Utilizing Pressure Waves for Sensing the Properties of Liquids

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We report on a concept for a fluid sensor utilizing pressure waves for sensing the fluid properties (e.g. viscosity, sound of speed). The detection of fluid properties is of importance for many technical processes. Requirements for such sensors are small size, robustness, lightweight and a reasonable price. An approach utilizing pressure instead of shear waves is introduced. With this approach it is possible to overcome the drawback of the small penetration depth of shear waves in liquids. The theoretical background, a simple 1D model, simulation results and first measurement results are presented.

Introduction

Sensors for liquid condition monitoring are an important asset for process control. Industrial applications require reasonably priced sensors which are small in size, lightweight, robust, need little maintenance, and are preferably suited for online monitoring. A lot of recent work has been focused on viscosity sensors (see e.g. [1]). Laboratory equipment for determining the shear viscosity involves motors and rotating objects immersed in the liquid and is commonly bulky, maintenance intensive, and not suitable for online monitoring. Miniaturized sensors for fluid viscosity (e.g. small, vibrating structures immersed in the liquid) often utilize shear vibrations. With these devices only a thin film of the liquid is measured, due to the small penetration depth (in the range of a few micrometers depending on the exciting frequency) of the shear waves [1]. To overcome this crucial disadvantage for many applications we use an alternative approach which is based on pressure waves such that the bulk of the sample is probed. With this approach instead of the shear viscosity the so-called longitudinal viscosity is determined, which can be equally useful for condition monitoring. At the moment material data for the longitudinal viscosity of fluids is rare because this parameter has not been widely experimentally investigated. Some experimental studies determining this parameter using the principle of acoustic spectroscopy can be found in [2], [3]. Compared to this laboratory equipment based approaches, we intend to achieve an integrated, resonant sensor system.

Theory

We use an approach based on the attenuation of pressure waves in a fluid. From the theory of acoustic wave propagation, the behavior of pressure waves in liquids is well known [4]. Figure 1 shows the basic arrangement of the sensor. Two parallel boundaries separated by a distance *h* form a sample chamber. One boundary carries a transducer which imposes pressure waves, resonating between the two boundaries, in the liquid. In addition to using the transducers impedance change as sensor output signal the second boundary can be optionally equipped with a pressure sensor whose output can also be used as sensor signal.

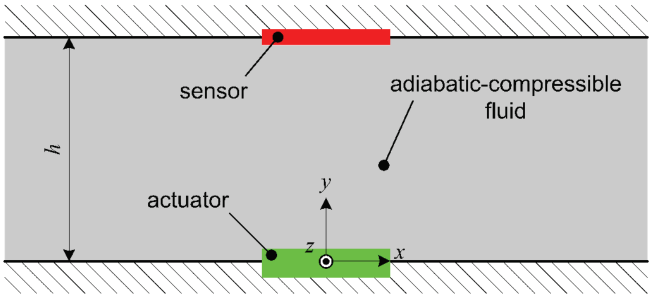

Fig. 1: Basic sensor arrangement.

Solving the linearized two-dimensional Navier-Stokes equation (displacement vector **u**, mass density ρ_0, and adiabatic compressibility ζ_S, μ is the coefficient which represents the shear viscosity and is often only termed viscosity, λ represents the dilatational viscosity associated with compressional stress components)

$$\rho_0 \ddot{\mathbf{u}} = \frac{1}{\zeta_S} \nabla(\nabla \cdot \mathbf{u}) + (\mu + \lambda) \nabla(\nabla \cdot \dot{\mathbf{u}}) + \mu \nabla^2 \dot{\mathbf{u}}$$

by using complex notation for time-harmonic signals and the spatial Fourier transform leads to an approximate solution for the fields which shows, that the attenuation due to viscous damping will always approximately depend on (λ+2μ) and that the two parameters can not be separated. So this concept only allows the measurement of the longitudinal viscosity (λ+2μ), [5] – [8].

Figure 2 shows the 1D model for the sensor setup. For the PZT disk, a commonly used three port model was applied [9], the fluid was modeled as acoustic transmission line and the boundaries of the fluid chamber as acoustic impedance. For a more detailed discussion see [5] – [7], [9].

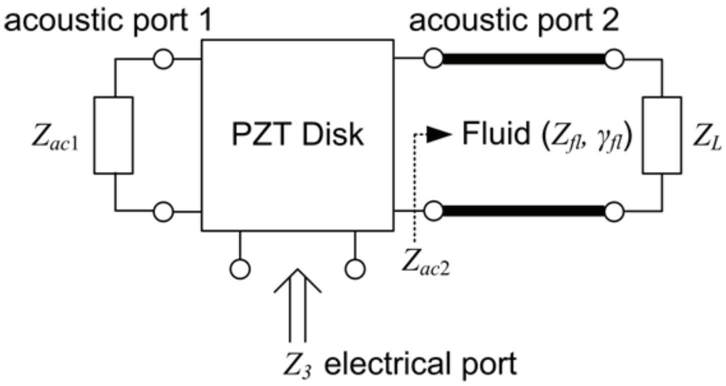

Fig. 2: 1D sensor model.

Results

In this section we provide some illustrative sample results of the approach, for more details we refer to [5] – [7]. Figure 3 shows simulation results for the 1D model with different media in the sample chamber while Fig. 4 shows measurement results obtained with a first prototype device. In this sensor setup, the fluid represents a resonating acoustic transmission line which yields a comb-like pattern in the transducer impedance. The spacing can be used to determine the sound velocity in the liquid while the damping is associated with the longitudinal viscosity [5]. The differences between model and experiment can be explained by several losses which are not yet included in the model such as losses induced by the mounting of the PZT disk and the non-ideal reflection of the acoustic wave at the boundaries.

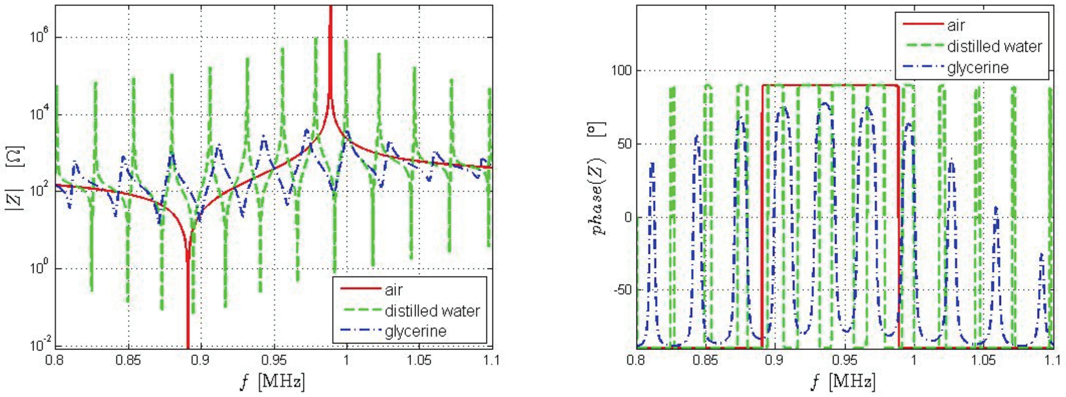

Fig. 3: Magnitude and phase of the piezo transducer for different media (simulation).

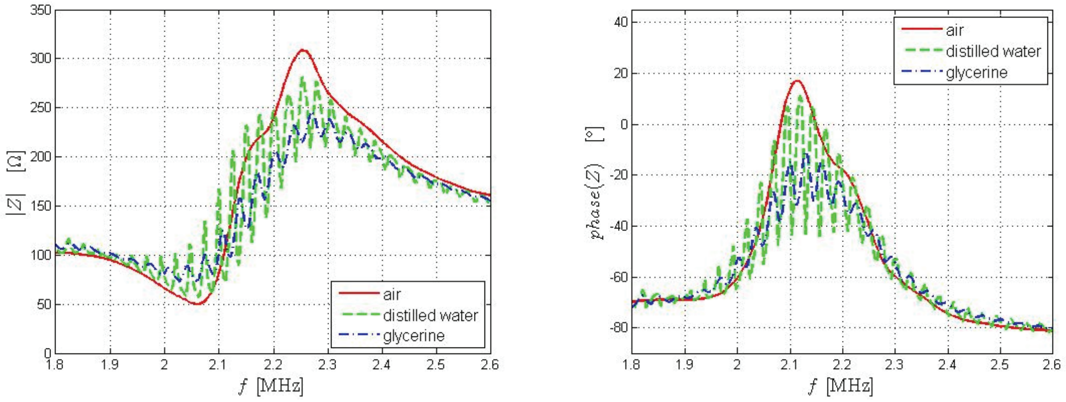

Fig. 4: Magnitude and phase of the piezo transducer for different media (measurement).

Conclusion

We presented a concept for a sensor measuring the so-called longitudinal viscosity. Results obtained with a first prototype device show a clear dependence of the electrical impedance on the fluid parameters. In particular the damping of the resonances is related to the viscosity and the spacing of the comb like resonances depends on the speed of sound in the fluid. The simple 1D model enables qualitative predictions of the experimentally generated data but needs further refinements to narrow the gap between simulation and measurement data.

Acknowledgements

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