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Remote acoustic imaging in liquids through a bundle of rod waveguides

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Acoustic imaging is an alternative way to see through aggressive media. Acoustic waves in contrary to electromagnetic waves can freely propagate through liquids, a tissue, and a variety of other materials that are non-transparent at many or all wavelengths of electromagnetic fields. Acoustic images are different from optical images in that they are essentially maps of density variations. Sound waves reflect from boundaries between different materials, carry back information about distances and changes in density and object shape to a receiving waveguide matrix. Proposing remote acoustic imaging is a new imaging technique that uses acoustic probe pulses and a receiving waveguide matrix to detect and view objects inside a liquid that is opaque to light. Spatial resolution of the method is derived by efficiency of ultrasonic scattering at objects, sensitivity of an ultrasonic radiation-reception matrix and the number of waveguides and the distance between them. The technique is useful when efforts are concentrated at revealing presence, location and shape of small objects. In the paper theoretical analysis of interaction of probe ultrasonic radiation with diverse types of small objects has been done. Performed theoretical assessments have been employed for interpreting acoustic images of objects in water.

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1. INTRODUCTION

Visualizing objects in opaque or aggressive liquids is a complex task in which ultrasound techniques can be very suitable. There are already several methods that allow obtaining images and detecting objects immersed in such liquids using acoustic waves.[1, 2, 3] When imaging at great depths and in aggressive liquids, these approaches have several limitations, such as low sensitivity and narrow viewing angle. This study examines the detection and visualization of objects using two-dimensional pulse-echo detection through acoustic waveguides in the form of solid rods. In order to irradiate the region of interest a short ultrasonic pulse is generated outside the aggressive fluid and transmitted to the depth through a metal rod, so that its distal end acts as a point source, generating a probe acoustic pulse that propagates into the fluid. To detect the ultrasonic echo from the imaging object a multichannel waveguide in the form of a bundle of metal rods is used, which allows the echo signals to be detected using an efficient two-dimensional array represented by the distal ends of the rods, which are located close to the object and thus provide a wide viewing angle, i.e., high resolution. In the case of rods with a diameter smaller than the wavelength, the waveguide will conduct only three modes — a fast quasi-longitudinal mode, slow flexural and torsional modes. For a sufficiently short probe pulse, these modes can be separated in time. Cross talk can be minimized by proper positioning of the waveguides in the frame and selecting spacer material with the necessary properties.

The signal processing method is based on the holographic approach,[4] which provides a complete spatio-temporal reconstruction of the incident acoustic field received by the waveguide system. In the current work, numerical simulation performed in COMSOL has been used to optimize parameters of the multichannel waveguide system and to build a receiving prototype for following experimental verification in water.

2. METHODOLOGY

In the following, the theory of propagation of elastic and acoustic waves in media is described. The formulation used for analysis for deformations is a Total Lagrangian formulation. An acoustic pulse applied to a radiating waveguide is a longitudinal elastic wave arising due to the oscillation of the waveguide surface. The distribution of displacement in a solid is calculated from the equation of motion as

$$\rho_0 \frac{\partial^2 \boldsymbol{u}}{\partial t^2} = \boldsymbol{F_V} - \nabla_x \boldsymbol{P} \tag{1}$$

where $\boldsymbol{u}$ is displacement vector of a medium and **P** is the first Piola-Kirchhoff stress tensor. The first Piola-Kirchhoff stress **P** relates forces in the present configuration with areas in the reference configuration. Here, the density ρ_0 corresponds to the material density in the initial undeformed state, the volume force vector $\mathbf{F}_V$ has components in the actual configuration but given with respect to the undeformed volume, and the tensor divergence operator is computed with respect to the coordinates on the material frame.

The Cauchy stress is a true stress that relates forces in the present configuration to areas in the present configuration, and it is a symmetric tensor. Eq. (1) can be rewritten in terms of the Cauchy stress σ as

$$\rho \frac{\partial^2 \mathbf{u}}{\partial \mathrm{t}^2} = \mathbf{f_V} - \nabla_\mathrm{x} \cdot \sigma \tag{2}$$

where the density ρ corresponds to the density in the actual deformed state, the volume force vector $\mathbf{f}_V$ has components in the actual configuration given with respect to the deformed volume, and the divergence operator is computed with respect to the spatial coordinates. The pressure is calculated as

$$p = -\frac{1}{3} trace(\sigma) = -\frac{\sigma_x + \sigma_y + \sigma_z}{3} \tag{3}$$

which corresponds to the volumetric part of the Cauchy stress is defined as

$$\sigma = \begin{bmatrix} \sigma_x & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_y & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z \end{bmatrix} \tag{4}$$

The Cauchy stress is a symmetric second order tensor consisting of nine values representing mechanical stresses (force/deformed area) in fixed spatial directions not following the body.[5, 6]

Therefore, by solving Eq. (2) for the considered system, it is possible to obtain the distribution of the stress tensor depending on space and time, which is directly related to the pressure and displacement arising during the propagation of an elastic wave in a solid. The Z component (the Z-axis passes along the waveguide) of the stress tensor characterizes the pressure of the longitudinal elastic wave propagating in the waveguide. After the wave passes through the waveguide in liquid, a pressure wave is excited, which is partially reflected, reflected from the interface and partially passes. Thus, knowing the characteristics of a pulse reflected from an object, it would be possible to characterize this object and determine its dimensions, shape, and location in space.

3. RESULTS AND DISCUSSION

A finite element method has been used to calculate a system consisting of one radiating rod and receiving rods placed in a liquid to study the object inside. Waveguides of the system are stainless steel rods of 1 mm diameter and 500 mm length (Figure 1). An elastic wave is excited in the form of a harmonic pulse at a frequency of 1 MHz with a Gaussian envelope on the radiating waveguide by a ceramic piezoelectric transducer. After the propagation of an elastic wave through a waveguide, a volume acoustic pulse arises in the liquid, which propagates in the liquid under study, is scattered and reflected from the investigated objects. After interacting with the object, the probe acoustic wave is detected by a matrix of coupled waveguides. The oscillations of the ends of the waveguides in the matrix are recorded by any known method, for example, piezotransducers, a laser vibrometer, etc. In numerical model the investigated object was a stainless steel sphere of 30 mm diameter placed at 100 mm in front of radiating rod with density $\rho_{sp} = 7967\ \mathrm{kg/m^3}$, the longitudinal wave speed $c_l = 5720\ \mathrm{m/s}$ and the shear wave speed $c_t = 3272\ \mathrm{m/s}$.

The idea of using a thin rod as waveguides to achieve a single-mode propagation condition, which makes it possible to avoid a complex deconvolution procedure. There are only two propagating modes, namely, a fast quasi-longitudinal mode and a slow flexural mode, which are high-intensity and basic for these waveguides. By increasing the length of the waveguide, it is possible to clearly separate the pulse signals corresponding to the two indicated modes and work only with the quasi-longitudinal mode by selecting an appropriate time window.[7, 8]

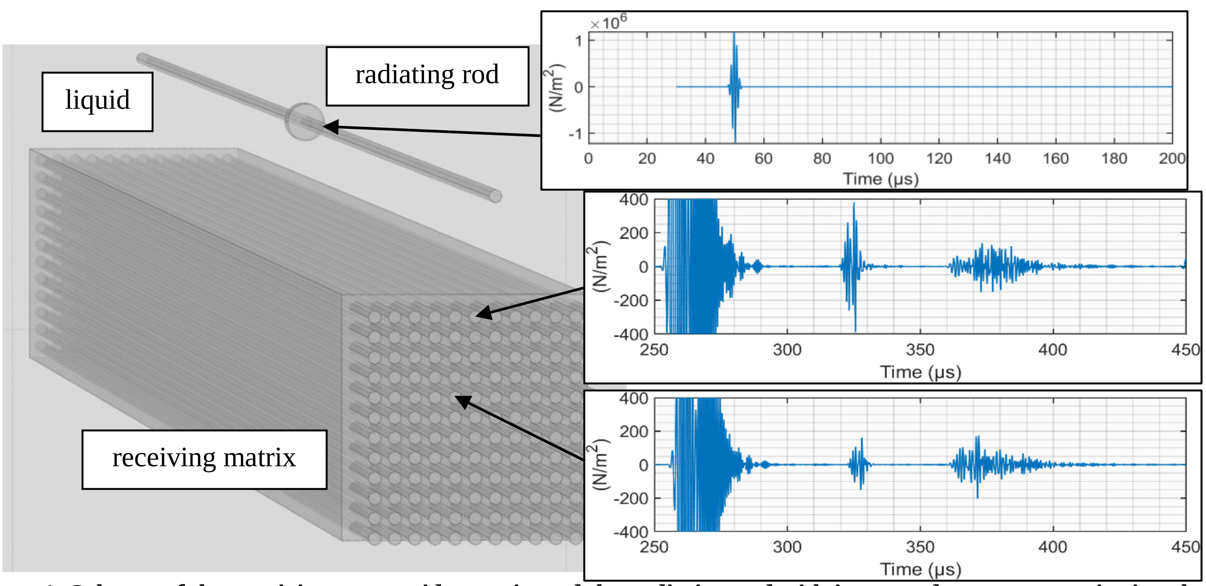

Figure 1. Scheme of the receiving waveguide matrix and the radiating rod with input and output acoustic signals of the rods obtained from numerical calculation of the system.

To create a point source of probe acoustic pulse in the liquid, a waveguide is used, which is a thin stainless steel rod. It is proposed to use a set of identical piezoceramic cylinders with 1 MHz thick resonance, the inner walls of which are glued to the rod, to excite the pulse in the rod. By changing the distance between the cylinders and their length, it is possible to obtain optimal parameters that allow achieving the maximum possible amplitude of the acoustic pulse at the output of the waveguide at a frequency of 1 MHz and at the same voltage amplitudes of the pulses supplied to the piezoelectric transducers. The optimal parameters of the emitted waveguide have been numerically calculated by the finite element method. It was found that the length of the cylinders should be equal to a half-length of the elastic wave in the rod, and the distance between the cylinders should be equal to a length of the elastic wave in the rod ($\lambda \approx 5.05$ mm) while applying voltage pulses to the piezoelectric elements simultaneously (Figure 2).

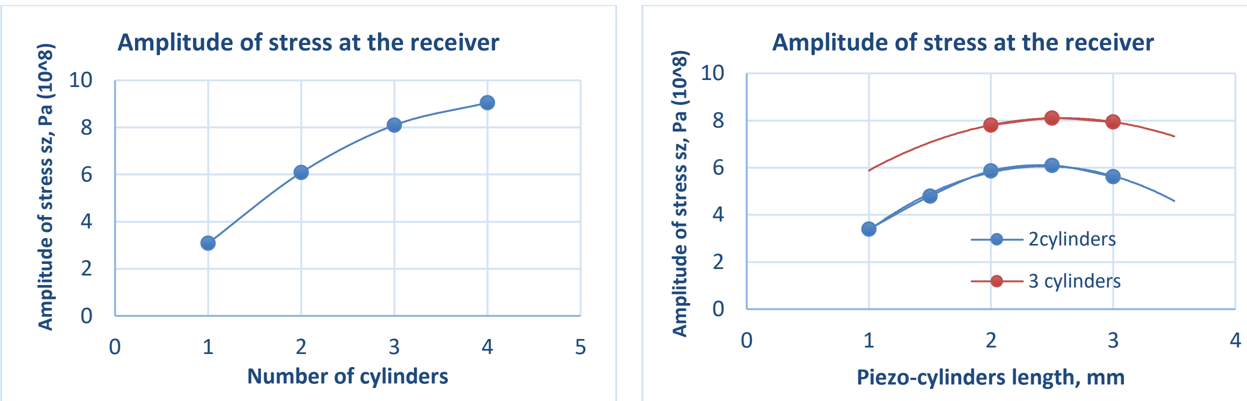

Figure 2. Dependencies of amplitude of stress at the end of the receiving waveguide matrix on number of piezo-cylinders and their length.

Knowing the acoustic properties of the investigated liquid and measuring the oscillations of the waveguides ends of the receiving matrix, one can calculate the distances to internal objects, inhomogeneities and determine their sizes. Moreover, by detecting oscillations of the waveguides ends, it is possible to calculate the acoustic field at the surface near the immersed side of the waveguide matrix. Measuring the acoustic field on the surface and applying the method of acoustic holography, one can reconstruct the acoustic field at another plane and obtain images of objects, inhomogeneities and scatterers immersed in this liquid.

Experimental verification was performed in passive receiving mode. Acoustic waveguide array in a form of 32×32 stainless-steel rods (1 mm in diameter, 0.5 mm pitch, 500 mm length) was placed in a 3D-printed plastic housing (Figure 3). Experimental images of mm-sized objects (Figure 4) placed in front of 1MHz piezoceramic focused transducer in water have demonstrated good imaging ability of the proposed system.

Figure 3. Prototype of receiving acoustic waveguide 1024 channel array.

4. CONCLUSION

In this article, the system consisting of an emitter of a probe acoustic pulse and a receiving waveguide matrix has been described. A radiating waveguide with cylindrical piezoelectric transducers of different arrangements and sizes was numerically modeled by the finite element method to achieve the best radiation and maximum amplitude of the output signal. It has been shown that in order to reach the maximum amplitude of the probe acoustic pulse it is necessary that the cylindrical piezo transducer length should be equal to a half-length of the elastic wave in the rod and the distance between the cylinders should be equal to one wavelength while applying voltage pulses to the piezoelectric elements simultaneously. It has been shown that the system allows obtaining an image of objects placed in liquid (Figure 4). By detecting the oscillations of the waveguides ends using an array of piezoelectric transducers or a laser scanning vibrometer and using acoustic holography to reconstruct the structure of the acoustic field at the plane, one can obtain an image of the surface relief of the objects and irregularities placed in a liquid.

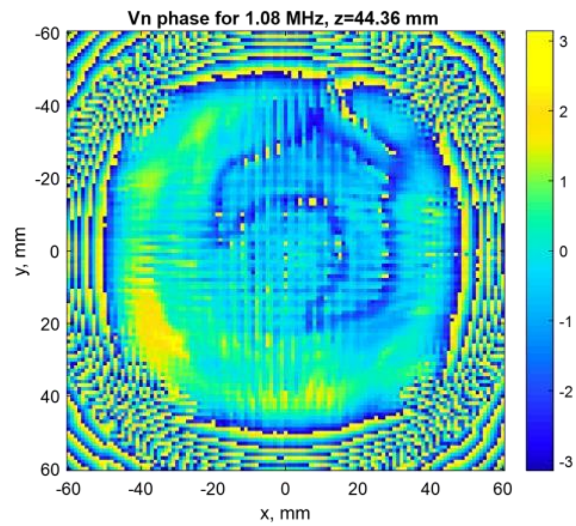

Figure 4. Transducer with an absorptive wrench contour (left), reconstructed phase distribution on its surface (right)

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