# IV. PHYSICAL ACOUSTICS*


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## A. GENERALIZED SOUND MODES IN GASES

We have been investigating the existence of "generalized sound" modes outside of the regime of classical hydrodynamics, for wavelengths shorter than the mean-free path.

In developing a theory to describe nonhydrodynamic behavior, traditional approaches such as implementation of the Boltzmann equation are not valid for values of the wavelength of the order of a molecular diameter because in such short-range probing the nonlocal nature of two-particle collisions is sampled. Our work has involved first, the development of a kinetic equation that is valid for moderately dense gases and for all frequencies and wave numbers, and second, the solution of this kinetic equation for the

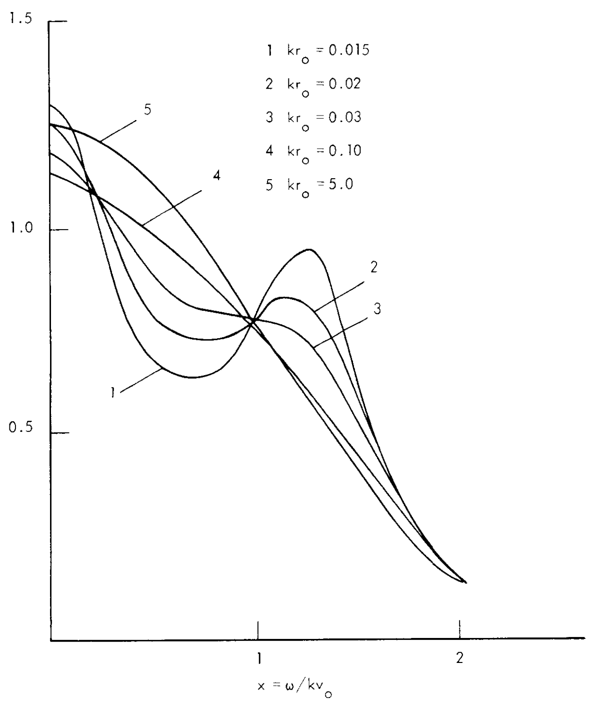


Fig. IV-1.
Normalized response function for a gas. $X = \omega/kV_o$, where $mV_o^2 = KT$, and $nr_o^3 = 0.01$, with m the molecular mass, K Boltzmann's constant, T temperature, $\omega$ frequency, and k wave number.


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special case of a hard-core interparticle potential. A detailed account of this work may be found in the author's thesis and in a recent paper.[1,2]

In this report we merely give examples of computed response spectra such as might be obtained in a scattering experiment. Thus in Fig. IV-1 we have plotted the response spectrum for a moderate density gas for various values of $kr_o$, where $r_o$ is the molecular diameter. We see that the excitation spectrum of the system changes from the

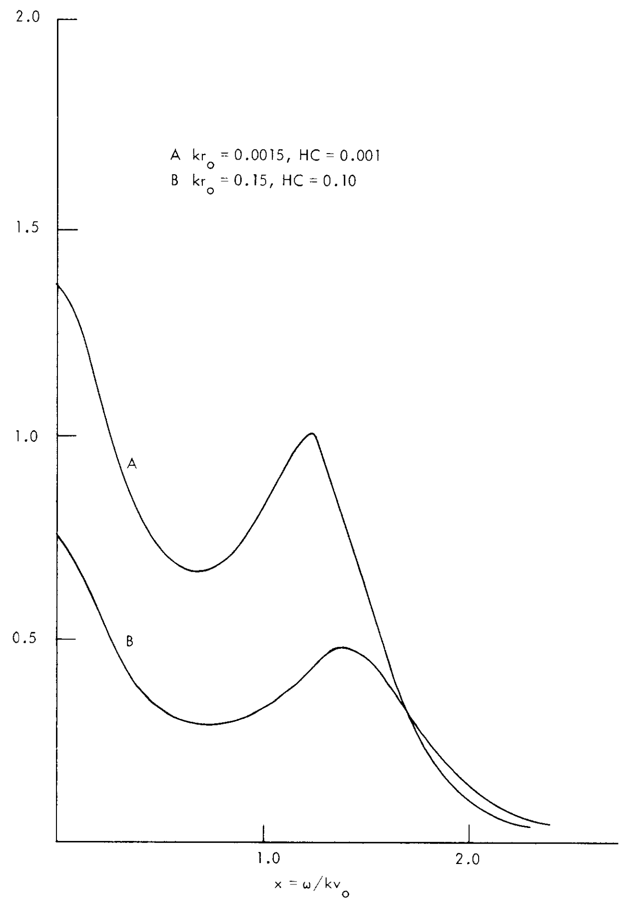


Fig. IV-2. Normalized response function for a gas. $X = \omega/kV_o$, where $mV_o^2 = KT$ and $nr_o^3 = 0.01$, with m the molecular mass, K Boltzmann's constant, T temperature, $\omega$ frequency, and k wave number. Curve A gives the predictions of the Boltzmann equation, whereas curve B gives the predictions of our theory (with $kr_o = 0.15$, $nr_o^3 = 0.10$).

two well-defined hydrodynamic peaks for $kr_o = 0.015$ to a free-particle Gaussian response for $kr_o = 0.10$. For intermediate wave numbers we have strongly damped collective modes. This damping is due to a phase-mixing effect caused by the interaction of collective and free-particle modes. We have found, for densities (n) such that $nr_o^3 = 0.10$ and wave numbers of the order of $kr_o = 0.15$, large deviations from the prediction of the Boltzmann equation (see Fig. IV-2). Our theory predicts more highly damped modes. Our predictions are being tested, at present, in a series of neutron scattering experiments.

G. F. Mazenko

References

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## B. ACOUSTICAL PROPERTIES OF LANTHANUM FLINT GLASS

We are, at present, investigating the acoustical and acousto-optical properties of lanthanum flint glass, using Bragg diffraction of light. The objective of this study is to determine the effect on the acoustical properties of introducing heavy dopants into glass. We are also interested in determining the possibility of utilizing this high-refractive-index glass in acousto-optic modulators.

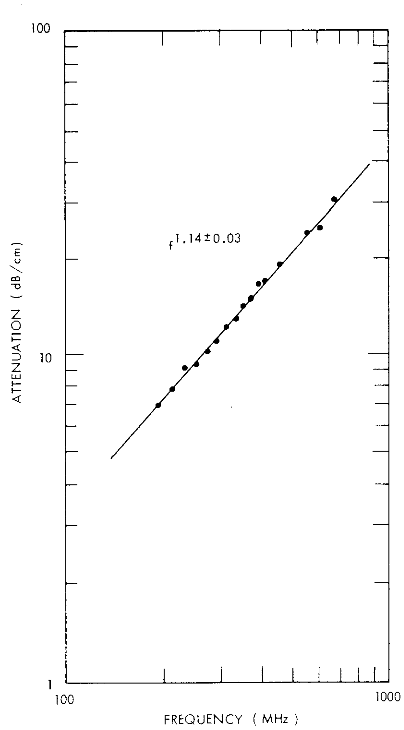


Fig. IV-3.

Ultrasonic attenuation as a function of frequency for longitudinal waves in B + L No. 867310 lanthanum flint at 25° C.

Measurements of the longitudinal-wave ultrasonic attenuation and velocity were made on a sample of Bausch and Lomb No. 867310 lanthanum flint. This glass has a density of 5.30 $gm/cm^3$ and a refractive index of 1.867 for the sodium D line.[1] The sample was a rectangular parallelepiped, $5 \times 2.5 \times 1$ cm, with 4 edges optically polished flat to 1/10 wave, and opposite surfaces parallel within 10 seconds of arc.

The longitudinal-wave pulses were excited by a bonded X-cut quartz transducer, of 10.1 MHz nominal fundamental-resonance frequency, driven at odd harmonics. The experimental apparatus and technique have been described, in detail, elsewhere.[2]

The longitudinal-wave velocity was measured at various frequencies in the range 190-920 MHz. We found that $v_\ell = (5.477 \pm 0.007) \times 10^5$ cm/s at 25°C, where the error brackets correspond to the $\pm 1\sigma$ points for our data.

Figure IV-3 shows the longitudinal wave attenuation as a function of frequency over the range 190-680 MHz. The observed frequency dependence $A(dB/cm) \sim f^{1.14}$ indicates that, in this frequency range, the dominant attenuation mechanism is neither a structural relaxation nor the interaction with thermal phonons, since both those processes give a square-law frequency dependence. We are now extending the range of measurements at both higher and lower frequencies, in order to obtain further information about the loss process.

C. Krischer, Jacqueline F. Whitney

References

1. "Optical Glass," Bausch and Lomb, Rochester, New York.

2. C. Krischer, "Optical Measurements of Ultrasonic Attenuation and Reflection Losses in Fused Silica," J. Acoust. Soc. Am. 48, 1086-1092 (1970); C. Krischer, "Measurement of Sound Velocities in Crystals Using Bragg Diffraction of Light and Applications to Lanthanum Fluoride," Appl. Phys. Letters 13, 310-311 (1968).

## C. FREQUENCY MIXING OF SOUND IN A NONLINEAR ORIFICE

Experimental data on nonlinear distortion of a pure sound tone when transmitted through a sharp-edged orifice have already been reported.[1]

In this work the spectrum of the transmitted wave is obtained when the incident wave is the superposition of two tones. A simple theoretical analysis will be used to predict the spectrum.

### 1. Experimental Arrangement

A simple diagram of the experimental arrangement is shown in Fig. IV-4. A high-impedance piston P is fitted to the left end of a cylindrical tube, 1 3/8 in. in diameter. The diaphragm D is 0.015 in. thick and has an orifice, 1/8 in. in diameter. The velocity

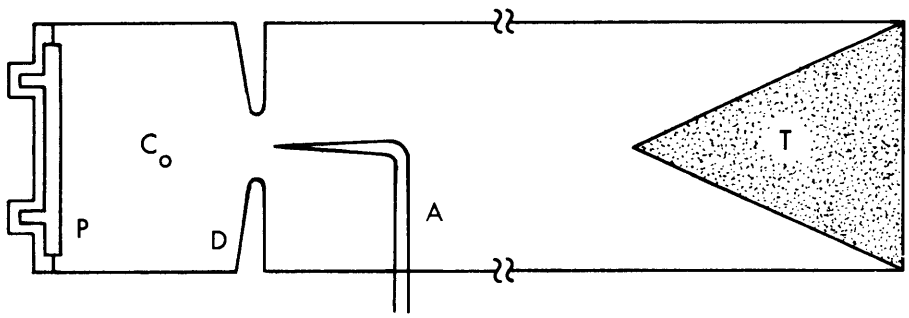


Fig. IV-4. Experimental arrangement. P = high-impedance piston, D = diaphragm with concentric orifice, A = hot-wire anemometer, T = $\rho c$ termination, and $C_o$ = driver cavity.

in the plane of the orifice is measured by the hot-wire anemometer A, and there is a $\rho c$ termination at the right end.

If $p_2$ and $p_3$ are the pressures at the left and the right of the orifice, then the velocity u at the orifice is in general given by

$$\Delta p \equiv p_2 - p_3 = \frac{\rho}{2C_1^2} |u| u + \rho c \theta \frac{A_o}{A_1} u + \rho t_m \frac{du}{dt} \tag{1}$$

where $\rho$ is the density of the air, c is the speed of sound, $C_1$ is the orifice coefficient, $A_o$ and $A_1$ are the cross sections of the orifice and the duct, respectively, $\theta$ is a friction coefficient that may be expressed in terms of the orifice geometry and the viscosity coefficient, and $t_m$ is the effective orifice thickness.

The pressure $p_3$ represents approximately an outgoing wave given by

$$p_3 \approx \rho c \frac{A_o}{A_2} u, \tag{2}$$

so that (1) may be written

$$p_2 = \frac{\rho}{2C_1^2} |u| u + \rho c \frac{A_o}{A_1} (1+\theta) u + \rho t_m \frac{du}{dt}. \tag{3}$$

The level $L_p$ of a sinusoidal wave p cos $\omega t$ is defined as

$$L_p = 20 \log \left(\frac{p}{p_u}\right), \tag{4}$$

where $p_u = 0.0002$ dyn/cm$^2$, and $L_p$ is measured in decibels.

In the low-pressure level regime ($L_p < 130$ dB) the nonlinear term of (3) may be omitted, and the orifice behaves as a linear RL circuit where the dissipative terms are $\rho c A_o u/A_1$ and $\rho c A_o \theta u/A_1$, that is, a friction and radiation term. The inertial term merely introduces a phase shift between the driving force $p_2$ and the response u of the system.

In the high-pressure level and low-frequency regime separation of flow appears in the vicinity of the orifice, and the nonlinear term is much larger than both linear terms which, consequently, are omitted.

Finally, in the high-pressure levels and high-frequency regime the inertial term is no longer negligible (being roughly proportional to the frequency of the incident wave) so both the nonlinear and the inertial terms must be included in the analysis. In this region, however, even the complete form of (3) is only an approximation to the actual behavior of the system.

2. Calculation of the Transmitted Spectrum

The flow velocity at the orifice is calculated by assuming that the process is described by the high-pressure level and low-frequency model outlined above,

$$p_2 = \frac{\rho}{2C_1^2} |u| u. \tag{5}$$

If

$$p_2 = p_o (\cos (x+A) + \cos (8x+B)) \equiv p_o f(x), \tag{6}$$

where $x = \omega t$, $\omega = 2\pi\nu$, $\nu = 250$ Hz, and A, B are arbitrary phase angles, then

$$u(x) = C_1\sqrt{\frac{2p_o}{\rho}} \begin{pmatrix} +\sqrt{f(x)} \\ -\sqrt{-f(x)} \end{pmatrix} \qquad \text{for } f(x) = \begin{pmatrix} +1 \\ -1 \end{pmatrix} |f(x)|. \tag{7}$$

If U(x) is defined by

$$U(x) = \frac{u(x)}{C_1\sqrt{\frac{2p_o}{\rho}}} = \pm\sqrt{\pm f(x)} \qquad \text{for } f(x) = \pm|f(x)|, \tag{8}$$

then U(x) may be expressed as a Fourier series

$$U(x) = \sum_{N=1}^{\infty} (C(N) \cos Nx + S(N) \sin Nx), \tag{9}$$

where the coefficients are given by

$$\begin{pmatrix} C(N) \\ S(N) \end{pmatrix} = \frac{1}{\pi} \int_{x=0}^{2\pi} U(x) \begin{pmatrix} \cos Nx \\ \sin Nx \end{pmatrix} dx. \tag{10}$$

The integrals of (10) are carried out on a computer. The predicted spectrum was obtained for different values of the phase angles, A, B. It was observed that C(N)

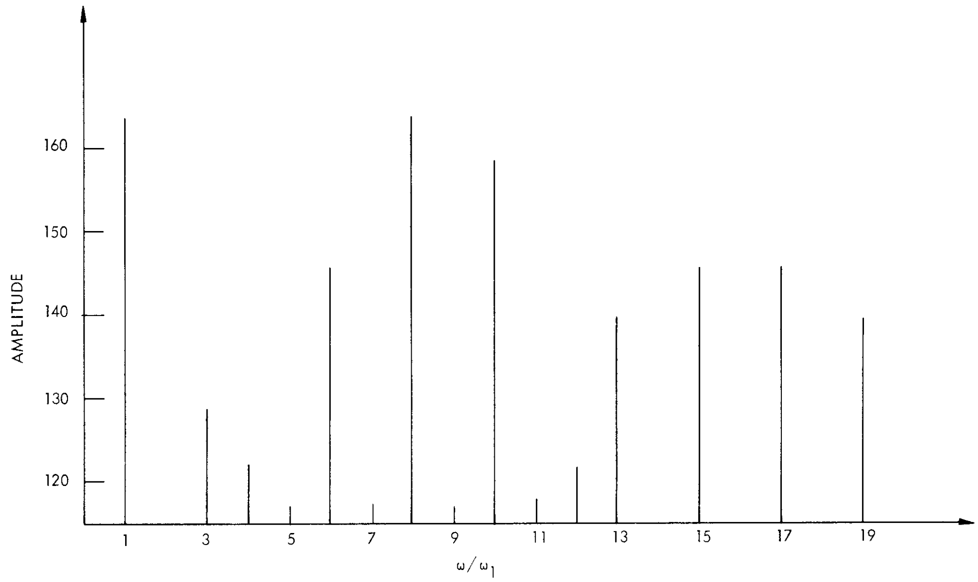


Fig. IV-5. Spectrum of transmitted sound through an orifice upon which two sound waves of frequencies $\omega_1$ and $\omega_2 = 8\omega_2$ are incident.

and S(N) are sensitive to phase changes while the total amplitude AM(N) of a particular harmonic,

$$AM(N) = [C(N)^2 + S(N)^2]^{1/2}, \tag{11}$$

was virtually independent, except for N = 2, 7, 9, 14, 16, 18 which exhibit 10% maximum variation of the total pressure level.

The transmitted spectrum for $A = 4\pi/5$ and $B = \pi/20$ rad is shown in Fig. IV-5.

A. G. Galaitsis, U. Ingard

References

1. U. Ingard, J. Acoust Soc. Am. 48, 32-33 (1970).