 3 shows the spatio-temporal signal $s(x,t)$ of $U_2$.

![Fig. 2. Experimental set-up for Lamb mode determination (measurements using the vibrometer).](image)

![Fig. 3. Time-space representation of the normal displacement $U_2$ on the plate.](image)

The signal observed on the figure results from the superposition of the incident wave and the reflected wave as:

$$U_2(x,t) = U_i e^{j\omega t - k x} + U_r e^{j\omega t + k x}$$

(1)

where $U_i$ and $U_r$ are respectively the incident and reflected wave magnitudes and $k$ is the complex wave number.

Note that the reflection coefficient $R$ can be extract from (1) and can be written by:

$$R = \frac{U_r}{U_i} e^{2jkx}$$

(2)

In order to determinate the reflected waves, two successive Fourier transforms (temporal and spatial) of the total signal $s(x,t)$ are computed to obtain the $\Psi(k,FE)$ signal [28]. The incident and reflected Lamb waves can be observed in the dual space, respectively for $k>0$ and $k<0$ in Fig. 4.
The theoretical dispersion curves of the Lamb waves have been reported in dashed lines on this figure. The different reflected modes ($A_1$ and the $A_0$ Lamb modes) can be then distinguished. The quantitative study is performed by measuring each magnitude mode and by computing energy balance for the given incident $A_1$ Lamb mode [29]. At $FE = 2.5$ MHz mm, 77% of the total energy is converted into $A_0$ mode and 23% into $A_1$.

C. $A_1$ Lamb Mode Evolution Versus Fluid Loading

If the edge of the stainless steel plate is in contact with a fluid, the energy balance is modified. According to the boundary conditions at the plate-fluid interface, the reflection coefficient magnitude depends of the fluid characteristics [30]-[31].

In order to confirm that the $A_1$ mode is significantly modified by the boundary conditions, the Lamb wave evolution is monitored for water and for glycerol. These fluids are chosen to monitor the $A_1$ mode evolution in a wide range of absolute viscosity (respectively $\eta = 1.005$ mPa.s and $\eta = 1.780$ Pa.s for water and glycerol).

Table I shows the modifications of the energy balance of the $A_1$ reflected Lamb mode.

<table>
<thead>
<tr>
<th>Loaded material</th>
<th>Energy reflected into $A_1$ (mPa.s)</th>
<th>Absolute viscosity $\eta$ (mPa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>23 %</td>
<td>18.4 $\times 10^{-3}$</td>
</tr>
<tr>
<td>Water</td>
<td>20 %</td>
<td>1.005</td>
</tr>
<tr>
<td>Glycerol</td>
<td>18 %</td>
<td>1780.83</td>
</tr>
</tbody>
</table>

These preliminary results validate that our device can be used to remotely characterize fluids.

III. VISCOUS FLUID CHARACTERIZATION

A. Experimental Set-up for Fluid Characterization

Now, the Lamb wave sensor is used to characterize viscous fluids in contact with the stainless steel plate. The wedge transducer is used in reflectometry. The plate can be then considered as a transmission line. The experimental set-up is shown in Fig. 5.

The reflection coefficient induced by the water-glycerol mixture can be extracted from the reflected mode magnitude $U_r$. Indeed, at the plate-fluid interface, the reflection coefficient expression is written as:

$$ R = \frac{U_r}{U_i} e^{\frac{k \omega d}{\rho_2}} $$

where $U_i$ is the magnitude of the incident $A_1$ Lamb mode and $d$ is the distance from the transducer to the plate end. This magnitude $U_i$ only depends on the magnitude of the electrical pulse and the mechanical conditions of the contact between the wedge transducer and the steel plate.

Then, the $U_i$ can be experimentally deduced from the free edge configuration (when keeping constant the incident amplitude in both experimental studies). The Lamb wave reflection coefficient is written as:

$$ R = \frac{U_r}{R_{\text{air}}} $$

where $R_{\text{air}}$ is the reflection coefficient for free edge configuration which is expressed as:

$$ R_{\text{air}} = \frac{U_r}{U_i} e^{\frac{k \omega d}{\rho_2}} $$

B. Extraction Of The Viscous Fluid Characteristics

In order to characterize the mechanical properties of the fluid in contact with the steel plate, the acoustic impedance $Z_m$ of the fluid can be extract from (5) introducing the acoustic impedance $Z_{\text{steel}}$ of the stainless steel:

$$ Z_m = Z_{\text{steel}} \frac{1 - R}{1 + R} $$

Introducing (5) in (6), the acoustic impedance of the fluid can be expressed as a function of the experimental parameters:

$$ Z_m = Z_{\text{steel}} \frac{U_{\text{in}} - U_r}{U_{\text{in}} + U_r} R_{\text{air}} $$

Taking into account that the boundary conditions at the plate-fluid interface generate a shear stress the acoustic impedance $Z_m$ of the fluid depends on the complex shear modulus [32]. For Newtonian liquid the acoustic impedance $Z_m$ can be then linked to dynamic viscosity $\eta$ of the fluid and the density $\rho$ of the fluid:

$$ Z_m = (j \rho \eta \omega)^{0.5} $$

where $\omega$ is the resonant angular frequency of the wedge transducer. Then, the acoustic impedance of the viscous fluid is proportional of the square root of the $\rho \eta$ product.
IV. RESULTS AND COMPARISON

Different water-glycerol mixtures are used to validate our fluid characterization device. The temperature fluid is maintained at 25°C by a thermostated cell. At this temperature the well known density $\rho$ (in kg/L) and dynamic viscosity $\eta$ (in mPa.s) are given in Table II.

In this table, the quantity of glycerol in water is given by the weight ratio $x_{m,\text{gly}}$ defined as follow:

$$x_{m,\text{gly}} = \frac{m_{\text{gly}}}{m_{\text{gly}} + m_{\text{water}}} \times 100 \quad (9.)$$

where $m_{\text{gly}}$ and $m_{\text{water}}$ are respectively the glycerol and water weight. Note that water without glycerol is written $x_{m,\text{gly}}=0\%$ and glycerol without water $x_{m,\text{gly}}=100\%$.

Water-glycerol mixtures used in this study are in weight ratio range from 0% to 100% with 10% step.

To experimentally extract the viscosity of mixtures, the acoustic impedance of fluid $Z_m$ is first measured from the evolution of the reflection coefficient. The figure 6 shows the evolution of $Z_m$ versus the density viscosity product $(\rho \eta)^{0.5}$. This figure shows that the measurements of absolute viscosity are in good agreement until with the tabulated values from $(\rho \eta)^{0.5} = 2.76 \text{ kg/m}^2/\text{s}^{0.5}$ (i.e. $x_{m,\text{gly}}=50\%$).

From $Z_m$ measurements, the experimental density-viscosity product is therefore computed. A comparison with the tabulated $(\rho \eta)^{0.5}$ values are reported in Table II.

![Figure 6. Comparison of the experimental acoustic impedance for water-glycerol mixtures versus tabulated values (the squares are the experimental data points, the continuous curve is the best fit using a logarithm function and the dashed line is the tabulated values).](image)

Consequently our Lamb wave sensor can accurately measure the absolute viscosity of weakly viscous fluid ($\eta \leq 7 \text{ mPa.s}$). This domain of validity is comparable to the usual techniques in the literature, such as using multiple reflections of ultrasonic shear horizontal waves [11-13] or using the phase shift of the reflected ultrasonic shear wave [12]. For more viscous fluids (ie 60% \(\leq x_{m,\text{gly}} \leq 100\%$), the error increases, pointing out the limits of the viscosity measurement with Lamb waves. Because of the dominant nature of the Lamb wave propagation, the determination of the high bulk viscosity becomes difficult due to the high dissipation of the shear wave energy in the fluid. In our model, the steel plate is considered as a lossless transmission line. In fact, at the $e$ depth contact layer between the stainless steel plate and the mixture (Fig. 1), the effective propagating medium depends on the local interactions (such as wettability, fluid-plate meniscus) and on the mechanical properties of the both materials in contact. Equations (3) and (4) should include these interactions which strongly increase for high $\eta$ values. Using Table II, such a steep transition of the dynamic viscosity occurs for $x_{m,\text{gly}} \geq 60\%$. A possible way to improve the accuracy is to take into account these propagation effects.

V. CONCLUSION

The experimentation performed with the A$_1$ Lamb mode shows that guided waves are able to detect the change of the viscous fluid parameters from their reflection coefficient. The acoustic impedance of the viscous material is expressed as a function of the reflection coefficient, and more particularly as a function of the experimental parameters. The experimental study with water-glycerol mixtures allows us to determine the absolute viscosity for weak viscous fluids. For Newtonian liquids, the extracted dynamic viscosity is in good agreement with the tabulated data for small values less than 7 mPa.s. The high dissipation of the shear wave energy in the strongly viscous fluids could explain the divergence of measurement.

However, taking into account the complex shear modulus the Lamb wave sensor presented in this paper should be used to characterize the viscoelasticity of fluids. This technique can be then a new way to monitor the first steps of weak gels formation.

<table>
<thead>
<tr>
<th>Glycerol in water $x_{m,\text{gly}}$</th>
<th>Tabulated $\rho$ (kg/L)</th>
<th>Tabulated $\eta$ (mPa.s)</th>
<th>Tabulated $(\rho \eta)^{0.5}$ (kg/m$^2$/s$^{0.5}$)</th>
<th>Experimental $(\rho \eta)^{0.5}$ (kg/m$^2$/s$^{0.5}$)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>1.000</td>
<td>1.005</td>
<td>1.002</td>
<td>0.954</td>
<td>4.7</td>
</tr>
<tr>
<td>10%</td>
<td>1.023</td>
<td>1.341</td>
<td>1.171</td>
<td>1.214</td>
<td>3.6</td>
</tr>
<tr>
<td>20%</td>
<td>1.048</td>
<td>1.844</td>
<td>1.390</td>
<td>1.376</td>
<td>1.0</td>
</tr>
<tr>
<td>30%</td>
<td>1.073</td>
<td>2.683</td>
<td>1.697</td>
<td>1.745</td>
<td>2.8</td>
</tr>
<tr>
<td>40%</td>
<td>1.100</td>
<td>4.093</td>
<td>2.122</td>
<td>2.199</td>
<td>3.6</td>
</tr>
<tr>
<td>50%</td>
<td>1.127</td>
<td>6.762</td>
<td>2.761</td>
<td>2.676</td>
<td>3.1</td>
</tr>
<tr>
<td>60%</td>
<td>1.155</td>
<td>12.474</td>
<td>3.796</td>
<td>3.369</td>
<td>11.2</td>
</tr>
<tr>
<td>70%</td>
<td>1.182</td>
<td>26.595</td>
<td>5.607</td>
<td>4.062</td>
<td>27.6</td>
</tr>
<tr>
<td>80%</td>
<td>1.210</td>
<td>72.721</td>
<td>9.380</td>
<td>4.415</td>
<td>52.9</td>
</tr>
<tr>
<td>90%</td>
<td>1.238</td>
<td>271.122</td>
<td>18.321</td>
<td>6.106</td>
<td>66.7</td>
</tr>
<tr>
<td>100%</td>
<td>1.263</td>
<td>1780.830</td>
<td>47.426</td>
<td>7.506</td>
<td>84.2</td>
</tr>
</tbody>
</table>
REFERENCES


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