

Using a Structure of Plane-Parallel Solid Layers to Suppress Multiple Reflections between a Piezoelectric Source and a Target Particle in the Study of Acoustic Radiation Force

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Received September 2, 2025; revised September 25, 2025; accepted September 29, 2025

Abstract—It was demonstrated that oscillations in the dependence of the acoustic radiation force on the distance between a focusing piezoelectric source and a spherical scatterer can be reduced by adding a layered structure consisting of plane-parallel acrylic glass plates to the space between the transducer and the scatterer. It was experimentally confirmed that the formation of standing waves, which cause oscillations, is minimized by absorbing and scattering acoustic waves reflected from the source. The ability to control the oscillation level by varying the number of plates was shown. The theoretically calculated radiation force levels in the presence of the layered structure agree with those measured.

Keywords: layered structure, scattering, acoustic radiation force, spherical scatterer, experiment

DOI: 10.1134/S106287382571428X

INTRODUCTION

The study of the impact of ultrasound waves on physical objects is a pressing practical problem. One of the effects created by such waves is the acoustic radiation force (ARF), which arises when the momentum of an incident acoustic wave is transferred to a scattering or absorbing object [1]. This phenomenon allows for the remote manipulation of small (millimeter- and micrometer-sized) objects, attracting and pushing them, which finds wide application in medicine, for example, for the targeted expulsion of kidney stone fragments [2–4] and in biofabrication applications [5, 6].

Modern research offers a wide range of theoretical models for calculating the ARF acting on scatterers of various types in heterogeneous media [7–11]. Our previous study [12] considered a situation where an arbitrary focused ultrasound beam in a liquid was incident on a spherical scatterer the dimensions of which were comparable to or exceed the wavelength. Accurate measurement of the ARF was complicated by the presence of oscillations in the dependence of the force on the distance due to the generation of standing waves between the source and the scatterer, which made comparison with the results of numerical modeling difficult. These phenomena arose as a result of multiple reflections of sound waves between the surface of the piezoelectric transducer and the target particle, which led to interference of the incident and

reflected waves and, as a consequence, to distortion of the acoustic field.

In our previous works [12, 13], to suppress multiple reflections from a piezoelectric transducer, we proposed to use an electrical load selected to reduce the acoustic reflection coefficient from the piezoelectric plate near the antiresonant frequency. This method allowed the oscillation amplitude to be suppressed by a factor of 1.5–4; however, complete elimination of the effect was not achieved due to the complex spatial structure of the acoustic field and the nonsphericity of the scattered wave front.

This paper proposes a fundamentally new approach to solving this problem, namely, introducing a layered acrylic glass structure between the source and the scatterer (Fig. 1). This structure is designed to absorb and scatter the multiply reflected acoustic waves passing through it, minimizing the formation of standing waves. A unique feature of the design is the ability to attach it to a piezoelectric transducer and adjust the loss level by varying the number of layers, allowing the system to be tailored to specific experimental conditions.

The aim of this study is to investigate the absorption properties of the fabricated layered structure and demonstrate its potential for suppressing oscillations in the dependence of ARF on distance. The study analyzes the effect of the number of layers on the ARF oscillation amplitude and compares it with force measurements without absorbing layers. The results

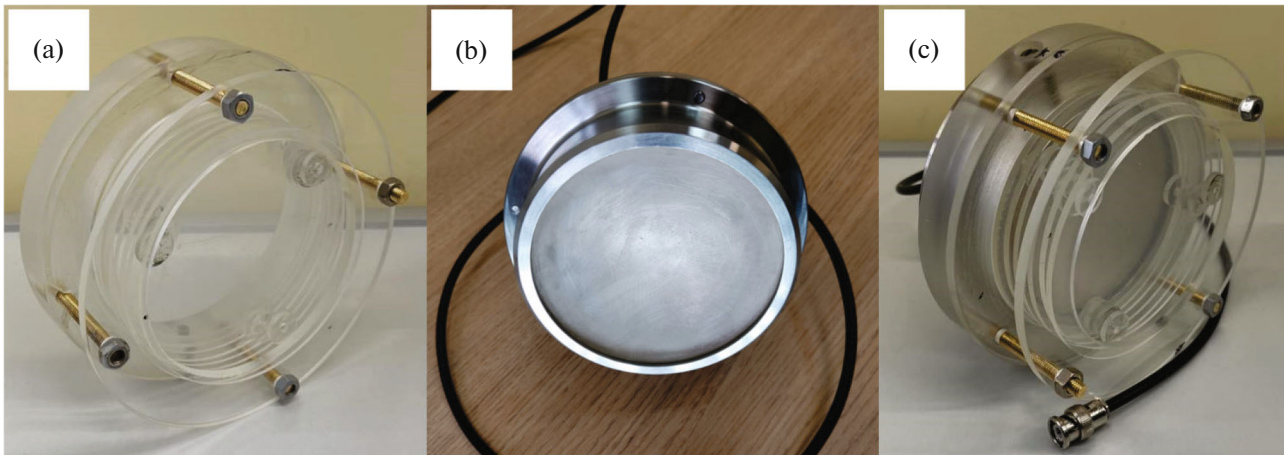


Fig. 1. (a) Layered structure, (b) piezoelectric transducer, and (c) piezoelectric transducer with attached layered structure.

demonstrate that the layered structure attenuates oscillations in the ARF dependence on the distance between the source and the scatterer, particularly in the focal region, which is critical for medical and industrial ultrasound applications.

STUDY OF THE PARAMETERS OF A LAYERED STRUCTURE

A layered structure (Fig. 1a) was fabricated from plane-parallel circular acrylic glass plates 3 mm thick and 110 mm in diameter, arranged parallel to each other with a 3-mm gap. The gap size was controlled using calibrated inserts ensuring the parallelism of the plates. A special overlay allowed the layered structure to be attached to the source (Fig. 1c), ensuring a tight fit within its frame. This provided uniform alignment of the structure relative to the transducer during various experiments. It was hypothesized that such a structure would effectively scatter and partially absorb ultrasound beams passing through it, especially in the presence of focusing, when the wavefront is not parallel to the surface of the layers.

To select the optimal number of layers for reducing the amplitude of reflected signals in the radiation force study, an experiment was conducted to estimate the losses during the passage of an ultrasound wave through the layered structure. For the measurements, a setup was constructed, allowing the determination of the transmission coefficient of the layered structure by comparing the signal transmitted through the medium without plates and the signal transmitted through the medium with the layered structure placed in it at various numbers of acrylic glass plates. Figure 2a shows a photograph of the experimental setup with all the main components indicated. During the study, a tank filled with degassed water was used, in which two flat broadband piezoceramic transducers with a diameter of 38 mm (V392, Panametrics, United States) were coaxially placed and fixed on guide rails. One of the

transducers served as an acoustic signal source, operating in pulse mode at a center frequency of 1 MHz, and the other was a receiver. The layered structure oriented parallel to the working surfaces of the transducers was installed between the transducers. The signal coming from the source passed through this structure and was recorded by the receiver. The receiver also measured the time signals obtained with and without the layered structure between the transducers. The transmission coefficient of the structure was determined using the equation

$$T(\omega) = \left| \frac{S(\omega)}{S_0(\omega)} \right|, \quad (1)$$

where $S(\omega)$ is the spectrum of the signal transmitted through the reference medium with the layered structure placed in it, and $S_0(\omega)$ is the spectrum of the signal transmitted through the medium in the absence of the structure. Figure 2b presents the frequency dependences of the transmission coefficient calculated using Eq. (1) at various numbers of plates.

When analyzing the dependences, of interest is the frequency of 1.072 MHz, which is the resonant frequency of the focusing piezoceramic source used subsequently for ARF studies. The dependences show that, at this frequency, with an increase in the number of layers, the transmission coefficient initially drops sharply (from 0.93 for one layer to 0.7 for two layers) and then changes only slightly. This indicates that the acrylic glass plates weakly absorb acoustic waves, and the main losses occur due to the scattering of these waves upon incidence on the layered structure. Based on this observation, the optimal number of layers for experimental ARF studies was chosen to be two. The attenuation introduced by the layered structure (the transmission coefficient is approximately 0.7) is sufficiently high to suppress multiply reflected waves between the source and the target particle.

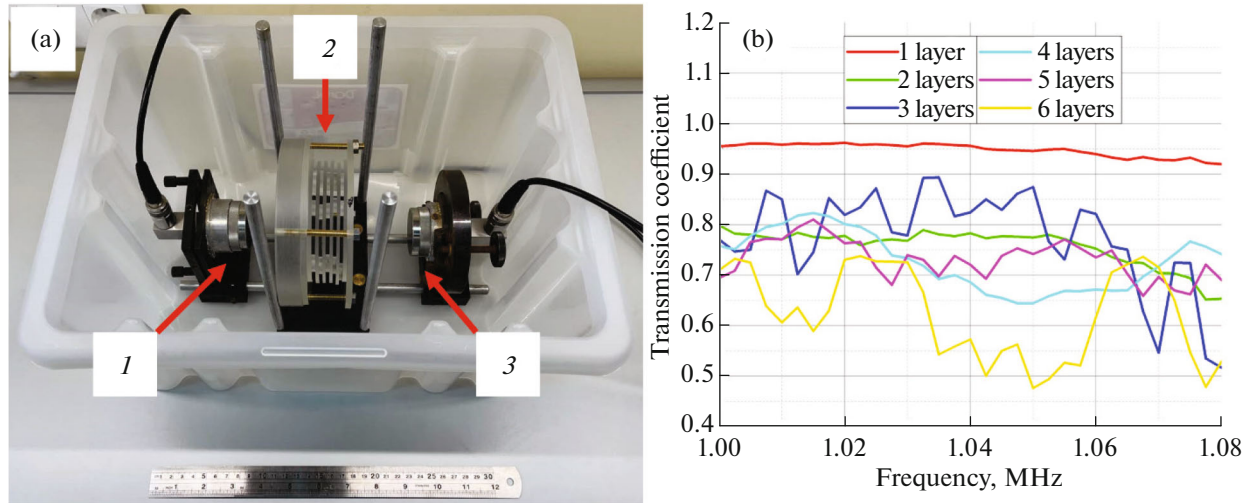


Fig. 2. (a) Experimental setup for analyzing the transmission coefficient through a layered structure: (1) source, (2) layered structure, (3) receiver; the elements of the setup are placed in a tank filled with water during the experiments; and (b) the dependence of the transmission coefficient on frequency at various numbers of acrylic glass plates.

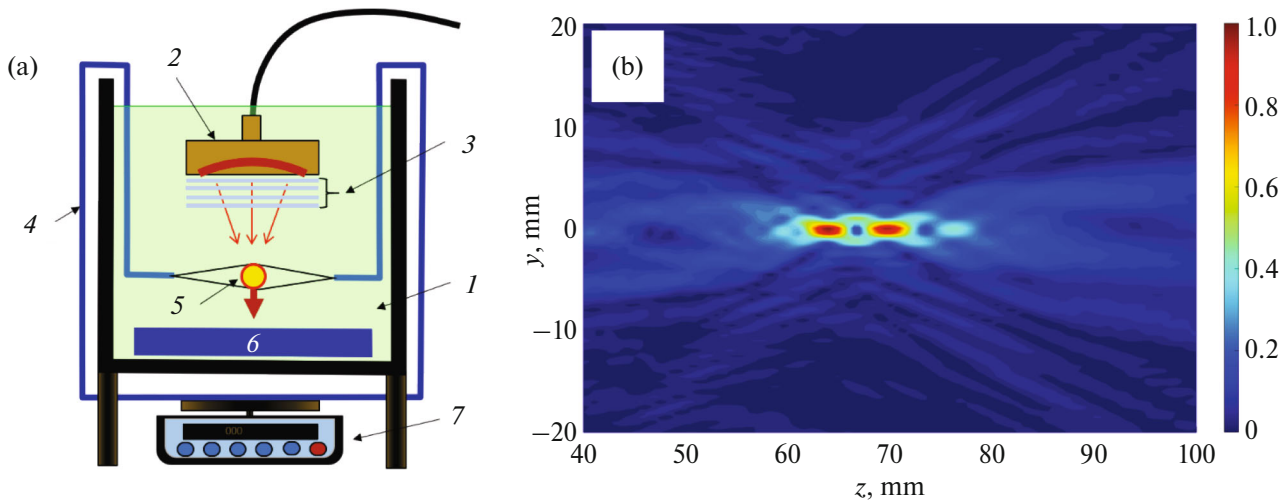


Fig. 3. (a) Schematic diagram of the experimental setup for measuring the acoustic radiation force: (1) tank with water, (2) ultrasound source, (3) absorbing structure, (4) rigid frame, (5) spherical target particle, (6) absorber for suppressing waves reflected from the bottom of the tank, and (7) electronic scales; and (b) the distribution of the acoustic pressure amplitude normalized to the maximum in the axial plane in the presence of the layered structure with two plates at an operating frequency of 1.072 MHz, as obtained by measuring the hologram.

MEASURING ARF USING THE LAYERED STRUCTURE

Experiments on suppression of multiply reflected waves during measurements of the vertical component of the ARF were carried out using our previously developed setup [13] modified by adding the layered structure to the space between the piezoceramic source and the spherical scatterer (Fig. 3a). The tank with degassed water contained a focusing piezoceramic transducer (Fig. 1b) with a resonant frequency of 1.072 MHz in the form of a spherical bowl with a diameter of 100 mm and a radius of curvature of

70 mm, fixed on a positioning system. The layered structure was attached to the source (Fig. 1c). The target particle was an 8-mm-diameter glass sphere located on the source axis. The sphere was fixed in a rigid frame in the form of a plastic ring with a diameter of 250 mm using a system of thin fishing lines. The frame was attached to a structure of rigid tubes and plates that curved around the tank wall without touching it and rested on an electronic scale (VI-3mg, Acculab, United States).

Before beginning the ARF measurements, the focus of the source was set on the target particle. To do

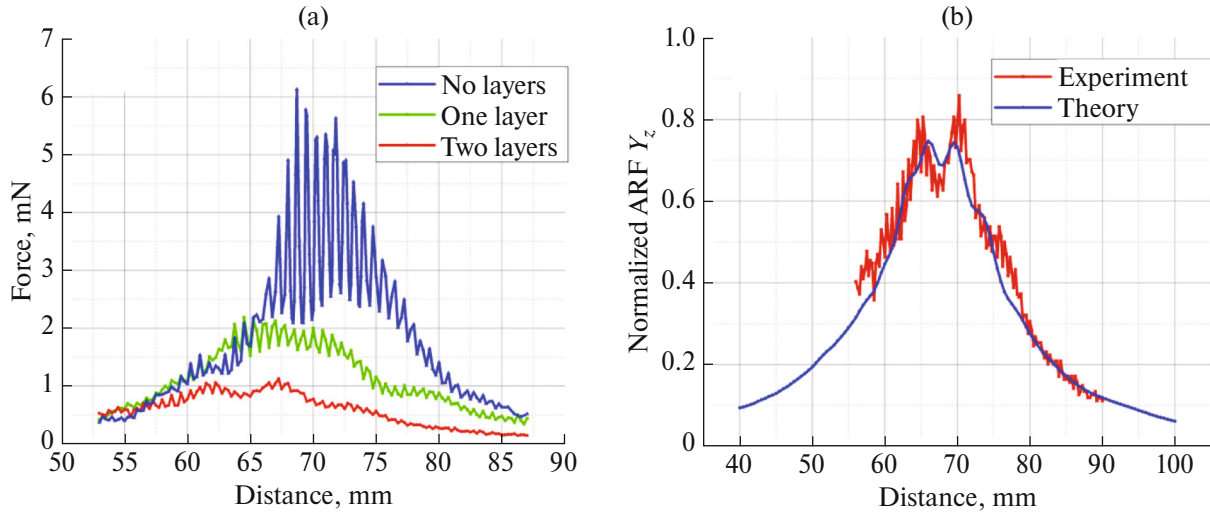


Fig. 4. (a) Dependences of the ARF on the distance between the piezoelectric source and the spherical scatterer in the absence of the layered structure (blue line) and in the presence of the layered structures with one layer (green line) and with two layers (red line); and (b) comparison of the experimental dependence of the dimensionless ARF normalized by Eq. (3) on the distance with the theoretical dependence calculated from the data of acoustic holography in the presence of the two-layer structure.

this, the piezoelectric transducer in the absence of the layered structure was excited in pulsed mode, and the reflected signal was observed on the screen of an oscilloscope (TDS5034B, Tektronix, United States) connected to the transducer. By moving the transducer using the positioning system (VP9000, Velmex, United States), the position at which the reflected signal was maximum was found, which occurred when the focal axis passed through the center of the target particle. In the subsequent ARF measurement experiment, the transducer was moved only in the vertical direction; that is, the target particle remained on the beam axis at all times.

During the ARF measurements, a continuous harmonic signal at a frequency of 1.072 MHz was applied to the source. The signal was generated by a generator (33250A, Agilent, United States) and then passed through a power amplifier (210L, Electronics & Innovation, United States). After the emission began, the target particle was subjected to ARF, the vertical component of which was measured using a balance with precalibrated (zero) readings. These measurements were conducted at various positions of the transducer, which was shifted along the symmetry axis of the setup using the positioning system. This resulted in the axial dependence of the ARF on the distance between the source and the scatterer, which was then analyzed.

Figure 4a illustrates the results of measurements of the vertical component of the radiation force along the acoustic axis of the source in three situations: when the layered structure was absent, when it was present and contained one acrylic glass plate, and when it was present and contained two acrylic glass plates.

An analysis of the graphical dependences shows that adding layers not only reduces the absolute mag-

nitude of the force but also decreases the relative amplitude of the oscillations by a factor of 4–5. Furthermore, the difference between the speeds of sound in water and acrylic glass alters the structure of the acoustic field incident on the scatterer, specifically, brings the primary focus of the beam closer to the emitter and extends the focal region. Interference in the presence of two parallel layers further distorts the field, which can be taken into account in the calculations.

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

To verify the measurement results, the radiation force was numerically calculated and the theoretical data were compared with experimental results in the case where the layered structure with two acrylic glass plates was located in front of the emitter.

The axial component of the ARF acting on the spherical scatterer can be calculated analytically by the angular spectrum method using the formula obtained by Sapozhnikov and Bailey [9]:

$$F_z = -\frac{1}{4\pi^2 \rho c^2 k^2} \operatorname{Re} \left\{ \sum_{n=0}^{\infty} \Psi_n \sum_{m=-n}^n B_{nm} H_{nm} H_{n+1,m}^* \right\}, \quad (2)$$

where B_{nm} are numerical coefficients, Ψ_n are coefficients characterizing the elastic properties of the scatterer and the medium, and H_{nm} are coefficients determined by the structure of the incident beam. Detailed expressions for calculating these coefficients were given in Sapozhnikov and Bailey's work [9].

To analyze the theoretical and experimental dependences, it is convenient to introduce a dimensionless (or normalized) value of the radiation force,

which is normalized to the total power of the acoustic beam:

$$Y_z = \frac{F_z c}{W}. \quad (3)$$

Here, c is the speed of sound in water, and W is the total power of the acoustic beam.

In these equations, the coefficients H_{nm} and the power W are calculated from the known angular spectrum of the acoustic field [9]. The angular spectrum, in turn, was obtained by measuring the acoustic hologram of the used source with the attached layered structure consisting of two layers [14]. Figure 3b presents the distribution of the normalized amplitude of the acoustic pressure in the axial plane in the presence of the layered structure with two plates at an operating frequency of 1.072 MHz. One can see the previously mentioned splitting of the focus in the longitudinal direction, which appears when introducing two or more parallel layers.

After completing all calculations, a theoretical dependence of the ARF on the distance between the source and the scatterer was obtained for the case of the layered structure with two acrylic glass plates. This dependence was then compared with the corresponding experimental dependence. Figure 4b shows good agreement, particularly in the focal region of the emitter, confirming the validity of the experimental data and the possibility of further using the layered structure to suppress multiple reflections between the source and the scatterer.

CONCLUSIONS

Thus, we have demonstrated the possibility of reducing oscillations in the dependence of the ARF on the distance between the source and the spherical scatterer by adding a layered structure consisting of plane-parallel acrylic glass plates to the space between these elements. This structure is designed to absorb and scatter acoustic waves reflected from the piezoelectric emitter, minimizing the formation of standing waves, which are the cause of oscillations. We have experimentally demonstrated the possibility of controlling the oscillation level by varying the number of plates. It should be noted that the proposed approach can be used not only for measurements in liquids but also in gases, where thin films can be used as reflective layers.

FUNDING

This work was supported by the Russian Science Foundation (project no. 25-12-00141).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by V. Glyanchenko

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