SCATTERING, REFRACTION AND REFLECTION OF SOUND UNDER THE ACTION OF INTENSE LIGHT ON THE MEDIUM

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Scattering, refraction and reflection of sound due to the action of a powerful flash of incoherent or laser light is considered. It is shown that the appearance of bubbles in the liquid or of local heating may considerably affect the sound propagation. The high efficiency of the effect of the light on the sound through bubble formation in the medium is estimated.

UNDER the action of powerful coherent or incoherent light (lasers, flash lamps) on a medium, inhomogeneities of heating can develop in it, and in a liquid, phase nuclei—vapor bubbles or dissolved gas.[1–4] Such inhomogeneities can strongly affect the acoustic properties of the medium, produce strong scattering reflection or refraction of the sound, which passes through the region of the medium which is moved under the action of the light. The appearance of bubbles in the liquid under the action of a powerful light is connected with the liberation of dissolved gas or the boiling up of the liquid in heating, especially near small absorbing inhomogeneities or at the surfaces of absorbing media.

We shall consider in more detail the formation of bubbles under the action of powerful light, inasmuch as the appearance of the bubbles sharply changes the compressibility of the liquid, and produces strong scattering, reflection and refraction of the sound. If the bubbles are due to boiling or degassing the liquid upon heating of the inhomogeneities which are always present in real liquids, then the threshold light flux density is

$$I_{\text{th}} \approx T_{\text{cr}} C\rho \sqrt{\varkappa} / \sqrt{t},$$

where T_c is the temperature that just suffices for strong boiling of the liquid, $C\rho$ the heat capacity per unit volume, κ the temperature conductivity of the medium, and t the time of the action. The dimension a of a bubble produced on an inhomogeneity of radius a_0 is determined from the relation

$$q \approx I_0 t \pi a_0^2 \approx {}^4/_3 \pi a^3 \lambda / V,$$

where λ is the heat of vaporization of 1 g of liquid and V is the volume of 1 g of vapor of the liquid. For example, for $C\rho \approx 4$ J/cm^3, $\kappa \approx 10^{-2}$ cm^2/sec, $t \approx 10^{-3}$ sec, $T \approx 300°$, we get $I_{th} \approx 3$ kW/cm^2, which is easily obtainable in laser beams even without Q switching, or from flash lamps, the use of which, in view of the large energy release, is more favorable for creation of bubbles in large volumes. For example, at a lamp energy release on the order of several kJ per millisecond, the necessary flux density of $I \sim 1$ kW/cm^2 is ensured at distances of the order of 10 cm.

For an inhomogeneity dimension $a_0 \approx 10$ microns we get $a^3 \approx V I_0 t a_0^2/\lambda \approx 5 \times 10^{-6}$ cm^3 for such an energy density, i.e., $a \approx 10^{-2}$ cm.

1. SCATTERING OF SOUND AT BUBBLES PRODUCED BY INTENSE LIGHT

The scattering cross section of sound on a bubble of radius $a \ll \lambda_0$ (Rayleigh scattering)[5] has the form

$$\sigma_s = 4\pi a^2 \left\{ \left(1 - \frac{\omega_r^2}{\omega^2}\right)^2 + k^2 a^2 \left(\frac{\omega_r}{\omega}\right)^4 \right\}^{-1}$$

where $k = \omega/c_s = 2\pi/\lambda_a$ is the wave vector of the sound wave, the resonance frequency $\omega_r = a^{-1}\sqrt{3\gamma p/\rho} = u_{eff}/a$ depends on γ, the adiabatic constant of the gas or vapor, the pressure p in the bubble and ρ the density of the liquid. (For very small bubbles $a < 10^{-2}$–10^{-4} cm, it is necessary to take into account the effect of the surface tension on the resonance frequency, which is simply done.[6]) For the conditions of interest to us, $u_{eff} \approx 3 \times 10^3$ cm/sec and $\omega_r \approx 3 \times 10^3/a$ for $a > 10^{-3}$ cm. For low frequencies, $\omega \ll \omega_r$, we get

$$\sigma_s \approx 4\pi a^2 (\omega/\omega_r)^4 \approx 4\pi a^6 \omega^4 / u_{eff}^4 .$$

For $\omega \approx \omega_r$, the quantity $\sigma_{sr} = \lambda_s^2/\pi$ and for high frequencies, $\omega \gg \omega_r$ (but for $\lambda_s > a$), $\sigma_s \approx 4\pi a^2$. In the case $\lambda_s \ll a$, we get the usual $\sigma_s \approx \pi a^2$.

The range of sound frequencies which interest us extends from the frequency of hypersound $\omega \sim 10^{10}$ rad/sec to ordinary ultrasound $\omega \sim 10^6$ rad/sec. In the case of the formation of vapor bubbles, the volume of the bubble

$$V_{\text{bub}} \approx {}^4/_3 \pi a^3 \approx qV/\lambda,$$

where q is the energy released, λ the heat of vaporization of 1 g of liquid, V(p) the specific volume of 1g vapor at a pressure p in the bubble. For bubbles of dimension $a \approx 10^{-2}$ cm, the resonance frequency $\omega_r \approx 3 \times 10^5$ rad/sec falls in the range of ultrasonic frequencies usually employed. Setting $\omega \sim \omega_r$ but not taking into account the exact hit of resonance, we get $\sigma_0 \approx 4\pi a^2$, $L_s \approx 1/N\sigma_s \approx 1$ m. The contribution of bubbles having the resonance frequency close to the sound frequency can still further amplify the scattering in view of the colossal resonance cross section.

We compare the sound scattering by the bubble with the sound scattering by local heating for the same energy production q (the particular form of the inhomogeneity can be realized by the choice of intensity). In the case of local heating, the cross section of Rayleigh scattering of sound[7] for $\lambda_s \gg a_{loc}$ has the form

$$\sigma_s^{\text{loc}} \approx \frac{a_{\text{loc}}^6}{\lambda^4}\left(\frac{\Delta K}{K}\right)^2 \approx \frac{a_{\text{loc}}^6}{c_s^4}\left(\frac{\Delta c_s}{c_s}\right)^2 \omega^4,$$

since the effect of density change can usually be neglected, inasmuch as in heating,

$$\Delta\rho/\rho \ll \Delta K/K = 2\Delta c_s/c_s,$$

where K is the compressibility and c_s the speed of sound in water. Setting

$$\Delta c_s = \frac{dc_s}{dT}\Delta T, \qquad a_{\text{loc}}^3 \Delta T = \frac{3}{4\pi}\frac{q}{C\rho},$$

where $C\rho$ is the heat capacity of 1 cm^3 of liquid, we get

$$\sigma_s^{\text{loc}} \approx \left(\frac{3q}{4\pi C\rho}\right)^2 \left(\frac{1}{c_s}\frac{dc_s}{dT}\right)^2 \frac{\omega^4}{c_s^4}.$$

Therefore, for $\omega \ll \omega_r$, we have

$$\frac{\sigma_s^{\text{bub}}}{\sigma_s^{\text{loc}}} = 4\pi\left(\frac{c_s}{u_{\text{eff}}}\right)^4 \left(\frac{VC\rho}{\lambda}\right)^2 \left(\frac{c_s}{dc_s/dT}\right)^2.$$

For example, for $c_s \approx 50\, u_{\text{eff}}$, $VC\rho/\lambda \sim 1\ \text{deg}^{-1}$ and $c_s^{-1}dc_s/dT \approx 3\times10^{-3}\ \text{deg}^{-1}$, we get $\sigma_s^{\text{bub}}/\sigma_s^{\text{loc}} \approx 10^{13}$.

We note that the predominance of the cross section of Rayleigh scattering of the bubbles over the scattering by local heating for the same energy release also takes place in the case of aureole light scattering,[1-4] since in this case

$$\sigma_s^{\text{bub}} \sim (\Delta n a_{\text{bub}}^3)^2 \text{ and } \sigma_s^{\text{loc}} \sim (\delta n a^3)^2 \sim (n_T'\delta T a_{\text{loc}}^3)^2 \sim (n_T' q/C\rho)^2 \text{ и}$$

$$\frac{\sigma_s^{\text{bub}}}{\sigma_s^{\text{loc}}} \sim \frac{VC\rho\Delta n}{\lambda n_T'} \sim 10^4 - 10^5$$

for most media (usually, $n_T' \approx 10^{-4}-10^{-5}\ \text{deg}^{-1}$). Thus the creation of strongly scattering centers with the formation of nuclei of the new phase is more favorable.

The flash of light which forms the scattering centers can be very short and after this time the scattering centers can no longer be formed and the light can act on the large volume of the medium without noticeable scattering. For example, in the case of bubbles of vapor, the bubbles grow to the dimensions $a_m \approx (qV/\lambda)^{1/3} \sim q^{1/3}$[J] within a time $\tau \sim a/u_{\text{eff}}$. The lifetime of the vapor bubbles $\tau \sim a^2/\kappa \approx 10^3 a^2$ sec, and if the temperature conductivity $\sim 10^{-3}$ cm/sec, then for a > 10 microns, $\tau >$ millisec. The lifetimes of the gas bubbles are still larger because of the slowness of the diffusion.

2. REFRACTION AND REFLECTION OF SOUND IN THE ACTION OF INTENSE LIGHT ON THE MEDIUM

The change in the speed of sound in the heating of a liquid, or the appearance of bubbles, can produce refraction or reflection of sound in regions of the medium subjected to the influence of intense light. The change in the sound speed because of heating and the bubbles is given by the formula

$$\frac{\delta c_s}{c_s} \approx \frac{1}{c_s}\frac{dc_s}{dT}\delta T - \frac{2\pi}{3\gamma}\frac{Na^3}{pK},$$

where $c_s^{-1}dc_s/dT \approx 3\times10^{-3}\ \text{deg}^{-1}$, N is the concentration of bubbles of radius a, K the compressibility of the liquid (usually $pK \approx 10^4-10^5$) which sharply increases the value of the bubble nonlinearity.

From the equation of refraction we obtain for the change in the angle of inclination of the θ ray $\partial\theta/\partial z \approx c_s^{-1}\partial c_s/\partial x_\perp$,

$$\delta\theta \sim \frac{1}{c_s}\frac{\partial c_s}{\partial x_\perp} l \sim \frac{1}{c_s}\frac{\delta c_s}{D} l \sim \frac{\delta c_s}{c_s},$$

if the length l of the region of the inhomogeneity is commensurable with its transverse dimension D. Estimates show that, with the help of intense light sources, one can change the speed and direction of the sound wave by a considerable amount.

Actually, the appearance of bubbles following the action of the light greatly changes the compressibility of the water. In the case $a \approx 10^{-2}$ cm, the relative change in the speed is $\delta c_s/c_s \approx 0.3-1$ for the values of concentration and dimensions of the bubbles of interest to us ($Na^3 \approx 10^{-4}$). Therefore, the method of action of light on sound through bubble formation is seen to be very effective. Reflection of sound can also occur at the boundary of the region of inhomogeneity, with an intensity reflection coefficient $\alpha \sim (\delta c_s/c_s)^2$. We note the possibility of the creation of systems of acoustic inhomogeneities (strips, spots, periodic systems) with the help of a beam of light of complex profile. For example, a spatially periodic "notch" of light intensity of a comb-like set of screens can create strong coherent sound scattering. Use of light flashes with high energy release, on the order of tens of kilojoules, makes possible such pulsed systems with sufficiently large dimensions, suitable for study and use.

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