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Experimental study of radiation force by a focused ultrasound beam on an elastic scatterer in a fluid

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The study aims to increase the accuracy of experimental methods for measuring acoustic radiation (AR) force acting on a millimeter-sized spherical scatterer in a liquid from a focused ultrasound beam[1], which was generated by a single-element, piezoceramic transducer positioned at the bottom of a water tank. The spherical scatterer was positioned on the vertically-oriented axis of the beam. The scatterer was fixed in a frame with 3-level trap of thin fishing lines. The measurement method is based on the balance between the AR, gravity, and buoyancy forces acting on the object, and initiation of its movement when the value of AR force crosses a certain threshold. The threshold power corresponded to the condition when the AR force was equal to the difference between the gravity and buoyancy forces. The AR force was calculated numerically using parameters of the scatterer and the known angular spectrum of the beam, which was determined from the acoustic hologram[2]. Experimental and theoretical results were in a good agreement in pre-focal and post-focal regions with an average error of 10%. If the beamwidth is smaller than the scatterer diameter, the most effective pushing occurred after the focus, where the beam was slightly wider than the scatterer.

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I. Introduction

A promising application of the ability of acoustic waves to create the AR force on scattering objects is used in the recently proposed method of non-invasive removal of stones from human kidneys [3, 4]. This technology can also be used to move stones inside the kidney's collecting system to stop renal colic and prevent an urgent surgery when a large stone is blocking the mouth of the ureter. The possibility of using the AR force of an ultrasonic beam for pushing kidney stones was shown in model experiments on kidney phantoms [3] and in *in vivo* experiments on pigs [4]. Moreover, recently more than a dozen volunteer patients have tried the realization of the force effect of acoustic fields [5]. The pushing of stones was made by standard diagnostic ultrasonic probes, which did not work in the usual mode of visualization but in the mode of radiation of long pulses. Confident movement of stones in the size range of 2 - 7 mm was observed with the maximum possible diagnostic power. Despite the success in the movement of stones, the problem of accurate measurements of the magnitude of the AR force has not yet been fully investigated. For the successful implementation of the procedure in clinical practice it is important to develop a numerical model and carry out high-precision experimental measurements of the AR force in the field of an arbitrary beam. This work presents a developed experimental setup for measuring the AR force acting on millimeter-sized elastic spherical scatterers made of various materials. The corresponding numerical calculations of the AR force for the considered scatterers were carried out on the basis of measuring the two-dimensional distribution of the amplitude and phase of the acoustic pressure in the beam cross section (acoustic hologram).

II. Methodology

The numerical calculation of the AR force acting from an ultrasound beam on an elastic sphere was carried out on the basis of a theoretical approach presented in [2]. The main features of the approach are briefly presented here. For a spherical scatterer in an ideal fluid the component of the AR force along the beam propagation axis *z* is analytically expressed as follows:

$$F_z = -\frac{1}{4\pi^2 \rho c^2 k^2} \mathrm{Re}\left\{ \sum_{n=0}^{\infty} \Psi_n \sum_{m=-n}^{n} B_{nm} H_{nm} H^*_{n+1,m} \right\}. \tag{1}$$

Here c is the speed of sound in the liquid, k is the wave number, ρ is the liquid density, the index Re means taking the real part of the expression in brackets. The coefficients B_{nm} and H_{nm} describe the structure of the incident field defined by the angular spectrum $S(k_x, k_y)$. Coefficients Ψ_n are determined by the properties of the scatterer and the surrounding liquid. They characterize the scattering of a plane wave on an elastic sphere of radius a. More detailed presentation of all the functions is given in [2].

When the scatterer is located on the axis of an axisymmetric acoustic beam, then Eq.(1) is sufficient to calculate the AR force. Indeed, in such a case the force magnitude is $F = F_z$ and the transverse components of the force are zero. In the current work the numerical and experimental calculation of the force was carried out only on the axis of the focused beam when Eq. (1) is sufficient for its calculation.

According to Eq. (1), for the numerical calculations of the AR force, the angular spectrum of the acoustic beam must be known. It can be found from the known distribution of the complex amplitude of the acoustic pressure P given in a certain plane in front of the acoustic source $(x, y, z = z_0)$:

$$S(k_x, k_y) = e^{-iz_0\sqrt{k^2 - k_x^2 - k_y^2}} \int_{-\infty}^{+\infty}\int dxdy\, P(x, y, z_0)\, e^{-i(k_x x + k_y y)} \tag{2}$$

Accurate calculations require an approach when the angular spectrum is found taking into account the true vibration pattern of the source surface. This can be performed using acoustic holography method [6]. According to this method, a two-dimensional distribution of the amplitude and phase of the acoustic pressure $P(x, y, z_0)$ is measured by a hydrophone in a plane in front of the acoustic source. This 2D record is an acoustic hologram, as it represents the entire 3D acoustic field. This projection from 2D to 3D can be done by calculating the angular spectrum $S(k_x, k_y)$ by Eq. (2) and then using it to express the 3D acoustic pressure distribution [6]:

$$P(x,y,z)=\frac{1}{4\pi^2}\iint_{-\infty}^{+\infty}S(k_x,k_y)e^{ik_x x+ik_y y+i\sqrt{k^2-k_x^2-k_y^2}z}dk_x dk_y \qquad (3)$$

The total acoustic beam power, W, can be also calculated from the angular spectrum [2]:

$$W=\frac{1}{8\pi^2\rho c}\iint_{k_x^2+k_y^2\le k^2}\sqrt{1-\frac{k_x^2+k_y^2}{k^2}}\left|S(k_x,k_y)\right|^2 dk_x dk_y \qquad (4)$$

The ratio represents a characteristic value for the AR force. It is usually used as a normalization parameter to express a dimensionless expression for the AR force: $Y_z = F_z/F_0 = F_z c/W$. Relations (1) – (4) completely determine the numerical calculation of the dimensionless parameter for the axial component of the AR force on the beam axis, which, in turn, is necessary for comparing the experimental results with the theoretically calculated force value.

The investigation of the AR force was performed under the following conditions. A single-element focused transducer in the form of a spherical bowl with a focal length F = 7 cm, a radius of aperture r = 5 cm and a frequency f = 1.072 MHz was considered. This acoustic radiator operates in the continuous harmonic wave mode. The parameters of the scatterers are presented in Table 1.

	Nylon 1	Nylon 2	Nylon 3	Glass	Steel
Radius, a, mm	2	3	4	2	1.375
Density, ρ_s, kg/m^3	1125	1125	1125	2390	7805
Speed of longitudinal waves, c_l, m/s	2620	2620	2620	5920	5950
Speed of shear waves, c_t, m/s	1080	1080	1080	3420	3350

Table 1: Scatterer parameters.

The acoustic hologram (the amplitude and phase 2D distributions) was measured at a distance of 55 mm from the surface (Fig. 1a) using a needle hydrophone ONDA HNA 0400. The measured voltage amplitude at the hydrophone output U was used to calculate the corresponding acoustic field pressure according to the sensitivity of the hydrophone G = 0.75 V/MPa, which was experimentally determined by the radiation force balance method [6]. Figure 1b shows the distribution of the absolute value of the angular spectrum obtained on the basis of Eq. (2) and the corresponding ultrasound field calculated by Eq. (3) in the transverse plane xz. The beam width determined from the closest to the focus zeros of intensity is a_0 = 2.4 mm.

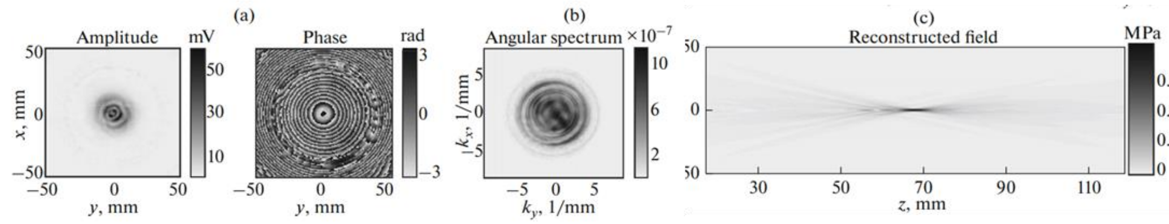

Figure 1: (a) Measured field amplitude and phase in the transverse plane of a transducer at 120 × 120 points with a spacing of 0.5 mm; (b) reconstructed angular spectrum of the transducer; (c) pressure field of the focused beam in the plane.

Measurements of the AR force were carried out using experimental setup shown in Fig. 2. The transducer was located at the bottom of a tank filled with degassed water. The spherical scatterer was placed in a specially designed mount consisting of 3 levels of parallel stretched thin fishing lines with a diameter of d = 0.08 mm. The mount could move in 3 orthogonal directions in increments of up to 0.1 mm using the positioning system. A three-level system of lines is necessary to ensure the following functions: the first level serves as a support for the pushed bead, the second level prevents the bead from moving sideways (in the horizontal direction), and, finally, the third level limits the lifting of the bead as it moves upward under the action of the AR force.

The measurements were carried out along the axis with a 0.2 mm step. Observation of the movement of the scatterer under the action of the AR force was conducted using a video camera by viewing through a hole in the mount. The dimensionless AR force Y_z at each point was determined by measuring the threshold field value, which corresponded to the moment when the axial component of the AR force acting on the scatterer balanced the force of gravity and the buoyancy force:

$$F_z = F_{\text{threshold}} = \frac{4\pi a^3}{3} g(\rho_s - \rho),$$

where a is the bead radius. The achievement of the threshold value F_z occurred at an appropriate level of acoustic power W, which, in turn, was determined by the voltage applied to the transducer. To determine the threshold voltage on the generator the following algorithm was used: at the first stage, a high voltage was applied, so that the scatterer broke off from the lower lines and rested against the upper ones. Then, gradually reducing the voltage, the moment of separation of the scatterer from the upper lines was recorded, which corresponded to the threshold value.

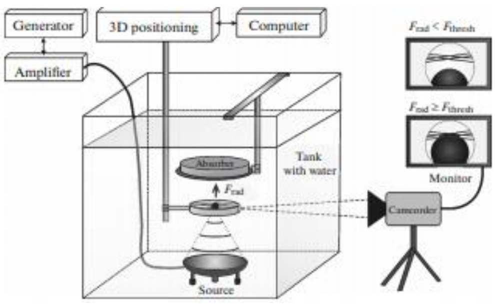

Figure 2: Experimental set-up for measuring the radiation force acting on elastic spherical scatterers.

III. Results and Discussion

The results of an experimental measurement of the force acting on spherical scatterers and the corresponding numerical calculations are presented in Fig. 3. Blue curves are the numerical calculations, black ones are measurements. The numerical and experimental results in the post-focal and pre-focal area are in a good agreement with an accuracy up to 10% for all scatterers except for the nylon sphere with a radius of a = 3 mm It showed a less accurate result (20 - 25%) in the pre-focal area. Oscillations that appear in the focus area are associated with the generation of a standing wave between the surface of the transducer and the scatterer. Despite the influence of standing waves the general trend of changes in experimental curves repeats numerical results.

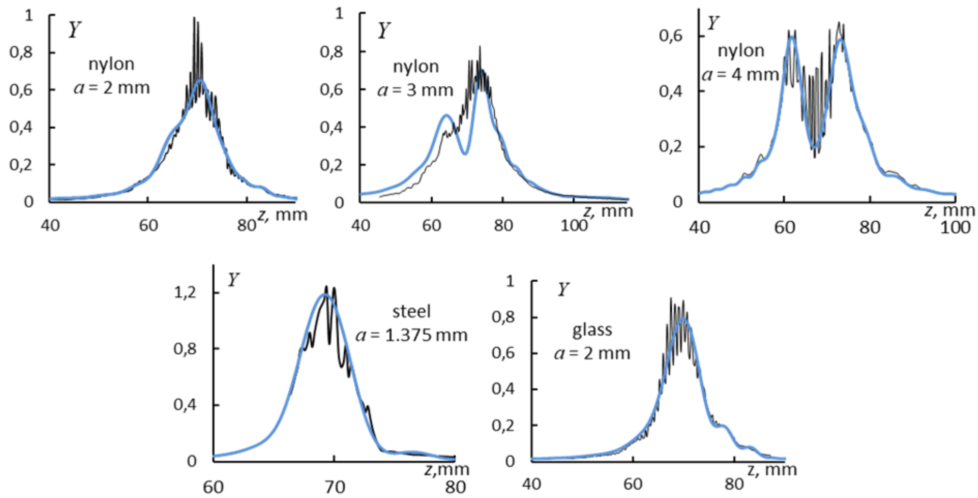

Figure 3: Numerical curves (blue) and experimental results (black) from measuring the radiation force for the scatterers.

Note an interesting effect for scatterers with a radius of a = 3 mm and a = 4 mm (Fig. 3b, 3c). Here, unlike scatterers with a = 2 mm, the maximum AR force on the axis is reached not at the focus of the beam but at some distance from it where the beam radius becomes close to the size of the scatterer. In the case of spheres with a = 2 mm at the focus the width of the focused beam is close to the beamwidth (a_0 = 2.4 mm), which corresponds to the maximum value of the force along the axis. This effect is associated with the generation of shear waves in the scatterer and more efficient transfer of the beam momentum to the scattering object. The effect is discussed in more detail in [7, 8].

IV. Conclusions

The measurement method proposed in this work allows determining the AR force value on spherical scatterers with high accuracy, which is confirmed by the numerical results obtained taking into account the actual structure of the acoustic beam.

Acknowledgements

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References

[1] M. Karzova, A. Nikolaeva, S. Tsysar, V. Khokhlova, O. Sapozhnikov*, Measurement and modeling of acoustic radiation force of focused ultrasound beam on an elastic sphere in water*, *POMA,* v. 32 **2017**, 045011/1-045011/6.

[2] O.A. Sapozhnikov, M.R. Bailey, *Radiation force of an arbitrary acoustic beam on an elastic sphere in a fluid*, *J. Acoust. Sos. Am*., v.133(2) **2013**, 661–676.

[3] A. Shah, N. Owen, W. Lu, et al., *Novel ultrasound method to reposition kidney stones, Urol. Res.* V. 38(6) **2010,**. 491–495.

[4] A. Shah, J.D. Harper, W. Lu *et al*., *Focused Ultrasonic Propulsion of Kidney Stones: Review and Update of Preclinical Technology, J. Urol.,* v. 187(2) **2012,** 739–743.

[5] P.C. May, M.R. Bailey, J.D. Harper, *Ultrasonic propulsion of kidney stones, Curr. Opin. Urol.,* v. 26(3) **2016**, 264–270.

[6] S. Tsysar, O. Sapozhnikov, W. Kreider, *Improved hydrophone calibration by combining acoustic holography with the radiation force balance measurements, POMA,* v. 19 **2013**, 055015/1 – 055015/6.

[7] A.V. Nikolaeva, O.A. Sapozhnikov, *Acoustic Radiation Force of a Quasi-Gaussian Beam Imparted to a Solid Spherical Scatterer in a Fluid, Bull. of the Rus. Academy of Sci.: Physics,* v. 81(1) **2017**,80 – 83.

[8] R.O. Cleveland, O.A. Sapozhnikov, *Modeling elastic wave propagation in kidney stones with application to shock wave lithotripsy, J. Acoust. Soc. Am*., v. 118 (42005) **2005**, 2667–2676.