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Measurement of the properties of liquids based on the dispersion of Lamb waves in an acoustic waveguide


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Abstract

An acoustic waveguide sensor consisting of two identical parallel plates on which surface acoustic waves are propagating allows the measurement of proportion of liquid properties taking advantage of the mode conversion of SAW via the measurement of the transmission time and amplitude of short wave pulses [1]. A favourable realization of such a sensor consists of thin plates of non-piezoelectric material with a thickness in the order of the acoustic wavelength for example glass plates of about 1 mm thickness at excitation frequency of 1 MHz on which Lamb waves are excited and detected by means of piezoelectric interdigital transducers attached at the rear surfaces [2]. Due to the dispersion of Lamb waves for a given material and excitation frequency, their propagation velocity depends on the thickness of the plates. Correspondingly for the lowest order symmetric and asymmetric modes of Lamb waves the Rayleigh angle at which mode conversion occurs and the acoustic velocity difference to the liquid will be different and will change in different ways with changes of properties of the liquids. This allows a novel access to the investigation of such liquids with enhanced sensitivity.

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1. Concept of the acoustic waveguide sensor

The mode conversion of surface acoustic waves (SAW) propagating along a solid-liquid boundary results in the generation of compression waves in the liquid in case of Rayleigh or Lamb waves on substrates, for which the surface acoustic wave velocity is larger than the velocity of sound in the liquid. Under such circumstances the compression wave is radiated off from the substrate at the Rayleigh angle

\[ \Theta_R = \arcsin \left( \frac{v_s}{v_l} \right) \]  

\( v_l \) sound velocity in the liquid, \( v_s \) wave velocity on the substrate, which depends on the material properties both of the liquid and the substrate [3,4].

Based on this effect, an acoustic waveguide sensor for liquid properties has been developed, which consists of two identical parallel plates on which surface acoustic waves are excited and detected by piezoelectric interdigital transducers.

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transducers attached to the outer surfaces of the plates (Fig.1). This concept allows the use of non-piezoelectric material, e.g. structural materials like metal or glass, for the construction of the waveguide and thus the easy integration of the waveguide into a fluidic set-up [5].

From the transition time of short wave pulses across the liquid and the amplitude of the receiver signal both the velocity of sound and the acoustic impedance can be determined and thus compressibility and density of the liquid can be calculated from the results. This sensor concept has been applied favourably for the analysis of the composition of binary and ternary liquids such as solutions of sugar and ethanol in water [5].

Fig.1 Schematic representation of the construction and the acoustic wave propagation within the waveguide.

Fig.2 Time run of the excitation and the receiver signal at an acoustic waveguide sensor filled with water.

Due to the reversibility of the mode conversion effect, surface wave excitation and reemission of acoustic radiation happens at any intersection of the trajectory of the compression wave in the liquid with the confining plates resulting in a zig-zag pathway of sound waves within the liquid. The time run of the receiver signal is split into several signal groups according to different pathways in the liquid (Fig.2).

Since the piezoelectric transducers are located at the outer surfaces of the plates in order to avoid any contact with the liquid, the plates should be thin enough for an effective generation of sound waves in the liquid. Typically, glass plates of 1 mm thickness are used together with an excitation frequency of 1 MHz, which means that the device is operating in the Lamb wave regime, where dispersion effects have to be taken into account and the surface acoustic wave is split into symmetric and antisymmetric fundamental modes, whose phase velocities and whose interaction with a liquid load are substantially different. Correspondingly, for a proper understanding of the wave propagation within the waveguide sensor, the distinct mode of the surface acoustic wave and the phase velocity of this mode have to be known exactly. This has been accomplished by numerical calculations and their verification with simple experiments. Moreover, the dispersion effect allows an optimization of the acoustic waveguide sensor by proper choices of the construction parameters, which will be explained below in more detail.

2. Dispersion in the waveguide set-up

The dispersion of Lamb waves in the region of interest for the waveguide sensor has been investigated both with numerical calculations following an approach described by Rose [6] and with corresponding experiments considering the thickness of the substrates as variable parameters for materials used for the construction of waveguide sensors: glass, aluminium and steel.

2.1. Numerical Calculations

With the Rayleigh-Lamb frequency equations resulting from the solution of the wave equation of a traction-free homogeneous and isotropic plate according to the displacement potential method for stress free boundaries,
Phase velocities of propagating waves can be calculated as a function of the frequency-thickness product for given values of elastic modulus, density and poisson’s number of the plate material [6]. The solutions consist of a discrete set of fundamental and higher order modes, each of them are split into a symmetric and an antisymmetric branch. Those of the fundamental modes converge towards the velocity of the Rayleigh wave \( v_R \) with increasing frequency-thickness product. Dispersion curves of the fundamental and the first order symmetric and antisymmetric modes calculated in this way for glass and aluminium are shown in Fig.3 and Fig.4.

In our set-up typical values of the frequency-thickness product are around 1 MHz·mm, this means that only the fundamental modes will be excited and that the phase velocities of the antisymmetric and the symmetric modes are substantially different. Moreover, both modes differ in the dependence of the slope of the dispersion curves and thus the group velocity from the frequency-thickness product: Whereas the slope of the antisymmetric mode increases with decreasing frequency-thickness product, the opposite happens with the symmetric mode. Consequently, the phase velocity of the antisymmetric mode will be much more sensitive to changes in the frequency-thickness product than the symmetric mode in the waveguide set-up.

2.2. Experiments

An experimental verification of the dispersion curves would demand for a change of the frequency-thickness product either by changing the excitation frequency or the thickness of the plates. Since interdigital transducers with a rather narrow bandwidth (1.00 +/- 0.03 MHz) are used in the waveguide, changes of the excitation frequency would allow only a very limited range of investigations. Therefore, the thickness of the plates was changed, for which three different approaches were chosen in order to obtain reliable results:

a) Large glass plates with different thicknesses (3, 1.5, 1 and 0.2 mm) were equipped with interdigital transducers at a distance of about 0.5 m and supported on air bubble film. The distance of the transducers is large enough in order to neglect uncertainties in the distance measurement due to the extension of the transducers (6 mm in the direction of wave propagation). Unfortunately, two different sorts of glass had to be used for the thicker plates (3 and 1.5 mm) and for the thinner plates (1 and 0.2 mm). The interdigital transducers were excited with short bursts (5 cycles) of three different frequencies within the bandwidth of the transducers and the leading edge of the receiver signal on the time scale was recorded; together with the narrow bandwidth of the transducers by this procedure the phase velocity was measured approximately rather than the group velocity. The results shown in Fig.5 together with the numerical calculations prove that the asymmetric mode has been excited and that at least a qualitative agreement
between calculation and measurement has been achieved. Moreover, as expected, changes of the frequency within the bandwidth caused at most small changes of the phase velocity, which are significant only at the thinner plates.

![Fig.5](image1.png)  
Fig.5 Phase velocities of Lamb waves measured with 1 MHz excitation frequency at glass plates of different thicknesses along with the calculated dispersion curve of the A_0 mode.

![Fig.6](image2.png)  
Fig.6 Phase velocities of Lamb waves measured with 1 MHz excitation frequency at aluminium plates of different thicknesses along with the calculated dispersion curve of the A_0 mode.

b) Using a series of aluminium plates of 8 x 3 cm of different thicknesses measurements of the phase velocity were performed with a fixed arrangement of two interdigital transducers at a distance of 5.9 cm, which could be positioned underneath the plates and acoustically contacted to the plates by means of a layer of ultrasonic gel. The results of the measurements shown in Fig.6 corroborate the excitation of the antisymmetric mode; the larger deviations from the calculations were attributed to the larger uncertainty in the determination of the phase velocity due to the shorter distance of the transducers.

c) In another approach with a steel plate of an initial thickness of 0.740 mm, on which two interdigital transducers were glued on the reverse side, the thickness of the plate was reduced by grinding down to 0.665 mm and a significant shift in the time run of the receiver signal was observed (Fig.7), from which a reduction of the phase velocity could be derived. Since the material properties of the steel plate were not exactly known, the obvious agreement of the calculated absolute values of the phase velocity with the measured results might be doubtful to some extend, but at least the slope of the dispersion curve in that region of the frequency-thickness product fits reasonably to the measured data (Fig.8).

![Fig.7](image3.png)  
Fig.7 Time run of the receiver signal after 1 MHz burst excitation of a Lamb wave of a steel plate before (blue) and after reducing its thickness by 70 μm by grinding.

![Fig.8](image4.png)  
Fig.8 Phase velocities of Lamb waves measured with 1 MHz excitation frequency at a steel plate whose thickness was subsequently reduced by grinding along with the calculated dispersion curve of the A_0 mode.
3. Discussion

Considering the results of the experiments concerning the employed set-ups the preferential excitation is the asymmetric fundamental mode. This mode suffers strong attenuation when the plate is loaded with a liquid (“leaky Lamb wave”) in contrast to symmetric modes [6], therefore, its excitation is of crucial importance for the function of the waveguide sensor.

Since the dispersion curve of this mode, however, decreases monotonously towards zero with decreasing frequency-thickness product, it can be utilized for an enhancement of the sensitivity of the waveguide sensor: Since the Rayleigh angle $\theta_R$ depends both on the speed of sound in the liquid and on the surface wave velocity, it will approach to 90° when this velocity becomes equal to the speed of sound in the liquid. Then the transmission signal in the waveguide sensor will vanish, since the mode conversion effect will no longer occur. Thus, for any given liquid, this situation can be achieved by a proper choice of the thickness-frequency products. Obviously, the set-up will become extremely sensitive to any changes of the liquid or of the properties of the substrate if it is operated near this intersection point. With respect to the wave propagation within the liquid-filled waveguide, however, the excitation of a Scholte wave propagating along the surface, but mainly localized in the liquid, has to be taken in account in addition to the leaky Lamb wave [7].

A precise knowledge of the Rayleigh angle as obtained from the dispersion curves, on the other hand, is of importance with respect to the evaluation of the acoustic impedance of the liquid in the waveguide from the measured amplitudes of the receiver signal. Both from the velocity of sound and the acoustic impedance the density of the liquid in the waveguide can be determined, which allows interesting applications in liquid process monitoring [8].

Another application may arise from the sensitivity with respect to changes in the thickness of the plate (as noticeable from Fig.8), a significant change in the phase velocity of the $A_0$ mode resulted from changes of about 10 μm in the thickness of the steel plate: An increase of the effective thickness of the plate by deposition of solid layers from the liquid could be expected to influence the phase velocity in a similar way depending on the mechanical properties of the deposit [7].

4. Conclusion

The dispersion of Lamb waves have been studied theoretically and experimentally in the range of construction and material parameters typical for an acoustic waveguide sensor for liquids driven with interdigital transducers at 1 MHz excitation frequency using glass or metal plates as wave guiding structures. Due to the fixed frequency of the narrowband transducers, the thickness of the plates has to be changed in order to obtain experimental values for the dispersion curves. It turned out that the fundamental antisymmetric mode was excited preferentially, which is strongly affected by mode conversion when the plate is in contact with a liquid and thus is of crucial importance for the function of the waveguide sensor. The dispersion effect can be used for the enhancement of the sensitivity of the waveguide sensor to changes of the properties of the liquid, if it is operated near the crossing point of the phase velocity of the Lamb wave and the speed of sound in the liquid.

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