Observation of a thermal self-effect of a sound beam in a liquid

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Experiments have been carried out on the self-effect of a sound beam in benzene. A thermal self-focusing of an ultrasonic beam at a frequency of 2 MHz was discovered when the radiated energy exceeded a certain threshold.

Experimental observation of the effects of an interaction of sound with nonacoustic motions of a liquid requires that the parameters of the liquid and of the sound field satisfy certain stringent conditions because of strong competing processes.[1] One effect of such an interaction, a self-effect of a sound beam, was predicted in Ref. 2. The strongest thermal mechanism for this effect (in an ordinary liquid) was described for the cw case in Ref. 3. The flow and temperature relaxation times $\tau(v)$ and $\tau(T)$ in beams with dimensions in the centimeter range are on the order of 10–10^2 s. According to the estimates of Ref. 1, therefore, at a sound pulse length $\tau < 10$ s the defocusing longitudinal flow will not have an effect if $A = c_p/c_0^2|\gamma_p| < 1$ [c_p is the specific heat, c_0 is the sound velocity, and $\gamma_p = (\partial \ln c_0^2/\partial T)_p$]. The threshold parameter for self-focusing in this necessarily transient regime is the energy $W_t = 0.15\rho_0 c_p c_0^2/\delta\,|\gamma_p|\,f^2$ (ρ_0 is the density, δ is the absorption coefficient, and f is the frequency). The most important competing processes are the acoustically induced convection, which breaks up the beam at $\tau > \tau_c = (\rho_0 c_p/\alpha g\delta I)^{1/3}$ (a is the beam radius, α is the thermal expansion coefficient, g is the acceleration due to gravity, and I is the sound intensity), and the cascade generation of harmonics. The latter process is completely suppressed at $\tau > \tau_p = 39.5 c_p \epsilon^2 f^2 a^2/\delta c_0^5|\gamma_p|$ (ϵ is the elastic nonlinearity, and a is the beam radius), but even at $\tau < \tau_p$ this process does not prevent self-focusing, although it does complicate a quantitative interpretation of this focusing. In particular, harmonics can lower the observed threshold, by virtue of the relation $W_t \sim f^2$.

Because of these requirements, we selected benzene as the working medium for our experiments to observe a thermal self-effect of a sound beam. The liquid was held in a rectangular cell ($4\times6\times20$ cm) with a disk transducer (TsTS-19 ceramic, 14 mm in diameter, resonant frequency of 1.972 MHz) at one end and a glass wool acoustic absorber at the other. To prevent an unwanted heating of the medium near the sound beam by the heat evolved by the working transducer, we placed a three-layer heat filter (a fluoroplastic film 0.05 mm thick) in front of the transducer. The cell had side windows of optical glass. The spatial distribution of the sound intensity in the liquid was studied by an optical dark-field method (in our case, a bright-field method). The acoustic power was determined within 30% from the number of alternating dark and bright fringes in the beam. The results were compared with electrical measurements.

In a control experiment in water, in which self-focusing is impossible ($\gamma_p > 0$; furthermore, δ is very small), we observed no changes in the beam profile at a power $P = 15$ W over a time $t \gtrsim 10$ s.

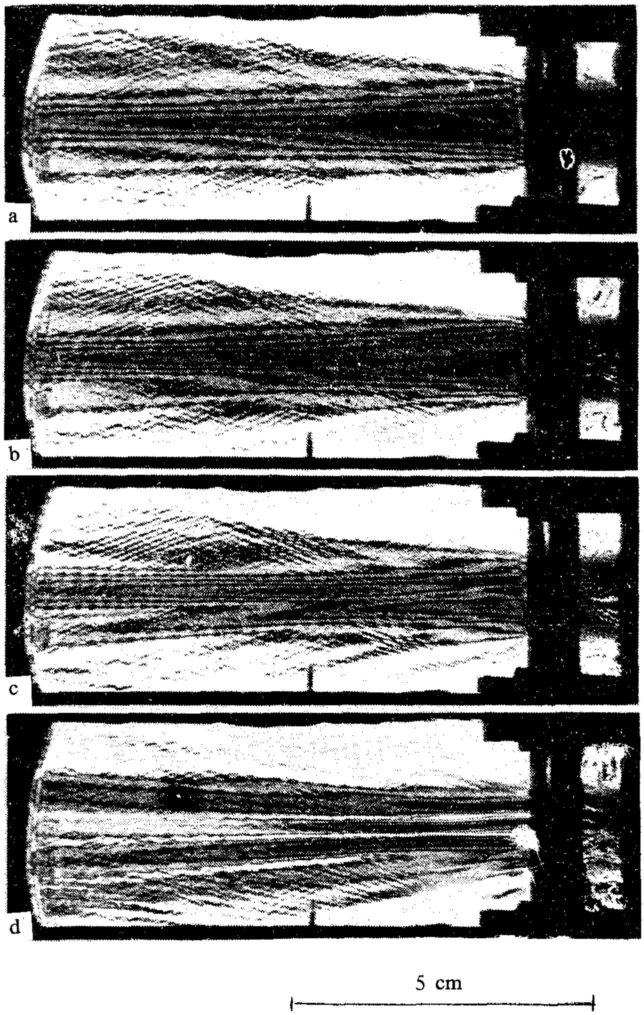

FIG. 1. "Shadow" pattern of the intensity distribution of the sound beam in benzene. The input power is $P = 15$ W. a—0.2 s after the transducer is turned on; b—0.5 s; c—1 s; d—2 s. The transducer is at the right; the heat filter can be seen in front of the transducer.

An experiment with benzene ($\gamma_p < 0$) showed that the change in the beam structure becomes noticeable when the energy $W = Pt$ reaches 2–3 J. The basic change is a contraction of the beam, by a factor of two at $W \cong 15$ J (Fig. 1, a–c). The edge of the contracted beam can be seen clearly on these photographs. (The blurred fringes at the top and bottom of the photographs correspond to the side lobes of the directional pattern and reflections from the cell walls.) After the fixed-power source is turned on, we observe a motion of the beam constriction which forms toward the transducer. With a further increase in the radiated energy, the beam breaks up into distinct filaments (Fig. 1d). At $W \gtrsim 30$ J ($t \gtrsim 2$ s) we observe a turbulent spreading of the beam, whose front moves toward the transducer. It can also be seen from Fig. 1 that the heat fluxes from the transducer do not penetrate into the working region.

Estimates based on the results of Ref. 1 for the present experimental conditions yield $A = 0.14$, $W_t = 3.9$ J, and $\tau_c = 1.4$ s. We find $\tau_p \cong 3.6$ s, which means that harmonics are generated, although not strongly. We link this generation with the observed lowering of the threshold to 2–3 J. The stratification of the beam at $W \gtrsim 20$ J ($\gtrsim 5W_t$) occurs because at these energy levels the threshold energy is "accumulated" at various inhomogeneities of the input profile. The velocity of the constriction also agrees with the theoretical predictions (the typical focal length is $L_f = 8.8t^{-1/2}$ at $P = 15$ W).

In summary, these experiments have revealed a thermal self-focusing of a sound beam at the frequency $f = 2$ MHz. The observed results agree well with the theory of Ref. 1.

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