

Reduction of systematic measurement deviation in acoustic absorption measurement systems

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Motivation

One major issue in the realization of acoustic absorption measurement systems is the fact that the absorption caused by dissipative effects in the fluid, such as viscosity, is superimposed by other losses resulting from the sound propagation in the respective measurement system. Examples for these effects are the spreading of the acoustic signal caused by diffraction and unwanted transmission at acoustic reflectors or waveguide boundaries. Unwanted reflected signals from planar surfaces included in the measurement system for constructive reasons may also interfere with the measurement. In this contribution, we describe several measures, which aim to reduce systematic measurement deviation by decreasing or compensating the aforementioned effects.

The measures are realized by modifying a measurement system originally designed for precision sound velocity measurement [1, 2] (figure 1) for fluids in varying thermodynamic states. This requires the measurement system to be applicable at high temperatures and pressures (up to 480 K and 200 MPa) thus limiting the materials and joining techniques to be used. Central element of the system is an X-cut quartz transducer that is mounted to allow for emission of acoustic waves in both directions. The emitted signals are reflected by two reflectors that are positioned at different distances (20 mm and 30 mm) to the transducers surfaces (figure 1). The reflected signals are received by the transducer, and the propagation time difference t_{Δ} is evaluated to determine the sound velocity of the fluid. The authors have already shown that the amplitude information of the signals acquired using this setup can be analysed to determine the acoustic absorption of the fluid [3]. However, the procedure relies on reference data to compensate for the systematic measurement deviation caused by the sound propagation in the measurement system. We aim to reduce this systematic deviation by modifying the measurement system to alleviate the reliance on reference measurements.

Application of diffuser surfaces

Due to the requirement that the fluid in the measurement system needs to be in thermodynamic equilibrium, a smaller measurement setup is advantageous. Thus, it is not generally possible to move the surfaces of passive mounting elements sufficiently far away from the acoustic wave propagation to not interfere with the measurement.

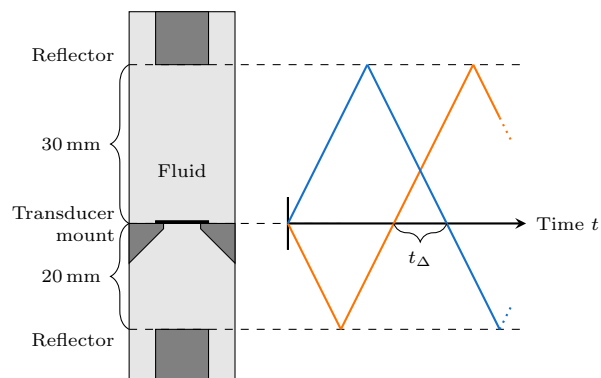


Figure 1: Schematic of the original precision sound velocity measurement set-up [1] with two reflectors and the propagation of acoustic signals over time.

As an alternative, the surfaces in question can be structured randomly to cause diffuse reflection of acoustic waves [4]. This is especially necessary if the material used for the surfaces has a significantly higher specific acoustic impedance than the fluid to be analysed. In the present setup (figure 1), one surface that can cause unwanted reflected signals is the area behind the reflectors. In the revised version of the reflector, a random surface structure is applied to this area (figure 2), consisting of uniformly distributed prisms with a maximum height of 3 mm, arranged in radial and azimuthal directions. A three-dimensional model of the entire reflector element is created and procedurally modified to create the randomly structured surface. The physical reflector element is then created additively by using selective laser melting. To enable applicability at high temperatures and pressures, the component is manufactured from stainless steel (1.4550).

Concept of the revised transducer mount

In this section, the revised transducer mount is described conceptually. The specific details on how the components are realized in the revised measurement setup are described in the following section.

Diffusion of structure-borne sound

When the measurement system (figure 1) is used to analyse fluids with low density and sound velocity (i.e. with low specific acoustic impedance), additional echoes are observed in the signals acquired. These signals are assumed to be caused by propagation of structure-borne sound in the transducer mount. When the transducer is excited

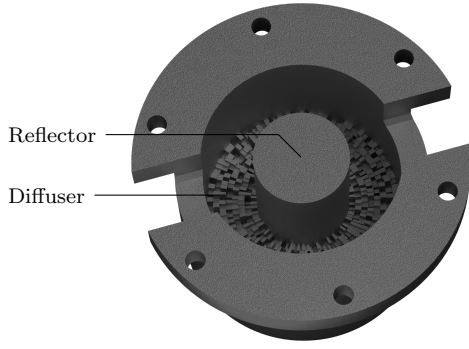


Figure 2: Model of the revised reflector element with diffuser structure.

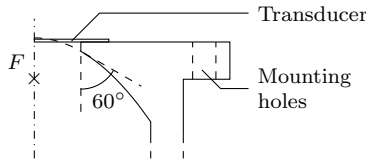


Figure 3: Revised lower element of the transducer mount with parabolic shape.

by the electrical signal, the acoustic signal is partially transmitted into the transducer mount, especially if the specific acoustic impedance of the fluid is low. Due to the fact, that the mount is cone-shaped with an aperture of 45° (figure 1), the signals transmitted into the mount's material (stainless steel) are predominately reflected to the outside boundary of the measurement system, where the incidence of the acoustic waves is approximately perpendicular. Thus, the signals are reflected back into the mount and the transducer, causing the additional signals.

Field simulations [5] show that increasing the aperture of the cone-shaped mount to 60° significantly decreases the occurrence of additional signals. However, applying a parabolic instead of a cone-shaped surface suppressed the structure-borne signals returning to the transducer further. Thus, a revised version of the transducer mount is developed (figure 3), keeping the angle at the edge of the opening in the mount at 60° as determined from the simulation study for cone-shaped mounts. The focus F of the resulting paraboloid is located above the transducer's position, discouraging waves in the fluid from being reflected from the parabolic surface to the transducer. For constructive reasons explained in the following paragraph, the opening in the transducer mount has a small, cylindrical ledge (1 mm), similar to the original setup [1].

Symmetrical transducer mount

In the original setup, the transducer mount consists of a cone-shaped element with a circular opening (figure 1). The quartz crystal is placed on the opening and fixed and electrical connected using small spring elements [1]. This results in a distinctly asymmetrical acoustic behaviour with regards to both emission directions. While the transducer is partially masked by the cone-shaped element on the side where the reflector is close (20 mm), it is unob-

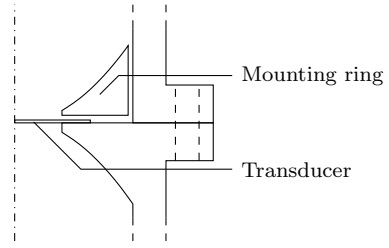


Figure 4: Schematic of the transducer mount to enable symmetrical emission of acoustic waves in both directions.

scured on the other side. This results in different emission characteristics and sensitivities in both directions, creating in part the systematic measurement deviation that needs to be compensated. Therefore, a revised version of the transducer mount is developed with the aim to create symmetrical emission characteristics in both directions. Special care is taken as the mount is also required to connect the transducer electrically, while avoiding materials that may be unsuited for the high temperature and pressure environment the setup is to be applied in.

To realize the symmetrical transducer mount, a mounting ring is positioned above the transducer (figure 4) to mask the upper surface of the transducer in the same way the lower element (figure 3) masks the lower surface. This ring is also used to contact the upper electrode of the transducer electrically and thus has to be insulated from the other components of the setup, which are electrically in contact with the lower electrode. This is realized by maintaining a gap between the ring and the outer wall of the measurement setup (figure 4). Direct mechanical contact of the mounting ring and the transducer is avoided to prevent damage to the transducer. The mounting ring has a cylindrical ledge, similar to the lower element of the transducer mount. However, the ledge of the ring is only 0.5 mm while the gap between the transducer and the ring is also 0.5 mm. The upper side of the mounting ring is parabolic to mirror the lower elements surface structure. So, if the influence of the gap is neglected, the surrounding surfaces of the transducer are symmetrical to the transducer plane.

Realization of the revised transducer mount using additive manufacturing

Due to the intricate nature of the parts, and the fact that they need to be made from temperature resistant materials, selective laser melting is used to manufacture the components from stainless steel (1.4550). To electrically connect the mounting ring to the upper electrode of the transducer, spring loaded pins (F708, *FEINMETALL GmbH*) are inserted into the ring. The simplified geometry of the mounting ring (figure 4) needs to be modified to accommodate for these pins, requiring housings that protrude from the parabolic surface (figure 5). Because one of the transducers to be used is a quartz crystal with so-called 'keyhole electrodes', two spring-loaded pins need to be on opposite sides of the ring. To further fix the transducer, two additional pins are inserted perpendicularly. Further, the mounting ring has to be fixed to the lower

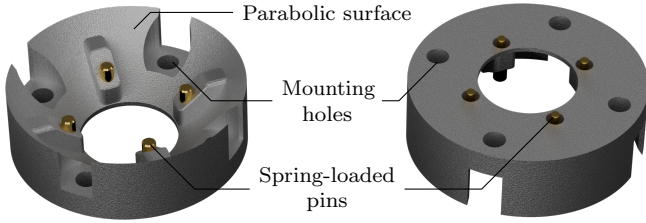


Figure 5: Upper and lower view of the model for the mounting ring with spring loaded pins inserted.

element of the transducer mount, requiring a number of mounting holes. For reasons of symmetry, four mounting holes are realized along with space for washers that are required for electrical insulation (figure 5).

To keep the surfaces surrounding the transducer as symmetrical as possible, the housings of the spring-loaded pins are mirrored on the lower element of the transducer mount as well. However, as no spring-loaded pins are required to contact the lower electrode, the housings are instead used to accommodate the screws, which hold the ring element in place. Figure 6 shows a sectional view of the realized transducer mount along with the spacers to place the reflectors at two different distances (20 mm and 30 mm). The shorter spacer and the lower element of the transducer mount are realized as a single component, which is also manufactured additively from stainless steel. Because the longer spacer has a relative simple, nearly axisymmetric geometry, it is manufactured by spin forming. Also note the washers made from polytetrafluoroethylene on the screws fixing the mounting ring, which ensure electrical insulation. The wire transmitting the excitation signal is connected to the mounting ring, while the rest of the setup is at ground potential. The six circumferential holes at the ends of both spacers are used to mount the reflector elements (figure 2). The technique is also used in the original setup [1] and enables interchangeability of the different elements between the original and the revised experiment.

The original measurement system [1] applies an X-cut quartz transducer with a resonance frequency of 8 MHz. Due to low losses in the quartz material, the quality factor of the quartz transducer is high [6], resulting in a low bandwidth. For sound velocity as well as absorption measurement, short signals are desirable. Thus, a ceramic, piezoelectric transducer is used in the revised measurement system to increase the bandwidth and thereby decrease the possible length of the transmission signal. Because of their lower temperature dependency, transducers made of hard piezoelectric material (PIC181, *PI Ceramic GmbH*) are selected. To lessen the effects of diffraction at the acoustic source, higher frequency waves are generally preferred. Thus, a piezoceramic disc with a resonance frequency of 11 MHz is used in the revised setup.

Results

To evaluate whether the measures described before significantly lessen the influence of systematic deviation on acoustic absorption measurements, methanol is analysed

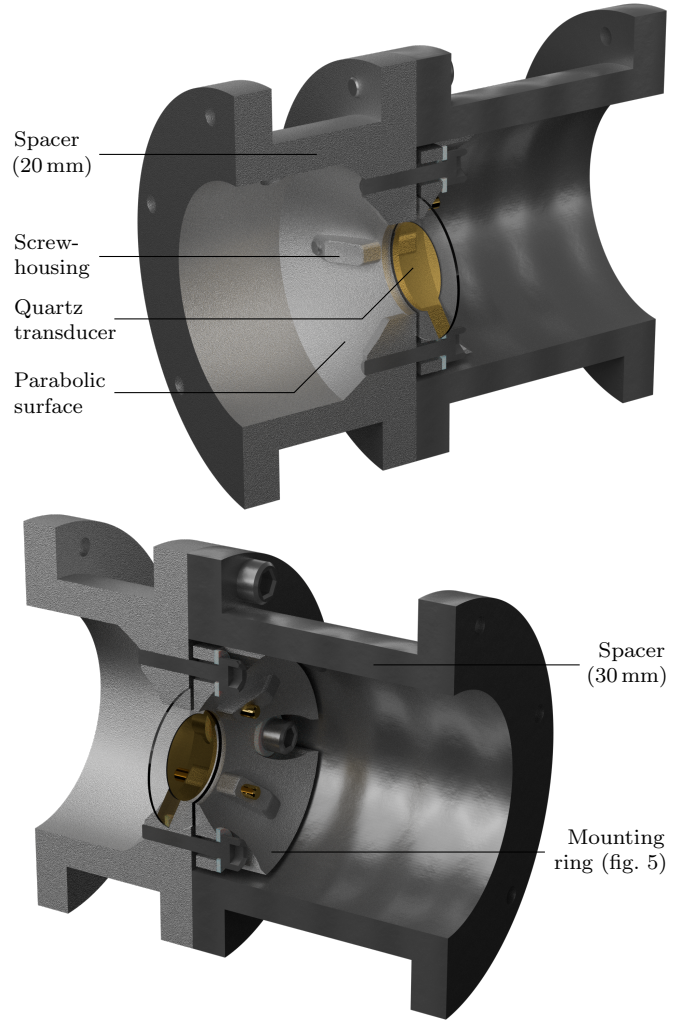


Figure 6: Sectional view of the transducer mount for symmetrical radiation from the direction of the parabolic lower element (top) and the inserted mounting ring (bottom).

at different thermodynamic states. However, instead of the acoustic absorption α , which shows quadratic dependence on the angular frequency ω in fluids [7], the sum of thermal and viscous losses μ is observed. This quantity related to acoustic absorption via the sound velocity c and the density ρ_0 of the fluid [7]:

$$\mu = 2c^3 \rho_0 \cdot \frac{\alpha}{\omega^2} = 2c^3 \rho_0 \cdot a. \quad (1)$$

An algorithm developed by the authors enables the determination of the frequency-independent absorption parameter a directly from the acquired signal spectra [8]. The results for μ_{meas} of measurements performed with the original and the revised setup are compared with reference data (figure 7). To generate the reference data, several thermodynamic properties of the fluid are required [7, 3]. Besides the volume viscosity, these properties are obtained from established equations of state [9]. The values for the volume viscosity are interpolated from other publications (Hawley et al. [10] and Kor et al. [11]). While the results of the revised setup (figure 7) show some scattering, which is less pronounced in the results from the original setup, the results of the revised setup are significantly closer to the

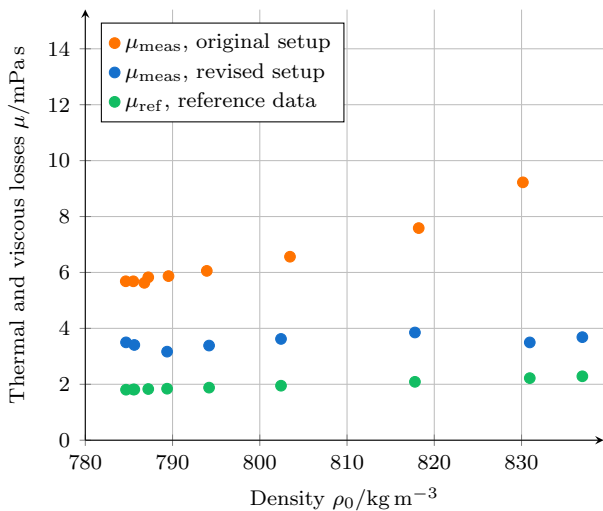


Figure 7: Sum of thermal and viscous losses of methanol at 300 K measured with the original and revised setup along with reference data [10, 11].

reference data. Of particular note is the fact, that the observed deviation from the reference data is less dependent on density in the revised setup. Because the systematic measurement deviation can be modelled mathematically dependent on density and sound velocity [3], the required expression is expected to be significantly less complex for the revised setup.

Conclusions

While measurements of acoustic absorption using transmission or reflection methods are generally superimposed by additional losses caused by the wave propagation in the respective measurement system, there are measures that can be applied to reduce the systematic measurement deviation caused by these effects. Especially emerging technologies, such as additive manufacturing, allow the creation of highly specialized components at moderate costs and fast turnaround.

To further reduce the systematic measurement deviation still observed, one approach is to increase the transmission frequency of the transducer further by exciting the first harmonic frequency of the transducer. As of now, this yields only signals with low signal-to-noise ratios because of sensitivity issues. Further, the revised transducer mount as of now has a gap with parallel surfaces between the transducer and the mounting ring. This causes a small amount of reverberation which can be suppressed by structuring the lower surface of the mounting ring similar to the surface of an acoustic diffuser [4].

Acknowledgments

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