SOUND EXCITATION IN AIR BY A CO-LASER BEAM

V.V. Vorob'ev, V.A. Myakinin, E.N. Lotkova, and P.A. Dubovskii

Institute of Atmospheric Physics,
Academy of Sciences of the USSR, Moscow
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Results are presented of measurements of the amplitudes of sound waves excited in air by absorbed modulated CO-laser radiation. The measured dependences of the sound amplitude on the laser radiation power and distance from the beam center agree well with theoretical calculations.

As demonstrated by theoretical estimates of the intensity of sound generated during the absorption of intensity-modulated laser radiation,[1] such sound may be loud enough to be measurable against the noise background. Measurements of sound generated in air by radiation from a CO_2 laser of 550 W power were conducted in Ref. 2. These measurements support the available theoretical estimates and demonstrate the possibilities of using acoustic measurements as a means of evaluating the absorption of laser radiation in air.

The present study presents the results of measurements of the intensity of sound generated during the absorption of CO-laser radiation in air. Electric discharge CO-lasers emit radiation in the 5–6 μm range,[3] the latter containing a number of strong water-vapor absorption lines.[4] By adjusting the parameters of the laser active medium, the wavelength of the emitted radiation can be varied and, consequently, the air absorption coefficients can be selected for this laser. The acoustic signal power is thus increased, so that confident measurements may already be conducted at a laser output power of about 1 W. Such a situation inspires the hope of employing acoustic measurements for operational in situ retrieval of, for example, the air humidity.

To elucidate the nature of the dependence of the sound wave pressure on distance from the beam and on its modulation frequency, we consider the case in which the sound is generated by a beam with a Gaussian intensity distribution I over its cross section, temporally modulated following some function $f(t)$, which is a series of unit amplitude pulses of duration $T/2$ with the same interval between successive pulses

$$I(x,\ y,\ t) = \frac{2W}{\pi a^2} \exp\left[-\frac{x^2 + y^2}{a^2}\right] f(t). \tag{1}$$

Here W is the average emitted radiative power, and a is the beam radius.

The variation of the sound wave pressure $P(x, y, z, t)$ is described by the equation

$$\frac{\partial^2 P}{\partial t^2} - u^2\left[\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2}\right] = \alpha\ (\gamma - 1)\ \frac{\partial I}{\partial t}, \tag{2}$$

where $\gamma = C_p/C_v$ is the ratio of the specific heats of air, u is the speed of the sound, α is the radiation absorption coefficient. If the function $f(t)$ is expanded in its Fourier series

$$f(t) = \frac{1}{2} + \frac{1}{\pi}\cos\omega t + \frac{1}{3\pi}\cos 3\omega t + \ldots, \quad \omega = \frac{2\pi}{T},$$

then the amplitude $P_0(x, y, \omega)$ of the steady-state pressure oscillations P(x, y, t) at the frequency ω can be calculated from the formulas which follow from the solution of Eq. (1) with the help of the Fourier transform with respect to the transverse coordinates

$$P(x,\ y,\ t) = A(x,\ y,\ \omega)\sin\omega t + B(x,\ y,\ \omega)\cos\omega t;$$

$$P_0 = \sqrt{A^2(x,\ y,\ \omega) + B^2(x,\ y,\ \omega)} \tag{3}$$

$$A(r,\ \Omega) + iB(r,\ \Omega) = c\int_0^\infty \frac{\Omega\kappa J_0(2\kappa r)\exp(-\kappa^2)}{\Omega^2 - \kappa^2}\,d\kappa.$$

Here $c = \dfrac{2\alpha(\gamma-1)W}{\pi^2 au}$; Ω and r are the dimensionless frequency $\Omega = \omega a/2u$ and distance $r = \sqrt{(x^2+y^2)/a^2}$ from the center of the beam to the observation point, and J_0 is the Bessel function of order zero.

The real part of integral (3) is equal to its principal value understood in the Cauchy sense, and its imaginary part is equal to half of the residue at the point $\kappa = \Omega$, i.e.,

$$B(r,\ \Omega) = c\,\frac{\pi}{2}\,J_0(2r\Omega)\exp(-\Omega^2). \tag{4}$$

The real part of A at $r = 0$ (in the center of the beam) is equal to

$$A(0,\ \Omega) = \frac{c}{2}\,\Omega E_1^\bullet(\Omega^2)\exp(-\Omega^2), \tag{5}$$

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where $E_1^*(\Omega^2) = \int_{-\infty}^{\Omega_2} \xi^{-1}\exp(\xi)d\xi$ is a tabulated function.[5] The dependence of $P_0(0, \Omega)$ on Ω is presented in Fig. 1. The value of P_0 reaches a maximum at $\Omega = \Omega_0 = 0.8$.

Note that the authors of Ref. 1 disregarded the imaginary part of the integral (3) when computing the sound pressure amplitude, which is incorrect. A similar mistake was, apparently, made by Kolosov et al.,[2] since the dependence of the sound amplitude on frequency, presented in Fig. 1, is proportional to $A(0, \Omega)$ given by formula (5).

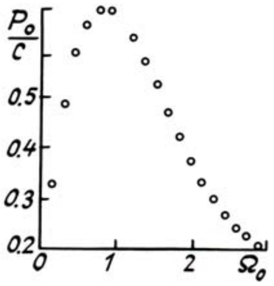

FIG. 1. The dependence of the sound pressure P on the frequency $\Omega_0 = \omega a/2u$ of the light intensity modulation at the beam center.

Outside the beam, at $r \geq 2$, $\Omega \geq 0.2$, the dependence $P_0(r, \Omega)$ is described with an error of no more than 2% by the relation

$$P_0(r, \Omega) = \frac{c}{2}\sqrt{\frac{\pi\Omega}{r}}\exp(-\Omega^2), \tag{6}$$

which follows from the asymptotic form of the integral (3). The main contribution to that integral at $r \gg 1$ is given by the point $\kappa = \Omega$ and it can be evaluated to yield

$$\int_0^\infty \frac{\kappa J_0(2r\kappa)\, e^{-\kappa^2} d\kappa}{\Omega^2 - \kappa^2} \simeq - K_0(-2ir\Omega)\, e^{-\Omega^2},$$

where K_0 is the Bessel function of imaginary argument; $|K_0(z)| \approx \sqrt{\pi/2}\cdot z$ at $|z| \gg 1$. The function $P_0(r, \Omega)\cdot\sqrt{r/c}$, calculated according to formula (6), is plotted in Fig. 2. The values of the same quantity computed by numerical integration of expression (3) at $r = 2$ and $r = 1$ are also plotted there. Note that the frequency dependence of $P_0(0, \Omega)$ and $P_0(r \geq 2, \Omega)$ differ both in the position of their maxima and in the more rapid decrease of the function $P_0(r > 2, \Omega)$ at high frequencies.

In our laboratory experiment, a diagram of which is given in Fig. 3, we employed a single-mode multi-frequency electric discharge CO-laser 1 with a total output power of 6 W. The spectrum of this laser covered the range 5.2–6.0 μm and corresponded to the transitions $v + 1 - v$ at high vibrational quantum numbers v (9–14), so that the absorption of the laser radiation by the CO molecules in the air was negligibly small. A modulator 3, which consisted of a duraluminium disk with 1 mm-diameter holes bored every 2 mm around the disk center at a radius of 127 mm. driven by an electric motor, was installed in the focal plane of the collimator 2, which consisted of two fluoride lenses with a 4 cm focal distance. The modulation frequency at the collimator exit was 17.5 KHz, and the exit output power of the collimator was 2 W. To monitor variations in the source power, a part of this radiation was channeled to a powermeter 5 by a fluoride plate 4.

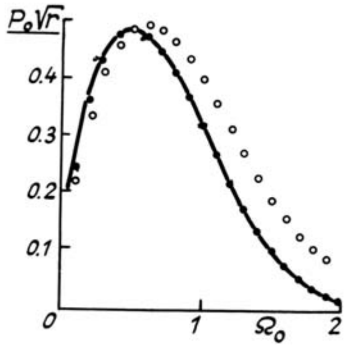

FIG. 2. Same as in Fig. 1 at various dimensionless distances r from the beam center Empty circles — r = 1; solid circles — r = 2; solid line — asymptotic limit.

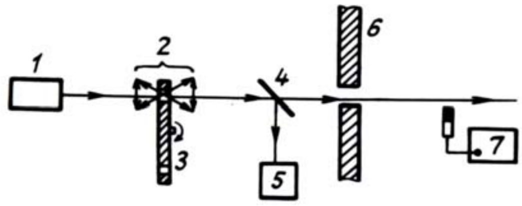

FIG. 3. Experimental setup.

The beam of radiation thus formed was directed through an opening in the sound-absorbing partition 6 (which considerably lowered the level of noise from the cooling and power supply systems) to the sound detecting system 7. The latter consisted of a high-precision 00 023 "Robotron" pulsed noise-meter. Measurements were taken with a three-octave filter with a 4 KHz bandwidth and a resonance frequency of 16 KHz, built into the noise-meter. Signal attenuation by the filter at 17.5 KHz constituted less than 3 dB compared against the resonance frequency. The noise level measured by such a filter did not exceed 15 dB with respect to the audibility level (P =20 μPa).

The air absorption coefficient α was obtained by measuring the extinction of laser radiation along a beam path 4 m in length. During the experiment it amounted to $3.5\cdot10^{-2}\text{m}^{-1}$ (at a relative humidity of 78%). In the region of the sound pressure measurements the beam radius was 0.5 ±0.1 cm. The dimensionless frequency $\Omega = \omega a/2u$ was thus equal to 0.81. As follows from Eq. (6), the pressure amplitude outside the beam should (at $r \geq 2$) then vary as

$$P_0(r, \Omega = 0.81)\ 10^3\ [\mathrm{Pa}] = 0.68\sqrt{a}/R \cdot W\ [\mathrm{W}] \quad (7)$$

Here R is the dimensional distance.

This dependence is presented in Fig. 4 by the solid line. Points show the measured values of $P(R)$. A good agreement may be noted between theoretical and experimental dependences obtained.

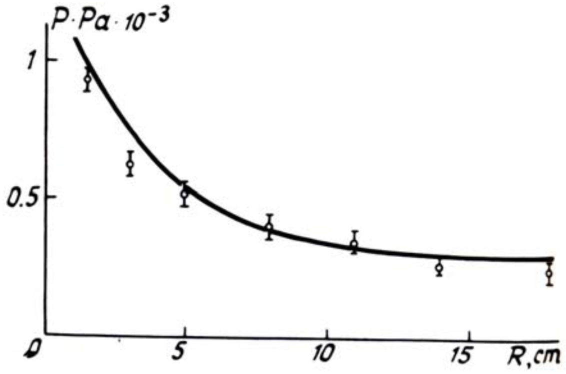

FIG. 4. Sound pressure amplitude P at various distances from the beam center.

Figure 5 presents experimental and theoretical dependences of the sound amplitude on the laser radiation power, measured at R = 1.5 cm. The measured dependence validates the assumption of the linear nature of the sound generation process.

We further increased the water vapor concentration in the beam path, putting a cell containing water heated to 90°C, 50 cm below the path. This led to significantly higher sound pressures. Moreover, rapid oscillations (at frequencies of 5–10 Hz) were observed on the oscillograph display. These were related to rapid water vapor concentration fluctuations in the convective updraft from the cell.

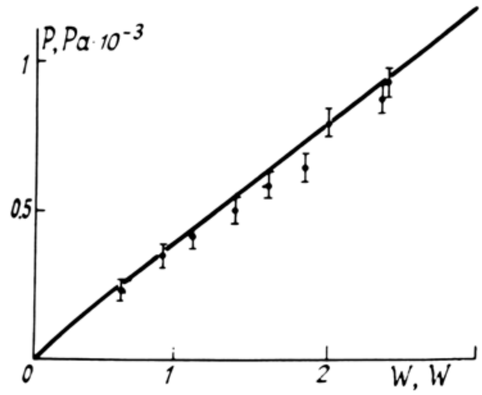

FIG. 5. Dependence of the sound pressure anphtvde P on the radiation power W for R = 1.5 cm.

To summarize: the possibility has been demonstrated of confidently measuring the intensity of sound generated by a 2 W-power CO-laser beam in air, employing standard instrumentation for the noise measurements. This result stimulates hopes of implementing an opto-acoustic technique for measuring rapid in situ variations of the air humidity.

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