Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Sensitive sound field parameters for the characterization of viscous fluids

Anke Burkhardt
TU Dresden
Solid-State Electronics Laboratory
Dresden, Germany
anke.burkhardt1@tu-dresden.de

André Juhrig
TU Dresden
Solid-State Electronics Laboratory
Dresden, Germany
andré.juhrig1@tu-dresden.de

Mario Wolf
TU Dresden
Solid-State Electronics Laboratory
Dresden, Germany
mario.wolf@tu-dresden.de

Elfgard Kühnicke
TU Dresden
Solid-State Electronics Laboratory
Dresden, Germany
elfgard.kuehnicke@tu-dresden.de

***Abstract*—Conventionally analysis of damping measurements assuming plain waves without considering the shape of the sound field lead to wrong damping coefficients. In this study, it is shown that the received signal strongly depends on the type and shape of the reflector, the applied transducer and sample medium and therefore the dependence of focus position and spectral distribution from sound velocity and damping is discussed. For instance, a change of the focal position between a nearly "non-damped" and damped media was observed.**

Keywords—ultrasound, sound field, damping, reflector

I. Introduction

Acoustic damping is an important physical effect occurring in ultrasonic measurements. On the one hand, a trade-off between the maximum frequency/resolution and penetration depth for the examination of a material or tissue by sound has to be found. On the other hand, damping is a measure value for the determination of the viscosity. Currently, for example in the case of blood measurements, various attenuation coefficients exist. Conventionally, measurements of the damping coefficient were done by determination of the decrease of the amplitude in dependence of the length of the sound path by transmission or in impulse echo mode. Either for that, the distance between the transmitter and receiver has to be changed or multiple echoes were used. In such procedures, the decrease of the amplitude in dependence of the alteration of the path length for a plain wave is determined. For elimination of the sound field effects (transducer characteristics) in fluids, new literature deal with comparative measurements between "non-damping" calibration medium and medium under testing in a defined measurement cell with high focusing transducers ("substitution method") [1, 2, 3] and the difference in signal intensity between the media is defined as damping. The reported values differ by orders of magnitude and furthermore, there is no agreement about the frequency dependence. There are numerous proposed measuring setups and only a few of them provide comparable results.

The goal of this study is to develop a technique to find material parameters regardless of the setup by evaluating sensitive sound field parameters for damped fluids. We will show that the received signal greatly depends on the reflector or receiver position in the sound field and therefore the conventionally measured damping coefficients are no material parameters, they are rather extremely dependent on the measurement setup. Furthermore, the influence of the speed of sound and damping on the sound field, especially on the focus position, was investigated.

II. Theory

In the simplest case of a Newtonian fluid for the determination of an attenuation coefficient at an adiabatic change a modified wave equation considering the attenuation can be derived from the Navier-Stokes equation, the equation of state and the equation of continuity (neglecting the thermal conductivity and the volume viscosity) [4, 5]:

$$\nabla^2 p = \frac{1}{c^2}\left(\frac{\partial^2}{\partial t^2} - \frac{4\eta}{3\rho}\frac{\partial}{\partial t}\nabla^2\right)p \tag{1}$$

p is the sound pressure, ρ – the density, c – the sound velocity, η the shear viscosity.

Using $k^2 \approx \omega^2/c^2$ as well as the approach:

$$p \simeq Ae^{j\frac{\omega}{c}(x-ct)} \tag{2}$$

the result is a correction of first order and for the wave number k follows:

$$jk \simeq \frac{\omega}{c}\left[j - \frac{2}{3}\frac{\omega}{c}\frac{1}{\rho c}\eta_s\right] = j\frac{\omega}{c} - \alpha \tag{3}$$

Thereby an attenuation coefficient for the even wave can be defined:

$$p = Ae^{j\frac{\omega}{c}(x-ct)-\alpha x} \tag{4}$$

with

$$\alpha \simeq \frac{2}{3}\frac{\omega^2}{c^2\rho c}\eta_s \qquad (5)$$

Since in the following the sound field is determined by summation over the fields of point sources and they possess a propagation term ${}^{1}/_{R}\, e^{jkR}$, a damping coefficient for spherical waves is necessary. The one-dimensional propagation of sound waves of spherical waves result in:

$$p = \frac{1}{R} A e^{j\frac{\omega}{c}(R-ct)-\alpha R} \qquad (6)$$

where R is the distance between source and reference point.

III. Materials and methods

The sound field contains all information about the damping mechanism in the media. If the sound field is known, inverse methods could be applied to receive these parameters. Since an exact scan of the sound field is very difficult the information obtained from several types of reflectors (spheres, wires) were examined. A scan with a point reflector in the range of the wavelength is an appropriate procedure to measure the sound field, but this measurement is problematic because of the manufacturing and handling of such reflectors as well as the low signal amplitude.

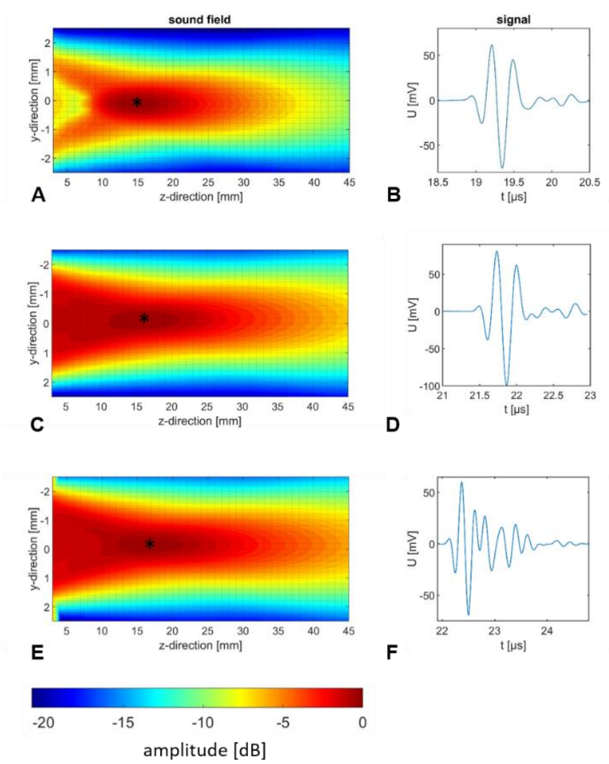

Fig. 1: Sound field of the unfocused transducer with center frequency of 3.5 MHz measured with: A) a spherical reflector of 3 mm diameter, C) a wire of 3 mm diameter and E) a wire of 400 µm diameter. * marks the region of the selected echo signal in the focal zone depicted in B), D) and F). Max=14.9 mm (A), 16.1 mm (B) and 16.9 mm (C).U – voltage, t – time.

Funding by Deutsche Forschungsgemeinschaft (DFG), 239880265

Since only the vertex of a sphere works as a reflector and a sphere with a diameter of 3 mm provides enough signal amplitude this reflector was chosen for the experiments. Because measurements on a sphere lead to a high experimental effort gaining a 2D sound field and a wire as reflector simplifies the adjustment, additional different wires were chosen for comparative measurements. For both, the sphere and the wires, an "equivalent near field length", at the maximum of the sound field is determined. As for plain sources N~1/c, the expected "equivalent near field length" can be calculated for different sound velocities. The 2D-sound fields were obtained by scanning the reflector target in two dimensions (y-z-direction). Therefore, the transducer was moved in two directions. For precision in the case of the spherical reflector, it was also scanned along the x-z-direction to avoid receiving a tilted sound field with wrong parameters. In preliminary experiments, sound fields of the selected reflectors were measured in water at 20°C.

Due to its negligibly small damping, water and saline solution and for different damped media glycerin-water mixtures were chosen as sample medium. The measurements were also carried out at 20°C and the signals were analyzed regarding their spectral composition. Because the sound velocity also depends on the concentration of glycerin this value had to be determined additionally. For the experimental determination of the shape of the sound field and all parameters in damped and nearly "non-damped" media, an unfocused transducer was utilized with a center frequency of approximately 3.5 MHz.

IV. Results and Discussion

Fig. 1 shows the measured sound fields of the preliminary experiments in water at approximately 20°C (sound velocity *c*=1487 m/s) using wires (c, e) or a sphere (a). The echo signals of the wires are an integral value and can additionally result in overlapping of circumferential echoes (figure 1d). Different shapes of the sound field especially concerning the maximum position and the shape of near field were observed. The determined near field length depends on the used reflector type. Comparison between sound fields measured with wire and sphere shows that the wire reflectors caused a blurred near field as result of the integration (figure 1c and d).

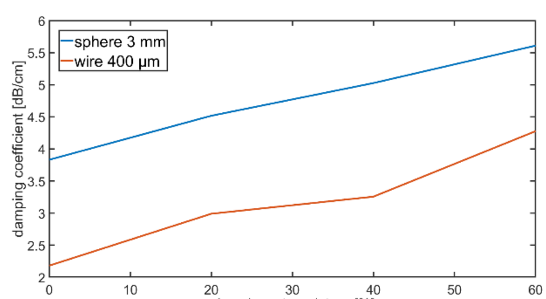

Fig. 2: Determined damping coefficients with sphere- and wire-reflector. The signal amplitudes measured at different points in the far field are evaluated by applying the conventionally plain wave model.

In a following experiment, the damping coefficient was conventionally determined for the glycerin-water mixtures. For this purpose, the amplitude was measured at three different positions in the far field with both, the 3 mm sphere and the 400 µm wire. Fig. 2 shows the determined damping coefficients as function of the glycerin-water concentrations. The damping coefficients differ by about 1.6 dB/cm for the measurements with sphere and wire and therefore the determined value is not a material parameter and depends on the measurement setup.

To investigate the influence of attenuation on the sound field the focal position was determined from the measured sound fields and depicted as function of the sound velocity (figure 3). Since the sound velocity depends on the glycerin-water concentration, (numbers in the figure indicate the concentration), figure 3 shows also both the relation between velocity and concentration and between concentration and focus position. In order to assess whether the damping has an additional impact to the focal-shift and to distinguish between the effects, the focal position was also determined from the near field length of the "non-damped" media. In figure 3, it becomes evident that applying the 400 µm wire provides totally different focal positions than with the 3 mm sphere. The focuses of the sound fields measured with the 400 µm wire are always farther away from the transducer. This can be a result of the circumferential echo, which is overlapping the echo from the wire, the integration of the signal along the wire or an interaction between both effects. Furthermore, a comparative measurement with a 3 mm wire and a 3 mm sphere showed that the focus position determined with the 3 mm wire is also farther from the transducer (figure 1a and c), but not so far like the focus determined with the 400 µm wire (figure 1e). The fact point up that the focal positions of the 400 µm wire is may be affected by both the integration and the circumferential echo and the focal position of the 3 mm wire only by the integration. To better estimate the effect of damping, figure 4 shows the sound fields in different damped and "non-damped" media scanned with the 3 mm sphere. By comparing the sound fields in the two "non-damped" media, water with c=1487 m/s (figure 4a) and NaCl-solution with c=1803 m/s (figure 4b) it becomes evident that an increase of sound velocity caused a shift of the focus position. This is in agreement with the near field length. Comparison of the 60 percent glycerin-water mixture (figure 4c) with the nearly

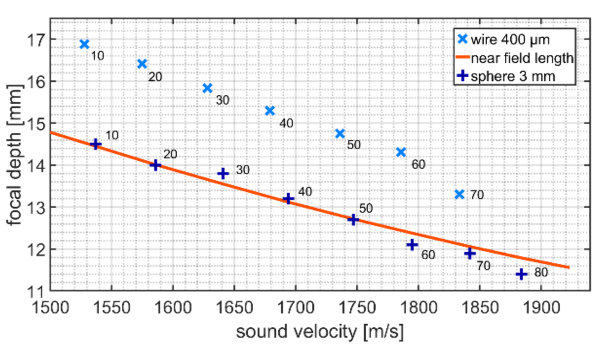

Fig. 3: Position of maximum in dependence of the sound velocity and damping for a piston transducer with a center frequency of 3.5 MHz measured with spherical (dark blue) and wire reflector (light blue). The numbers in the figure indicate the glycerin concentration in percent by weight.

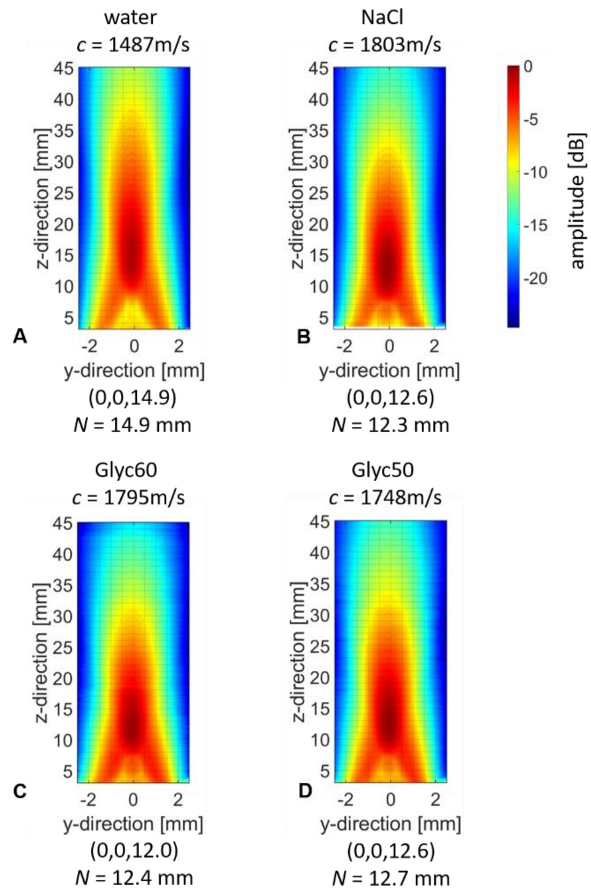

Fig. 4: Comparison of the sound fields and focal depth between damped (Glyc60, Glyc50) and nearly "non-damped" fluids (water, NaCl) with given location of maximum. *N* indicates the near field length in a non-damped medium with same sound velocity.

"non-damped" saturated saline solution (figure 4b) showed, that the damped fluid with approximately the same sound velocity had a focus position that is around 500 µm shorter than the nearly "non-damped" medium. The damped medium with the same focus position had a sound velocity that is approximately 50 m/s slower (figure 4d). Therefore, the expected effect of a focal shift towards the transducer in the case of a damped fluid could be observed [6]. However, the effect is very small and hard to determine and need further investigations. It can be assumed that glycerin-water mixtures up to 70 percent does not have enough damping to show strong effects. Until now, glycerin-water mixtures with more than 70 percent of glycerin are not showing enough signal quality at constant measurement conditions. That is the reason why so far no statement could be made at higher damping. In addition, until to now there is no possibility to produce a sample medium with the same frequency like the glycerin-water mixtures above 60 percent with nearly no damping.

According to (5), attenuation is expected to result in a shift of the spectrum to lower frequencies. Measurements showed that no frequency shift occurs when the reflector is placed in the focus (figure 5a). If the reflector is placed at a point in the far field (figure 5b), the spectral analysis even leads to higher

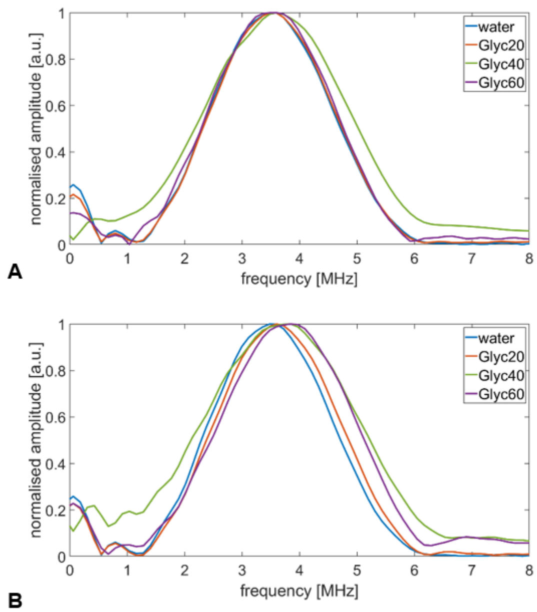

Fig. 5: Frequency spectrum in different damped fluids measured with the sphere at A) focus position and B) exemplary z-position in the far field. For instance, Glyc20 = glycerin-water mixture of 20 percent.

frequencies with increasing attenuation. That is in contradiction to the expectations and requires further research.

V. Conclusion

For sound field measurements the choice of the appropriate reflector is of great importance. Choosing a wrong measurement target can lead to completely different sound field parameters. It is not sufficient to select the reflector only by choosing one that is much smaller than the wavelength. Also the type and shape of the reflector, the applied transducer and the sample medium have to be set in context.

Numerous experiments are necessary to investigate damping mechanisms. Measurements on sample media with much higher damping must be carried out. Therefore, measurement parameters have to be changed and comparative fluids with nearly no damping and high velocities have to be produced.

References

[1] R. Callé, C. Plag, F. Patat and F.Ossant, “Interest of the attenuation coefficient in multiparametric high frequency ultrasound investigation of whole blood coagulation process”, J Acoust So Am 125 (1), 530–538, 2009.

[2] M. M. Calor-Filho and J. C. Machado, “Measurement of the ultrasonic attenuation coefficient of human blood plasma during clotting in the frequency range of 8 to 22 MHz”, Ultrasound Med Biol 32 (7), 1055–1064, 2006.

[3] C.-C. Huang and S.-H. Wang, “Characterization of blood properties from coagulating blood at different hematocrits using ultrasonic backscatter and attenuation”, Jpn J Appl Phys 45 (9A), 7191-7196, 2006.

[4] P. M. Morse and K. U. Ingard, Theoretical Acoustics, New York: McGraw-Hill Book Co., 1968.

[5] J. Wauer, Kontinuumsschwingungen. Vom einfachen Strukturmodell zum komplexen Mehrfeldsystem. 2. Auflage, Springer Vieweg Wiesbaden, 2014.

[6] A. Burkhardt, A. Juhrig, M. Wolf, L. Timmermann, E. Kühnicke, „Schallfeldbasierte Dämpfungsmessung“, 44. Jahrestagung für Akustik - DAGA, 19.-22.03.2018, München, Proceedings, 1403-1406, 2018