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The propagation of horizontally polarized shear waves in plates bordered with viscous liquid

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ABSTRACT

Requirements for ultrasonic horizontally polarized shear waves based viscosity sensors and their applicability for continuous in-line measurement are presented and discussed. The results reveal, that sensors using non-piezoelectric plates as well as wave guides and sensing surface have application-oriented advantages in corrosive and hot liquids.

For such non-piezoelectric plate sensors, the dispersion relations are found and the linking equation among propagation velocity as well as attenuation coefficient and Newtonian liquid parameters are obtained. The findings show that in presence of viscous liquids the propagation parameters of horizontally polarized shear waves (HPSW) in non-piezoelectric plate change and a viscosity depending attenuation occurs. It is shown that the measurement sensitivity, in physical terms, of the investigated device highly depends on plate thickness, shear wave impedance of the plate material, and the shear wave impedance of the ambient liquid. Further, reasonable geometrical optimizations and suited plate materials are discussed.

Contents

1. Introduction

Measurement of liquid properties with horizontally polarized shear waves (HPSW) has received high attention in ultrasonic research community for recent decades. The wave propagation parameters are strongly linked with the physical and chemical properties of the plates surrounding medium. One scope of application for HPSW-based sensors is to detect smallest concentrations of substances in gases and liquids. A typical sensor consists of piezoelectric wave guide layer, which is attached to a concentration sensitive layer. Usually in this configuration interdigital transducers (IDT) are used to excite and receive the HPSW. In order to characterize fluids, the change in the transmission parameters of the sensitive layer or of the wave guide itself are measured and evaluated.

Such sensor layouts are also used to carry out viscosity measurements. The interactions of the HPSW with viscosity liquid result in wave parameters change like resonance, phase shifts,

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propagation time, and wave attenuations of the received wave [1–11]. An overview of typical design and application of acoustic wave sensors is given in [12].

Analogous measurements are also carried out with Love waves. In [13] an additional layer is used in order to excite and receive Love waves in continuous mode. Another Love Wave sensor for viscosity sensing, which operates in pulse mode, is proposed and theoretically investigated in [14]. Love wave sensors suffer from some constructional disadvantages. The required velocity difference, between the layer and the semi-space, limits the potential number of possible material combinations. One more practical challenge is to suppress excitation and reflection of waves in the semi-space. This leads to high damping needs in the substrate and reduces the geometric flexibility of the wave guide design.

All the presented HPSW sensor designs are stretched to their limits in presence of hot and corrosive environments. Therefore theoretical investigations on propagation and damping parameters of plates coated with viscoelastic materials are under investigation to discover new application fields [15,16].

For viscosity measurements in hot or corrosive liquids a sensor design, which uses a non-piezoelectric plate as wave guide and sensitive surface, has undoubtedly constructive advantages. To excite and receive the HPSW in the non-piezoelectric plate, two wedge transducers are suggested, which are mounted outside the measurement chamber to protect them from the rough conditions. The section of the plate, which is not covert by the transducers, is in contact with the investigated liquid. Changes of wave parameters, which are influenced by the surrounding liquid, are measured and the shear viscosity is calculated. A possible sensor design is visualized in Fig. 1 [17].

Hence a non-piezoelectric and not layered plate is utilized, the wave guide can have a curved shape to increase the interaction surface with the measured liquid. This sensor design suits a wide range of temperatures and corrosive liquids, because chemical and temperature resistant materials can be used for both wave guide and chamber. Also, different excitation and reception methods like bulk wave transducers and piezoelectric film/block transducers are conceivable [18].

However, the insufficient development of theory between measured wave properties and liquid viscosity inhibits a wide application of such sensor design. In addition, the estimation of the achievable measurement accuracy and the optimization of the sensor spatial dimensions, require further theoretical analyses. One of the main goals of the presented work is to obtain explicit mathematical relationships between the measured wave parameters – propagation velocity and attenuation – of the HPSW in non-piezoelectric plate and the viscosity of the ambient liquid.

2. Dispersion equations

One of the first theoretical investigations was done by Meeker and Meitzler [19]. He examined the setup of a solid plate and cylinders, which are bounded by air. For this particular case, he formulated and solved the boundary value problem and described the HPSW symmetrical and antisymmetrical modes in the plate. A theoretical analysis of a horizontally moving plate in liquid, which cause shear waves in viscous liquid, is carried out in [20]. An approach for Lamb waves in a plate bordered with non-viscous liquid is presented in [21] and an approach for Lamb waves in a plate bordered with viscous liquid is presented in [22].

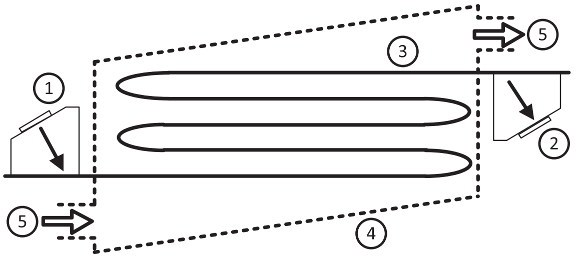

Fig. 1. Schematical design of the proposed HPSW sensor: (1) transmitter (2) receiver (3) non-piezoelectric and not layered wave guide (4) measurement chamber (5) liquid flow direction.

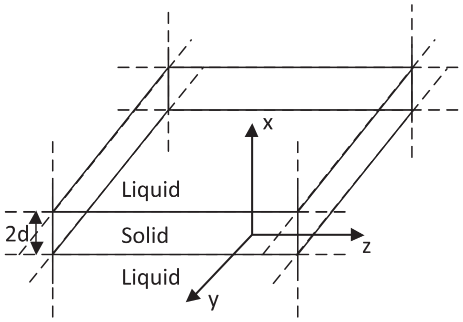

Fig. 2. Illustration of the arrangement and the coordinates.

This work is focused on a plate bordered with viscous liquid media, in which a horizontal polarized wave propagates in z direction. It is assumed, that the plate is infinite in z and y direction and is bounded by a viscous liquid in x direction on both sides. In HPSW particles moves only in the y horizontal plate plane and perpendicular to the propagation z direction. The arrangement and the coordinates are illustrated in Fig. 2.

The arrangement leads to new boundary conditions. At the upper and lower solid-liquid interface the nonslip conditions should be satisfied. In particular, stress tensors and particle displacement vector should be continuous along the y tangential directions. In the following, relevant equations for HPSW in solid media are presented and discussed.

2.1. HPSW in solid media

The work in [19] presents the differential equation governing small elastic periodic motions in solid plates in absence of further forces. In [23] is shown that all solutions of differential equations can be formed from a combination of a vector potential function $\boldsymbol{\psi}_s$ and a scalar potential function ϕ_s, where bold variables represent vectors [24]. At first, the equation for the solid plate are deduced and presented.

As mentioned before, the plate is assumed to be infinite extended in the z and y direction and to be bounded by planes $z = \pm d$ in the x direction. The plate wave propagates in z direction. Consequently, the potential functions are independent of y. The three components of the displacement vector in the plate $\boldsymbol{u_s}$ are described by the potential functions

$$
\begin{aligned}
u_{s,x} &= \frac{\partial \phi_s}{\partial x} - \frac{\partial \psi_{s,y}}{\partial z} \\
u_{s,y} &= -\frac{\partial \psi_{s,z}}{\partial x} + \frac{\partial \psi_{s,x}}{\partial z} \\
u_{s,z} &= \frac{\partial \phi_s}{\partial z} + \frac{\partial \psi_{s,y}}{\partial x}
\end{aligned}
\tag{1}
$$

plus the vector potential needs to satisfy.

$$
\frac{\partial \psi_{s,x}}{\partial x} + \frac{\partial \psi_{s,z}}{\partial z} = 0 \tag{2}
$$

If the horizontal polarized shear waves travel in z direction and the particle displacement occur only in y direction, the $u_{s,x}$ and $u_{s,z}$ component of the displacement vector must be zero. Hence it is