Observation of the self-induced thermal action of a high-intensity ultrasonic beam in water

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The self-induced effects of light beams in nonlinear media are well known. On the other hand, the possibility of the self-action of acoustic beams has only been studied theoretically in the literature (see Refs. 1–3 and the literature cited therein). In the present study we have attempted to observe the self-induced thermal action of a high-intensity ultrasonic beam in water.

In acoustics, self-action occurs in the absence of dispersion against the background of strong second-order effects (the formation of shock fronts and nonlinear attenuation), which, as a rule, yield a much larger contribution to the variation of the acoustic wave than the third-order effects responsible for the self-action. The latter is therefore manifested primarily in a variation of the phase of the wave.

In the experiments we determined the phase shift of the wave in a finite-amplitude acoustic beam by the method of Lissajous figures. The actual measured quantities were the phase shifts $\phi_1$ and $\phi_2$ of the zero points of the wave profile (see Fig. 1), in contrast with the procedure used in Ref. 4, where only the phase shift of the first harmonic was measured.

The experiments were carried out in an underwater testing tank, which was filled with settled tap water, at various distances from the radiator and for various pump levels in the range of intensities 0.1–5 W/cm$^2$ at an ultrasonic frequency ~1 MHz. A harmonic signal from a Chê-31 frequency synthesizer was sent to a power amplifier and then to a piezoceramic radiator, which generated ultrasonic waves in the water. The signal from the master oscillator was also used to sweep the beam along the X axis of an SI-71 oscilloscope; the signal from a wideband hydrophone placed in the acoustic beam was sent to the Y axis of the oscilloscope.

For a weak pump (such that the hydrophone signal was harmonic), a zero phase shift was established between the directions to the radiator and the receiver (Fig. 2a); the instrumental error was $\pm 1.5^\circ$. The distance and frequency were fixed. Nonlinear distortion of the hydrophone signal set in with an increase in the transducer voltage (the level of higher harmonics did not exceed ~30 dB), and the Lissajous figure acquired the characteristic shape for the summation of signals with frequencies $\omega$ and $2\omega$ (Fig. 2b). With a further increase in the pump level, the wave profile acquired a shock front, and the Lissajous figure assumed the form shown in Fig. 2c.

It was noted in the course of measurement of the phase shifts of the zero points $\phi_1$ and $\phi_2$ that the Lissajous figures are not time-invariant. This was observed only when a shock front was formed between the radiator and the receiver, resulting in an effective nonlinear dissipation of wave energy. The following was noted: The quanti-
ties $\varphi_1$ and $\varphi_2$ decreased after the radiator was turned on, and the pattern stabilized after a certain time (see Fig. 3). The rate of change of the phases increased with the wave intensity. After the radiator was switched back to weak-signal operation, the linear signal no longer had a zero phase shift (as in the initial setting); it tended to zero gradually with time. This additional phase shift could be compensated by increasing the signal frequency by several tens of hertz.

These data can be interpreted within the framework of the mechanism of the self-induced thermal action of a high-intensity ultrasonic beam. The heating of the medium is slight for a weak pump (when the shock formation length is greater than the distance to the hydrophone), owing to the small linear wave absorption. Nonlinear wave absorption becomes appreciable for large pump levels, resulting in effective heating of the medium and a variation of the sound velocity. The temperature field is stabilized by heat diffusion across the beam. The heat-release intensity in the acoustic beam can be determined from measurements of the wave intensity as a function of the distance from the radiator (see Ref. 5). These data were used to determine the rate of change of the temperature at the instant when the radiator was turned on; it was found to be equal to $7 \times 10^{-3}$ K/s for a wave intensity $\sim 4$ W/cm$^2$. This caused the phase of the wave to drift at a rate of the order of 0.3 deg/s, which concurs with the measured value. The sign of the phase variation also corresponds to the self-induced thermal mechanism, because the temperature coefficient of the sound velocity in water is positive.

Other mechanisms can also produce a phase shift in a high-intensity ultrasonic beam (e.g., scattering by acoustic streaming). However, the contribution of these mechanisms to the measured values of the phase shift is small in the reported experiments (the measured velocity of acoustic streaming did not exceed 2 cm/s). It can therefore be stated that the observed phenomenon was the self-induced thermal action of sound.

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Transfer constant of an acoustic interferometer with rod-type acoustic lines

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We have previously\(^1\) derived an expression for the transfer constant of an acoustic interferometer with a transition layers, defined as the ratio of the voltage on the receiving piezoelectric transducer to the voltage of the master oscillator, and we showed that the modulus of the transfer constant $K$ passes through relative maxima and minima as the length $l_C$ of the investigated medium is varied. Its values at those points are

\[
|K|_{\text{max}} = \frac{1}{\sqrt{(1 + C + D)^2 - 4(A + BD)^2 \cdot \text{sh}(\alpha_{\text{max}} + \beta)}}
\]

\[
|K|_{\text{min}} = \frac{1}{\sqrt{(1 + C + D)^2 - 4(A + BD)^2 \cdot \text{sh}(\alpha_{\text{min}} + \beta)}}
\]

where $\alpha_C$ is the sound absorption coefficient in the

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