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Hydroacoustic Pressure Gradient Recording by a System of Two Fiber-Optic Accelerometers

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Abstract—The paper presents the results of experimental studies of a portable measuring system based on two inertial fiber-optic accelerometers with a multiturn optomechanical transducer placed in a Mach—Zehnder fiber-optic interferometer arm used as a sensitive element. Passive phase demodulation using a fiber-optic splitter 3 × 3 makes it possible to record interferometer output signals in the presence of a thermal drift of the operating point. The possibility of recording using such an acoustic and hydroacoustic pressure gradient system is shown.

Keywords: fiber-optical sensor, interferometer, accelerometer, hydroacoustic signal

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In [1], the possibility of recording the hydroacoustic pressure by an inertial accelerometer based on the Mach—Zehnder fiber-optic interferometer was demonstrated. It was shown that an accelerometer fixed on the surfaces of an elastic membrane interacting with an acoustic or hydroacoustic wave can record vibrations caused by acoustic pressure. Such a method for receiving hydroacoustic signals should be used, e.g., when deploying systems of acoustic monitoring and seismic exploration on the ice surface [2, 3] or when an accelerometer is placed within an underwater vehicle whose hull is a natural receiver of hydroacoustic signals.

In this paper, we present the portable measuring system based on two inertial fiber-optic accelerometers with a multiturn optomechanical transducer placed in the Mach—Zehnder fiber-optic interferometer arm as a sensitive element. The possibility of recording the gradient of acoustic and hydroacoustic pressure using such a system was experimentally shown.

The block diagram of the structure of the multiturn optomechanical transducer based on the a Mach—Zehnder fiber-optic interferometer is presented in [4]. Phase demodulation of the accelerometer output signal was performed by a method based on a fiber-optic splitter 3 × 3 [5] whose signals of the output of three ports are shifted in phase by 120°. Such an approach negates the need for control of the interferometer operating point position and enables recording of weak signals even under conditions of significant external influences on the accelerometer (wind load, acoustic perturbations, temperature drift, and others).

Figure 1a shows the block diagram of the measuring system.

The system includes two vertical inertial fiber-optic accelerometers, a recorder, and a computer.

The use of the passive form of phase demodulation based on a fiber-optic splitter 3 × 3 requires recording of three interferometric signals shifted in phase by $2\pi/3$ with respect to each other.

Therefore, six signals are recorded, by three from each accelerometer, by which the change in the phase difference $\Delta\varphi$ between signal and reference waves of the Mach—Zehnder interferometer is then reconstructed [5]. For the developed accelerometers, this change in the phase difference appears proportional to the acceleration a of the membrane surface on which the accelerometer is fixed [1].

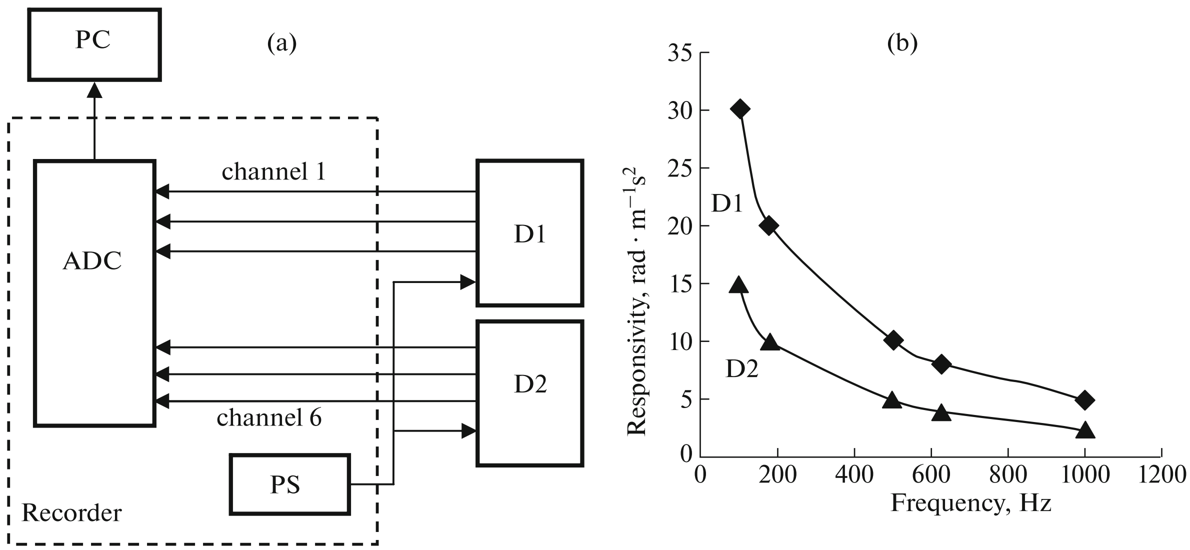

Fig. 1. (a) Block diagram of the measuring system based on fiber-optic accelerometers: PC is a computer, ADC is an analog-to-digital converter, PS is the self contained power supply, PC is the personal computer, and D1 and D2 are fiber-optic accelerometers and (b) their frequency responses.

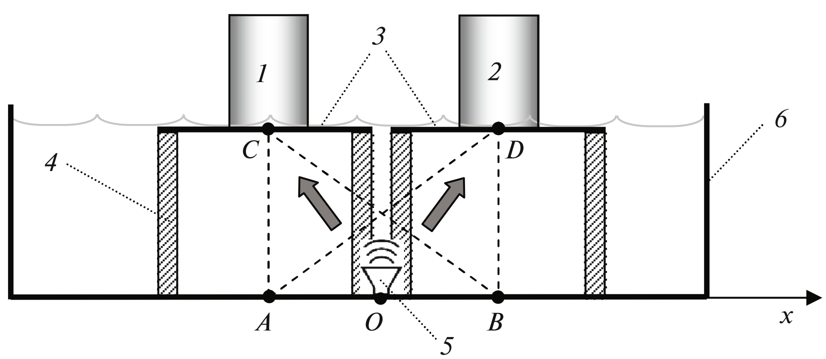

Fig. 2. Schematic of the experimental setup for recording the acoustic field gradient: (*1*) transducer D1, (*2*) transducer D2, (*3*) metal membranes, (*4*) frame stands, (*5*) acoustic/hydroacoustic emitter, (*6*) pool (was filled with water in the second testing stage).

According to the results of experimental studies of accelerometers, their frequency responses were constructed at a vibroacceleration amplitude of 0.02 m/s^2 (Fig. 1b). We can see that the sensitivity of the first transducer is two times the sensitivity of the second one. Since the sensitivity of two transducers in the gradient receiver should be identical, all obtained values for transducer D2 were multiplied by a correcting coefficient k equal to the ratio of sensitivities of the second and first transducers ($k = 2$). With allowance for correction, the sensitivity of accelerometers in the frequency range of 100–1000 Hz was 200–1.2 rad · m^{-1} s^2. At the frequency used in the experiment (630 Hz), the accelerometer sensitivity was 8 rad · m^{-1} s^2. To convert the acceleration to the acoustic/hydroacoustic pressure, a conversion coefficient was determined, which for the presented measuring system was 8.5×10^{-7} m s^{-2}/Pa. Thus, the sensitivity of the measuring system to pressure at a frequency of 630 Hz was 6.8×10^{-6} rad/Pa.

At the first stage, the measuring system was tested in an air medium. The experimental scheme is shown in Fig. 2.

The acoustic emitter, i.e., a broadband head of a 3GDSh-8 electrodynamic loudspeaker, was initially placed at the point O equidistant from transducer centers (points C and D), then, at the point A under the transducer D1, after that, the point B under the transducer D2. The distances are as follows: $AC = BD =$ 0.38 m, $AD = BC =$ 0.57 m, and $AB = CD =$ 0.42 m.

Figures 3a and 3c show the output signals of transducers for different emitter positions (at points O and A).

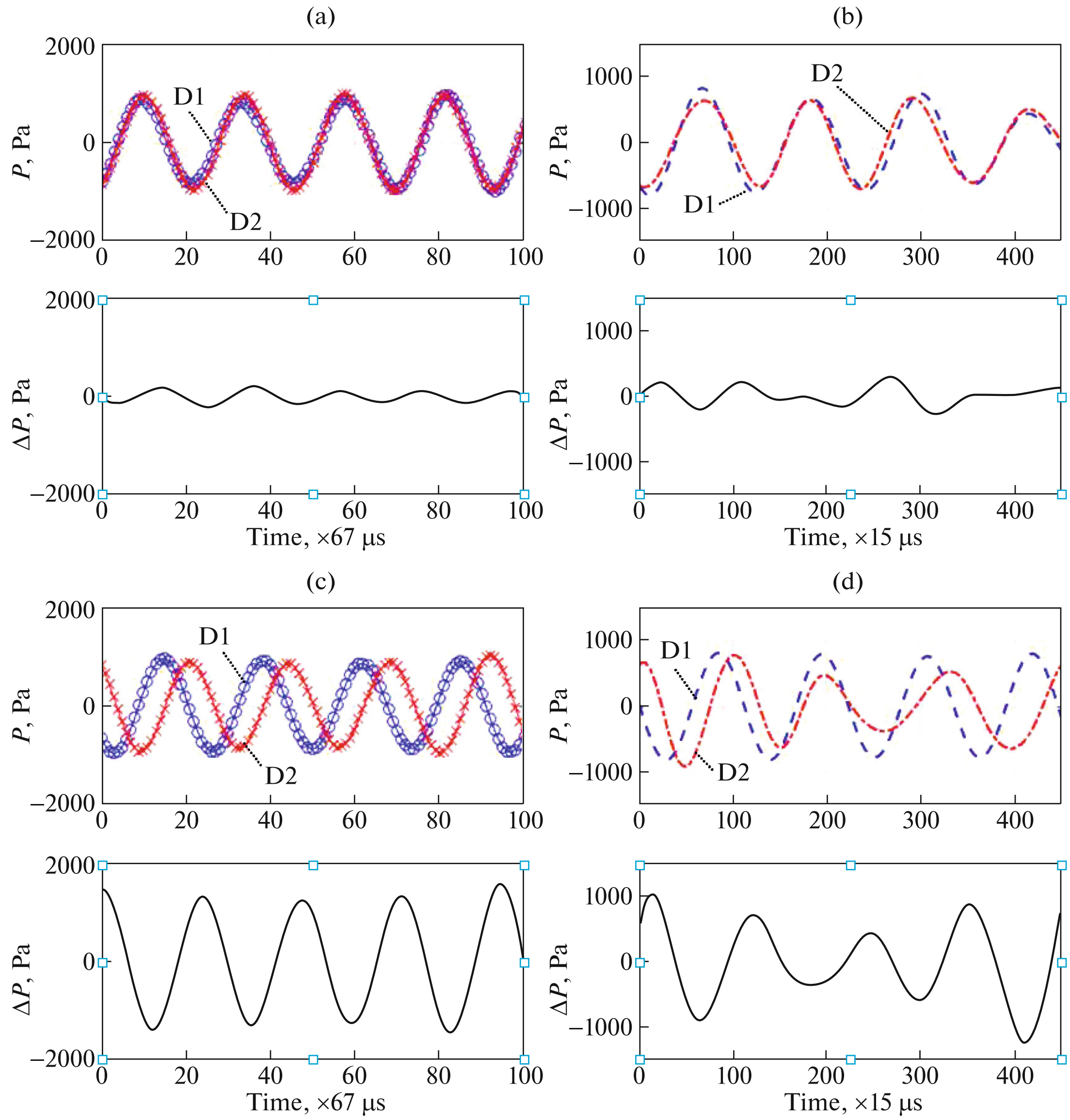

Fig. 3. Output signals recorded by two transducers of the measuring system, and their difference for different acoustic emitter positions: (a, b) at the point *O* and (c, d) at the point *A* when the acoustic wave propagates in air (a, c) and in water (b, d).

The time shift between signals of transducers D1 and D2 equal to 536 ± 11 μs, observed when the emitter is at points *A* and *B* (Fig. 3c for point *A*) corresponds to the speed of sound in air at a temperature of 22°C, 344.2 m/s, which is completely consistent with experimental conditions.

At the second stage, the measuring system was tested in a pool 1.4 × 2.8 m^2 in size with rigid walls and filled with water up to a level of 1 m.

The acoustic emitter had a directional pattern with a width of 120° and provided an acoustic pressure of 1000 Pa at its center.

Similarly to the procedure performed at the first stage, the emitter was initially placed at the point *O* equidistant from transducers, then, at the point *A* under transducer D1, and, after that, at the point *B* under transducer D2. The distances are as follows: $AC = BD = 0.38$ m, $AD = BC = 0.68$ m, and $CD = 0.56$ m.

Figures 3b and 3d show the output signals of transducers for different emitter positions (at points *O* and *A*) when the pool was partially filled with water. The time shift between signals of transducer D1 and D2 equal to (210 ± 5) μs observed when the emitter is placed at points *A* and *B* (Fig. 3d for point *A*) corresponds to the speed of sound in water at a temperature of 10°C, 1447 m/s, which is completely consistent with experimental conditions.

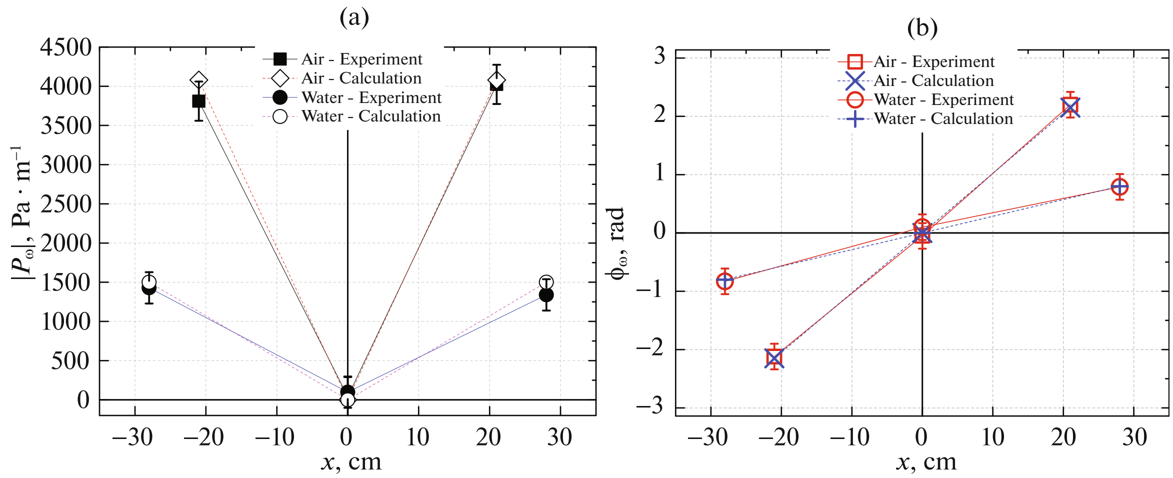

Fig. 4. (a) Amplitudes of the acoustic pressure gradient and (b) its phases as functions of the acoustic emitter position, determined using the measuring system and calculated from the experimental geometry.

These pressure differences ΔP_t shown in Fig. 3 are used to obtain the projection of the acoustic pressure gradient onto the X axis, calculated as

$$\nabla P_\omega = |\nabla P_\omega| \exp i\phi_\omega = \frac{F(\Delta P_t)}{\Delta x}, \tag{1}$$

where $F(..)$ is the Fourier transform, $\omega = 2\pi f$ is the cyclic frequency of the acoustic field, and Δx is the distance between centers of accelerometers (CD distance).

Figure 4 shows the pressure gradient amplitudes $|\nabla P_\omega|$ and phases ϕ_ω measured at various positions of the acoustic emitter on the X axis. As can be seen, they are identical with high accuracy (within experimental error) to the corresponding data calculated based on the experimental geometry.

Thus, the two-channel measuring system based on two inertial fiber-optic accelerometers was proposed. A multiturn optico-mechanical converter placed in the arm of the Mach–Zehnder fiber-optic interferometer was used as a sensitive element of accelerometers. The possibility of recording the acoustic and hydroacoustic pressure gradient using such a system was experimentally shown.

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