Using acoustic holography to characterize absorbing layers

Dmitry Nikolaev, Sergey Tsysar, Anna Krendeleva, Oleg Sapozhnikov, and Vera Khokhlova

Citation: Proc. Mtgs. Acoust. **38**, 045012 (2019); doi: 10.1121/2.0001120
View online: https://doi.org/10.1121/2.0001120
View Table of Contents: https://asa.scitation.org/toc/pma/38/1
Published by the Acoustical Society of America

Proceedings of Meetings on Acoustics

Volume 38 http://acousticalsociety.org/

2019 International Congress on Ultrasonics

Bruges, Belgium

3-6 September 2019

Physical Acoustics: EAH Presentation 3

Using acoustic holography to characterize absorbing layers

Dmitry Nikolaev, Sergey Tsysar, Anna Krendeleva, Oleg Sapozhnikov and Vera Khokhlova
Department of Physics, Lomonosov Moscow State University, Moscow, 119234, RUSSIAN FEDERATION; da.nikolaev@physics.msu.ru; sergey@acs366.phys.msu.ru; krendeleva.ad17@physics.msu.ru; oleg@acs366.phys.msu.ru; vera@acs366.phys.msu.ru

In most applications of ultrasound, it is important to know acoustic characteristics of the propagation medium such as the speed of sound and absorption coefficient within a certain frequency range. By definition, these parameters refer to the propagation of a plane wave [1]. Most methods for measuring such characteristics use flat receiving and transmitting emitters [2] and for many applications such an approach is not accurate enough. The current work is devoted to the experimental study of acoustic parameters of the propagation medium using holography-based method. Soft rubber material has been characterized. It was shown that the proposed method allows to accurately measure the speed of sound and absorption coefficient in a wide frequency range.

Published by the Acoustical Society of America

 https://doi.org/10.1121/2.0001120

2019 INTERNATIONAL CONGRESS ON ULTRASONICS
BRUGES, BELGIUM, 3-6 SEPT 2019

1. INTRODUCTION

No real sources radiate a plane wave; instead, finite acoustic beams with heterogeneous spatial structure are generated. This makes acoustic measurements in plane wave approximation inaccurate and sometimes even impossible, especially in the nearfield of the beam. Acoustic holography method [3] can be used to implement a plane-wave mode for transmitting ultrasound through a layer of a final aperture. The angular spectrum of a beam, that represents the acoustic field as a superposition of plane waves travelling in different directions, can be determined from a 2D holography field scan measured with a small-size hydrophone. In the linear regime, these plane waves propagate through the absorptive layer independently of each other. In addition, for narrow acoustic beams, such a layer of a finite aperture can be considered as infinite in the transverse direction for incident plane waves. Consequently, normal transmission of a plane wave through the infinite layer can be realized by considering the perpendicular angular component of the wave spectrum.

2. METHODOLOGY

The angular spectrum of the wave [4] changes according to the formula (1) when propagating in water at a distance H. When propagating at the same distance, if a plate of thickness h is installed parallel to the source, the angular spectrum changes according to the formula (2).

$$S_1(k_x, k_y, \omega) = S_0(k_x, k_y, \omega) e^{iH(\sqrt{(k_1+i\alpha_1)^2 - k_\perp^2})} \quad (1)$$

$$S_2(k_x, k_y, \omega) = S_0(k_x, k_y, \omega) e^{i(H-h)\left(\sqrt{(k_1+i\alpha_1)^2-k_\perp^2}\right)+ih\left(\sqrt{(k_2+i\alpha_2)^2-k_\perp^2}\right)} T_{12}T_{21} \quad (2)$$

where S_0 is the angular spectrum in a plane Z_0, $k_\perp^2 = k_x^2 + k_y^2$, where k_x, k_y are components of the wave vector in the water along the axes x and y respectively, ω is the angular frequency of the wave, α_1, α_2 are the absorption coefficients in water and test plate, respectively, for frequency ω, $k_1 = \frac{\omega}{c_1}, k_2 = \frac{\omega}{c_2}$ are the wave numbers in water and the layer material, c_1, c_2 is the speed of sound in water and the test material and T_{12}, T_{21} are the transmission coefficients of the wave through the interface water-plate and plate-water. In linear mode these plane waves propagate through the absorbing layer independently of each other. In addition, for limited acoustic beams, such a layer of a finite aperture can be considered infinite in the transverse direction. Consequently, the normal passage of a plane wave through an infinite layer can be realized by isolating the perpendicular component of the angular spectrum of a real wave beam.

A soft rubber sample was investigated in the following experiment (Fig.1). A wide-band Panametrix transducer with resonance frequency $f_0 = 1MHz$, aperture $D = 1.5''$, and focal length $\mathrm{F} = 2.5''$ was placed in degassed water. The emitter was excited by a short pulse with a carrier frequency f_0 with a length of 5 periods. The spectrum of such a pulse is wide enough to obtain the desired parameters in a wide frequency band with a single measurement. The measurements were carried out on a plane parallel to the source of size $L_x = L_y = 75mm$ with the help of a hydrophone Onda HGL−0200 with a sensing element diameter of 200 μm. The hydrophone was moved by the Precision Acoustics UMS-3 positioning system in a plane with a step $dx = dy = 0.5\ mm$. The measurement plane was between the sample and the transducer focus at a distance $H = 45mm$. The first measurement of the hologram was carried out without the test layer, the second measurement was conducted along the same surface after the installation of the layer between the transducer and the measurement plane. Layer thickness was $h = 19.5\ mm$.

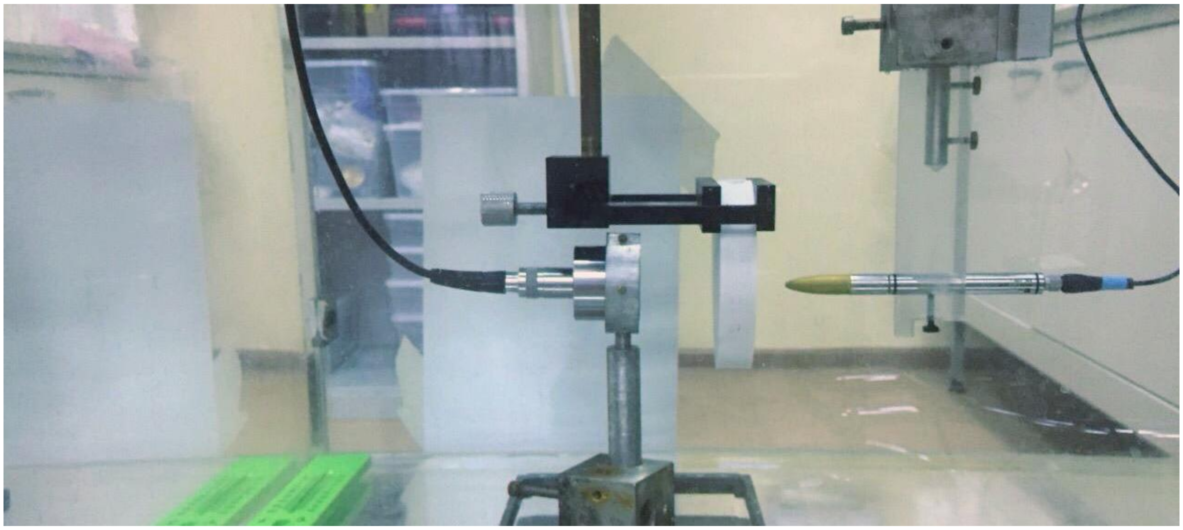


Figure 1. Experimental setup.

Based on the obtained measurements, the angular spectrum of the two holograms was calculated and their ratio was found. From equations (1), (2) this relation has the form

$$R\left(k_x, k_y, \omega\right) = \frac{S_2(k_x,k_y,\omega)}{S_1(k_x,k_y,\omega)} = e^{-ih\left(\sqrt{(k_1+i\alpha_1)^2-k_\perp^2}\right)+ih\left(\sqrt{(k_2+i\alpha_2)^2-k_\perp^2}\right)} T_{12}T_{21} \quad (3)$$

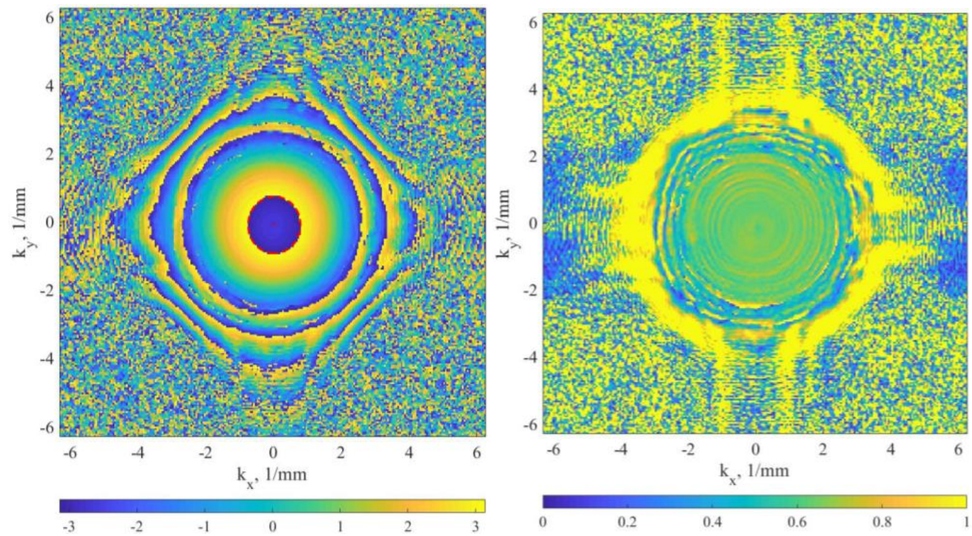
The full phase was determined by the delay of the pulse when passing through the layer, then this value was adjusted using the value of $Arg\left(R\left(k_x, k_y, \omega\right)\right)$. The phase of the ratio given in equation (3) contains information about the speed of sound in the layer material as a function of frequency. Assuming that the absorption is small on the wavelength scale, we obtain the dependence on the frequency of the speed of sound in the material:

$$c_2(\omega) = \omega * \left(\left(\frac{Arg\left(R\left(k_x,k_y,\omega\right)\right)}{h} + \sqrt{k_1(\omega)^2 - k_\perp^2}\right)^2 + k_\perp^2\right)^{-1/2} \quad (4)$$

It is also possible to determine the components k_x, k_y of a plane wave that propagates perpendicular to the investigating layer using the phase of the ratio given in equation (3). For a perpendicular wave the transmission coefficients are $T_{12} = \frac{2Z_2}{Z_2+Z_1}, T_{21} = \frac{2Z_1}{Z_2+Z_1}$, where Z_1, Z_2 are the acoustic impedances of water and investigating material, respectively. The center of the constant phase curve was determined; a plane wave with such k_x, k_y was considered falling perpendicular to the layer (Fig.2a). To find a perpendicular plane wave at each frequency, such a wave was first found at the resonant frequency of the transducer f_0. Based on this value, the angles $\varphi_x = \frac{k_x}{k_1}, \varphi_y = \frac{k_y}{k_1}$ were calculated. Then the values of the spatial frequencies $k_x,\ k_y$ for the remaining time frequencies were calculated. The absorption coefficient and sound velocity were calculated using such plane waves. In this experiment, the calculation showed that the alignment deviation of the rubber layer and the hologram plane parallel geometry is $\varphi = 1.7°$.

The modulus of the ratio given in equation (3) shown in Fig. 2b contains information about the absorption coefficient of the wave in the material. In the weak absorption approximation, the dependence of material absorption on frequency was found from equation (3):

$$\alpha_2(\omega) = \left(\frac{-ln(|R(k_x,k_y,\omega)|/(T_{12}T_{21}))}{h} + \alpha_1(\omega)/\sqrt{1 - \frac{k_\perp^2}{k_1^2}}\right)\sqrt{1 - \frac{k_\perp^2}{k_2^2}} \quad (5)$$

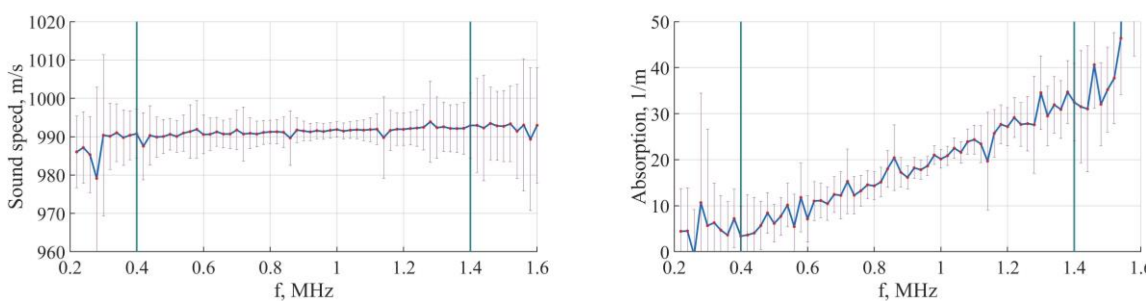


a)b)

Figure 2. Phase (a) and amplitude (b) ratios of the angular spectra, calculated from the holograms measured with and without the test layer.

3. RESULTS AND DISCUSSION

Using the known acoustic parameters of water and sound speed in material calculated by the equation (4), the transmission coefficients of a plane wave T_{12}, T_{21} falling perpendicular to the interface were calculated. The case of a single passage of the pulse was considered. The source was excited by a short pulse so that the length of the emitted signal was less than double the thickness of the layer. This means that the signal did not overlap with that reflected from the boundary. From equations (4), (5), the sound speed and absorption in the material under study were obtained (Fig. 3).



a)b)

Figure 3. The speed of sound (a) and the absorption coefficient (b) of a plane acoustic wave in the material under study and measurement error, depending on the frequency.

Vertical lines at frequencies of 0.4 MHz and 1.4 MHz limit the area in which the measurements have sufficient accuracy since the spectral power of the signal in this area is significantly greater than noise. Figure 4 shows the normalized spectra of a plane wave perpendicular to the sample in the presence and without it. Outside this boundary, as well as in the regions where spectrum is close to zero values, the measurement noise has a big impact. The width of the spectrum can be increased by reducing the duration of the applied pulse to the transducer, while reducing the measurement accuracy, because the spectral power of the signal decreases. If necessary, other emitters with higher or lower resonant frequencies or signal amplifiers should be used. If it is necessary to accurately obtain the acoustic characteristics of the material at one frequency, measurements should be made while the radiator is operating in continuous mode. In this case, the most accurate results will be obtained, but only for a single frequency.

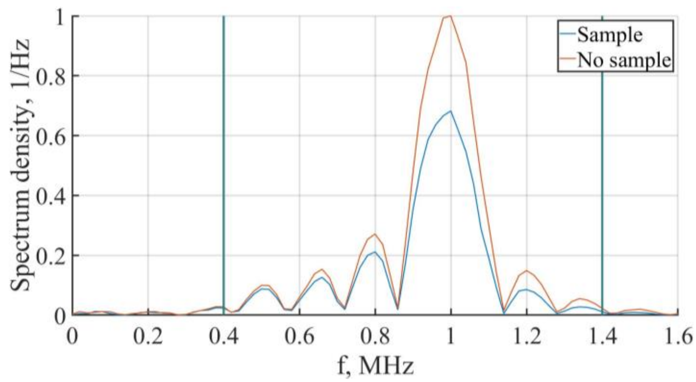


Figure 4. Spectra of a plane wave, perpendicular to the sample in the presence of the sample (blue line) and without it (red line).

A focusing transducer was chosen for the measurement, since it has a sufficiently wide angular spectrum. In practice, this means that it is possible to find such an angular component that will fall perpendicular to the sample even with unavoidable deviations in the mutual orientation of the transducer and the layer under study during their installation, and at the same time will have a sufficiently large spectral power. By selecting the aperture and focal length of the source, as well as by choosing an amplifier, one can adjust the level of measurement error. When measuring with a flat emitter, it is necessary to set parallelism with high accuracy, which is not always possible. Other advantages of the focusing transducer are the possible reduction of the hologram size, which leads to a reduction in scanning time, and the use of significantly smaller sample, if placed in the focus.

For investigating material, an additional measurement of acoustic properties at a frequency of $f_0 = 1\ MHz$ was carried out by the following method. The sample was placed between two transducers, one of which was excited by a short pulse. The second transducer recorded the transmitted, comparing this signal with the case without the layer, the sound speed and the absorption was calculated at the frequency of filling the pulse. The following results were obtained: $c = 990 \pm 4\,m\,/\,s,\ \alpha = 22.6 \pm 3\,m^{-1}$. Using the method described in the work at this frequency, the following values were obtained: $\mathrm{c} = 991.9 \pm 2\,m\,/\,s, \alpha = 20.2 \pm 2m^{-1}$.

4. CONCLUSIONS

In conclusion, it should be noted that in a various applications of ultrasound, particularly therapeutic, to improve efficiency and safety by calculations the amount of energy delivered to the area of impact, it is necessary to accurately know the properties of tissues through which ultrasound propagates. This paper presents an effective and accurate method for measuring the acoustic characteristics of various materials in a wide spectral range.

ACKNOWLEDGMENTS

This study was supported by the Russian Science Foundation (RSF) grant no. 19-12-00148.

REFERENCES

[1] M.B. Vinogradova, O.V. Rudenko, A.P. Sukhorukov. Wave Theory. Nauka, 1977.

[2] C.R. Hill, J.C. Bamber, G.R. ter Haar. Physical Principles of Medical Ultrasonics, John Wiley & Sons, March 2004

[3] O.A. Sapozhnikov, S.A. Tsysar, V.A. Khokhlova, W. Kreider. Acoustic holography as a metrological tool for characterizing medical ultrasound sources and fields // Journal of the Acoustical Society of America. — 2015. — Vol. 138, no. 3. — P. 1515–1532.

[4] P. Yuldashev, V. Khokhlova. Simulation of three-dimensional nonlinear fields of ultrasound therapeutic grids, Akust. Journal., 2011, V. 57, No. 3, p. 377-347.