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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 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 reflected 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

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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 $\rho = 7800 \text{ kg/m}^3$, longitudinal and transversal velocities respectively $c_L = 5850 \text{ m/s}$ and $c_T = 3150 \text{ m/s}$). This plate is 150 mm long, 30 mm wide and 2 mm thick (thickness E). Its extremity is a normal free edge (Fig.1).

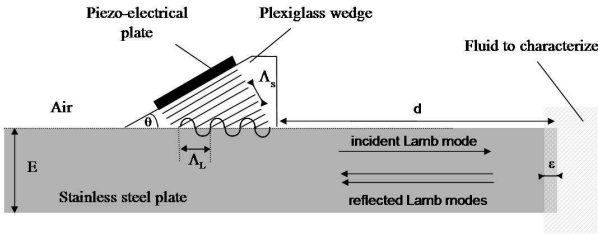


Fig. 1. Description of the Lamb wave sensor.

The transducer is made of a 1.5 mm thick piezoelectric plate (25x35 mm) and a plexiglass wedge to have a θ angle with the plate. The wedge is placed at $d = 10 \text{ cm}$ from the plate end. This wedge transducer is chosen to generate a linear Lamb wave front (25 mm wide) at the resonant frequency $F = 1.25 \text{ MHz}$. 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.

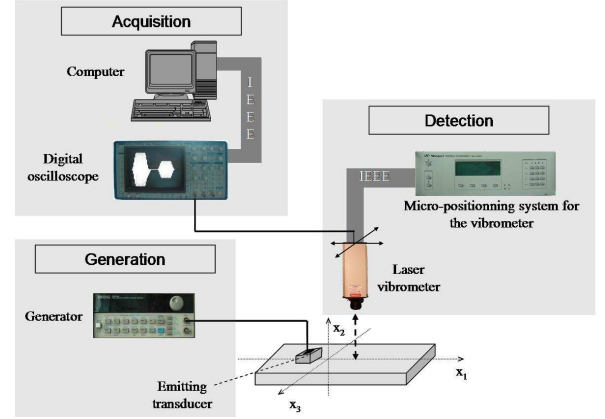


Fig. 2. Experimental set-up for Lamb mode determination (measurements using the vibrometer).

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 $s(x_1, t)$ of U_2 .

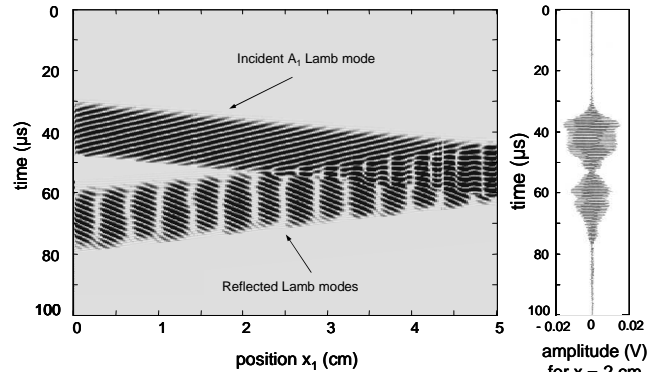


Fig. 3. Time-space representation of the normal displacement U_2 on the plate.

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

$$U_2(x, t) = U_i e^{j(\omega t - kx)} + U_r e^{j(\omega t + kx)} \quad (1.)$$

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:

$$R = \frac{U_r}{U_i} e^{2jkx} \quad (2.)$$

In order to determinate the reflected waves, two successive Fourier transforms (temporal and spatial) of the total signal $s(x_1, t)$ are computed to obtain the $\mathcal{P}(k, FE)$ 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.

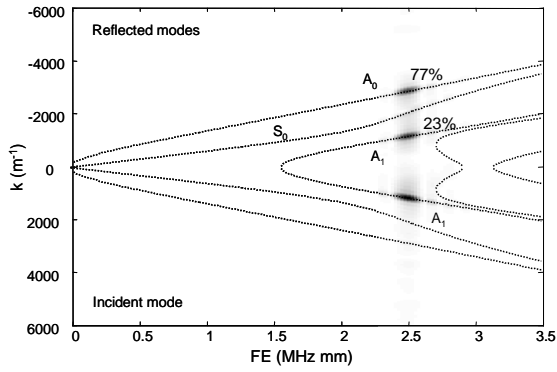


Fig. 4. Dual space representation of the normal displacement on the plate.

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 I
PERCENTAGE OF THE INCIDENT ENERGY REFLECTED INTO THE A_1 LAMB MODE

Loaded material	Energy reflected into A_1 Lamb mode (%)	Absolute viscosity η (mPa.s)
Air	23 %	$18.4 \cdot 10^{-3}$
Water	20 %	1.005
Glycerol	18 %	1780.83

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.

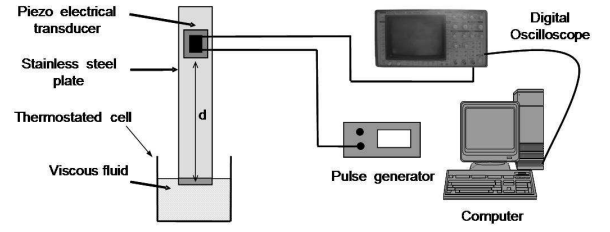


Fig. 5. Experimental set-up for fluid characterization.

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

$$R = \frac{U_r}{U_i} e^{2jk d} \quad (3.)$$

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 :

$$R = \frac{U_r}{U_{r_{air}}} R_{air} \quad (4.)$$

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

$$R_{air} = \frac{U_{r_{air}}}{U_i} e^{2jk d} \quad (5.)$$

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_{steel} of the stainless steel:

$$Z_m = Z_{steel} \frac{1-R}{1+R} \quad (6.)$$

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

$$Z_m = Z_{steel} \frac{U_{r_{air}} - U_r R_{air}}{U_{r_{air}} + U_r R_{air}} \quad (7.)$$

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 η of the fluid and the density ρ of the fluid:

$$Z_m = (j \rho \eta \omega)^{0.5} \quad (8.)$$

where ω 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 ρ (in kg/L) and dynamic viscosity η (in mPa.s) are given in Table II.

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

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

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

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. $x_{m, gly}=50\%$).

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.

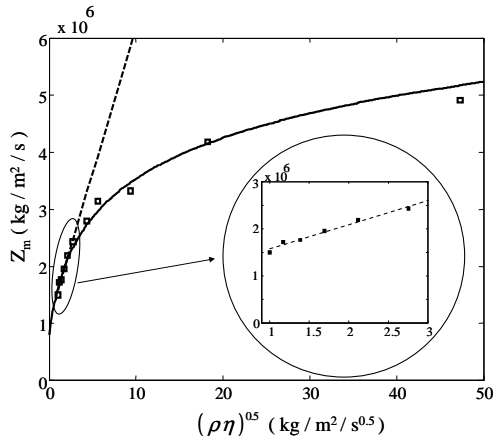


Fig. 6. Comparison of the experimental acoustic impedance for water-glycerol mixtures versus tabulated values (the squares are the experimental data points, the continuous curve is the best fit using a logarithm function and the dashed line is the tabulated values).

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 $60\% \leq x_{m, gly} \leq 100\%$), 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 ε 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 η values. Using Table II, such a steep transition of the dynamic viscosity occurs for $x_{m, gly} \geq 60\%$. 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 II
TABULATED VERSUS EXPERIMENTAL $(\rho\eta)^{0.5}$ VALUES FOR WATER-GLYCEROL MIXTURES AT 25°C

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

REFERENCES

- [1] Y.D. Yan, J.H.R. Clarke, "In-situ determination of particle size distributions in colloids", *Advances in Colloid and Interface Science*, vol. 29, pp. 277-318, 1989.
- [2] S.G. Bike, "Measuring colloidal forces using evanescent wave scattering", *Current Opinion in Colloid and Interface Science*, vol. 5, pp. 144-150, 2000.
- [3] A. Ponton, S. Barboux-Doeuff C. Sanchez, "Rheology of titanium oxide based gels: determination of gelation time versus temperature", *Colloid Surface A*, vol. 162, pp. 177-192, 1999.
- [4] P. Griesmar, A. Ponton, S. Serfaty, B. Senouci, M. Gindre, G. Gouedard, S. Warlus, "Kinetic study of silicon alkoxides gelation by acoustic and rheology investigations", *Journal of Non-Crystalline Solids*, vol. 319, pp. 57-64, 2003.
- [5] B. Senouci, S. Serfaty, P. Griesmar and M. Gindre, "Acoustic resonance in tetramethoxysilane matrices: A new tool to characterize the gel formation", *Review of Scientific Instruments*, vol. 72 (4), pp. 2134-2138, 2001.
- [6] M. Matsukawa, K. Yamada, I. Nagai, "An ultrasonic evaluation of the sol-gel synthesis of silica glass", *Ultrasonics*, vol. 34, Issue 2-5, pp. 335-338, 1996.
- [7] Z. Zhu, J. Wu, "The propagation of Lamb waves in a plate bordered with a viscous liquid", *Journal of the Acoustical Society of America*, vol. 98 (2), pp. 1057-1064, 1995.
- [8] B. Bianco, T. Tommasi, "Influence of viscosity on the reflection coefficient at a fluid-solid interface", *Journal of the Acoustical Society of America*, vol. 98 (4), pp. 2374-2376, 1995.
- [9] V. Shah, K. Balasubramaniam, "Effect of viscosity on ultrasound wave reflection from a solid/liquid interface", *Ultrasonics*, vol. 34, pp. 817-824, 1996.
- [10] G. L  v  que, J.Y. Ferrandis, J. Van Est and B. Cros, "An acoustic sensor for simultaneous density and viscosity measurements in liquids", *Review of Scientific Instruments*, vol. 71 (3), pp. 1433-1440, 2000.
- [11] M.S. Greenwood, J.D. Adamson and L.J. Bond, "Measurement of the viscosity-density product using multiple reflections of ultrasonic shear horizontal waves", *Ultrasonics*, vol. 44, pp. 1031-1036, 2006.
- [12] V. Shah, K. Balasubramaniam, "Measuring Newtonian viscosity from the phase of reflected ultrasonic shear wave", *Ultrasonics*, vol. 38, pp. 921-927, 2000.
- [13] M.S. Greenwood, J.A. Bamberger, "Measurement of viscosity and shear wave velocity of a liquid or slurry for on-line process control", *Ultrasonics*, vol. 39, pp. 623-630, 2002.
- [14] V.S.K. Prasad, K. Balasubramaniam, E. Kannan and K.L. Geisinger, "Viscosity measurements of melts at high temperatures using ultrasonic guided waves", *Journal of Material Processing Technology*, vol. 2007, pp. 315-320, 2008.
- [15] Bernard Hosten, Michel Castaings, "FE modeling of Lamb mode diffraction by defects in anisotropic viscoelastic plates", *NDT & E International*, vol. 39 (3), pp. 195-204, 2006.
- [16] B. Hosten, M. Castaings, "Comments on the ultrasonic estimation of the viscoelastic properties of anisotropic materials", *Composites Part A: Applied Science and Manufacturing*, vol. 39 (6), pp. 1054-1058, 2008.
- [17] R.W. Cernosek, S.J. Martin, A.R. Hillman, H.L. Bandey, "Comparison of lumped-element transmissions line models for thickness-shear-mode quartz resonator sensors", *IEEE Trans. UFFC*, vol. 45 (5), pp. 1399-1046, 1998.
- [18] H.L. Bandey, S.J. Martin, R.W. Cernosek, "Modelling the response of thickness-shear-mode resonators under various loading conditions", *Analytical Chemistry*, vol. 71, pp. 2205-2214, 1999.
- [19] H.M. Farrell, P.H. Cooke, G. King, P.D. Hoagland, M.L. Groves, T.F. Kumosinski, B. Chu, "Particle sizes of casein submicelles and purified k-casein - Comparisons of dynamic light scattering and electron microscopy with predictive three-dimensional molecular models", *Macromolecular Interactions in Food technology (Washington : American Chemical Society)*, vol. 650, pp.61-79, 1996.
- [20] C.Ould-Ehssein, S. Serfaty, P. Griesmar, J.Y. Le Hu  rou, L. Martinez, E. Caplain, N. Wilkie-Chancellier and M. Gindre, "Ultrasonic monitoring of yoghurt formation by using AT-cut quartz: lighting of casein micelles interactions process during the acidification", *Ultrasonics*, vol. 44 (1), pp. 875-879, 2006.
- [21] C.Ould-Ehssein, S. Serfaty, P. Griesmar, J.Y. Le Hu  rou, L. Martinez, E. Caplain, N. Wilkie-Chancellier, M. Gindre, G. Gouedard and P. Figui  re, "Kinetic study of silica gels by a new rheological ultrasonic investigation", *Ultrasonics*, vol. 44 (1), pp. 881-885, 2006.
- [22] V. Raimbault, D. Rebi  re and C. Dejous, "A microfluidic surface acoustic wave sensor platform : Application to high viscosity measurements", *Materials Science and Engineering*, vol.28, pp. 759-764, 2008.
- [23] P.J. Torvik, "Reflection of Wave Trains in Semi-Infinite Plates", *Journal of the Acoustical Society of America*, vol.41, pp. 346-353, 1967.
- [24] J.L. Rose, *Ultrasonic waves in solid media*, Cambridge University Press, 1999, pp. 308-334.
- [25] E. LeClezio, M. V. Predoi, M. Castaings, B. Hosten, M. Rousseau, "Numerical predictions and experiments on the free-plate edge mode", *Ultrasonics*, vol. 41 (1), pp. 25-40, 2003.
- [26] Nicolas Wilkie-Chancellier, Hugues Duflo, Alain Tinel et Jean Duclos, "Numerical description of the edge mode at the beveled extremity of a plate", *Journal of the Acoustical Society of America*, vol. 117 (1), pp. 194-199, 2005.
- [27] N. Wilkie-Chancellier, H. Duflo, A. Tinel and J. Duclos, "Experimental study and signal analysis in the Lamb wave conversion at a bevelled edge", *Ultrasonics*, vol.42, pp. 377-381, 2004.
- [28] D. Alleyne. and P. Cawley, "A two-dimensionnal Fourier transform method for the measurement of propagating multimode signals", *Journal of the Acoustical Society of America*, vol. 89 (3), pp. 1159-1168, 1991.
- [29] B. Morvan, N. Wilkie-Chancellier, H. Duflo, A. Tinel and J. Duclos, "Lamb wave reflection at the free edge of a plate", *Journal of the Acoustical Society of America*, vol. 113 (3), pp. 1417-1425, 2003.
- [30] C. Arist  gui, M.J.S. Lowe, P. Cawley, "Guided waves in fluid-filled pipes surrounded by different fluids", *Ultrasonics*, vol. 39, pp. 367-375, 2001.
- [31] Peter B. Nagy and Adnan H. Nayfeh, "Viscosity-induced attenuation of longitudinal guided waves in fluid-loaded rods", *Journal of the Acoustical Society of America*, vol. 100 (3), pp. 1501-1508, 1996.
- [32] R.M. Christensen, *Theory of viscoelasticity : an introduction*, New-York : Academic Press, 1982.



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