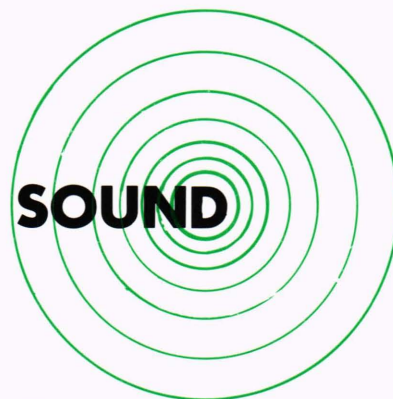


RADIATION-PRODUCED SOUND



By combining the principles of acoustic resonance and relaxation of internal degrees of freedom of gas molecules, a sensitive converter of radiation to sound has evolved. Radiant energy absorbed in vibrational or rotational modes is very rapidly converted to translational energy. The accompanying pressure rise, augmented by acoustic resonance, generates a sound field easily detected by a condenser microphone. This article discusses the theory of operation, provides a quantitative comparison of theory and experiment, and estimates the increase in sensitivity achievable by future improvements.

Many years ago Alexander Graham Bell^{1,2} observed that sound could be produced when a gas sample was exposed to an interrupted light beam. Inspired by his observations, he went on to build a device which would be used to study the relative amplitude of sound produced by spectrally resolved light. This device was appropriately named the spectrophone.

The operation of the spectrophone requires the use of a radiation-absorbing gas to convert radiant energy into heat, or kinetic energy, of the gas molecules. Basically, this conversion is a two-stage process, in which the incident radiation first excites certain vibrational or rotational modes of the molecules and then the energy stored in these modes is transferred to translation by collisions. In

general the conversion of rotational energy to translational energy is a very rapid process requiring fewer than 10 collisions; however, conversion of vibration to translation can be much slower, requiring in some cases as many as 10^6 collisions. Thus heating of the gas due to the conversion of vibrational energy involves a time lag depending on the characteristics of the particular molecule involved and the mean time between collisions. This fact has made the spectrophone a useful tool for the study of vibrational energy transfer in gases.^{3,4,5} Further applications have been found

³ P. V. Slobodskaya, "Determination of the Transition Rate of Molecular Rotational Energy into Translational Motion Energy with the Aid of a Spectrophone," *Izvest. Akad. Nauk. S.S.S.R. (Ser. Fiz.)*, **12**, 1948, 656.

⁴ W. E. Woodmausee and J.C. Decius, "Vibrational Relaxation in Carbon Monoxide by the Spectrophone Frequency-Response Method," *J. Chem. Phys.*, **36**, 1962, 1831.

⁵ M. G. Ferguson and A. W. Read, "Vibrational Relaxation of Carbon Monoxide at Room Temperature," *Trans. Faraday Soc.*, **61**, 1965, 1559.

¹ A. G. Bell, "On the Production and Reproduction of Sound by Light," *Proc. Am. Assoc. Sci.*, **29**, 1880, 115.

² A. G. Bell, "Upon the Production of Sound by Radiant Energy," *Phil. Mag.*, **11**, 1881, 510.

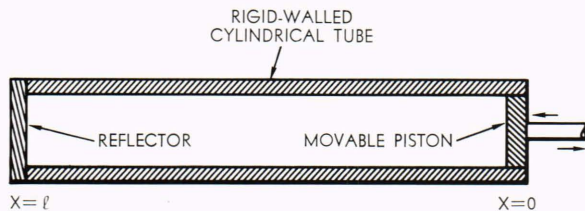


Fig. 1—Basic acoustic resonance tube.

in the construction of a gas analyzer⁶ and also in the field of radiation detection as evidenced by the “selective” Golay detector.⁷

Interest at the Applied Physics Laboratory in the study of radiation-produced sound has arisen from gas dynamic investigations in which the acoustic resonance tube is used. Schematically this tube appears as shown in Fig. 1. Essentially the device consists of a gas-filled cylindrical tube with a piston-type driver as a source at one end and a reflector plate containing a condenser microphone at the other end. As the frequency of the driver is changed, various resonances of the gas column occur. The condition that a resonance occur is that the phase of the reflected wave upon returning to the driver end be equal to that of the wave initiated at the driver. Mathematically, this condition is expressed as

$$f_n = \frac{nc}{2\ell}; \quad n = 1, 2, \dots \quad (1)$$

where f_n is the frequency corresponding to the n th mode, c is the velocity of sound in the gas and ℓ is the length of the tube. Variation of the sound pressure P_n at the reflector in the neighborhood of the n th resonance is given by⁸

$$P_n = \frac{\rho_0 c U}{\sigma \ell} \left\{ 1 + \left[\frac{2\pi}{\sigma c} (f - f_n) \right]^2 \right\}^{-\frac{1}{2}} \quad (2)$$

providing $\sigma \ell \ll 1$. Here ρ_0 is the gas density, U the velocity amplitude of the piston, and σ the amplitude absorption coefficient of the gas. A plot of P_n versus frequency, f , results in a bell-shaped curve disposed symmetrically about the resonance frequency, f_n , and the width of this curve varies directly with σ . The magnitude of

σ depends on the losses experienced by the sound waves as they travel down the tube. Primarily these losses arise from the viscous drag exerted on the wave by the tube walls and also from heat losses to the walls of the tube. Quantitatively, the wall losses σ_w may be expressed,

$$\sigma_w = \frac{K}{a} \sqrt{\frac{f}{P_0}} \quad (3)$$

where K is determined from thermodynamic gas properties involving temperature alone, a is the tube radius, and P_0 is the gas pressure.

In the case of an infinitely long tube, end reflections are absent and the magnitude of sound pressure generated by the moving piston is $\rho_0 c U$, assuming no dissipation. It is to be noticed from Eq. (2) that the expression for P_n at resonance may be written

$$P_n \text{ (resonance)} = \frac{2\rho_0 c U Q}{\pi n} \quad (4)$$

where

$$Q = \frac{\pi n}{2\sigma \ell} = \frac{\pi n a}{2K\ell} \sqrt{\frac{P_0}{f}}, \quad (5)$$

is the so-called Q -factor of the tube. This Q -factor provides a measure of the ability of the resonance tube to intensify the sound pressure wave generated by the moving piston. From Eq. (5) it is clear that the magnitude of Q is determined by the product $\sigma \ell$, which in turn is governed by the losses within the tube. Thus the acoustic resonance tube may be thought of as a device that may be used to intensify a signal of given sound pressure level to a higher level, whose amplification factor is significantly affected by tube geometry and the state of the gas contained in the tube.

To provide a feeling for values of Q realizable in a practical system, we might consider the case of a tube of 1 cm radius filled with 1 atmosphere of CO_2 at 300°K and operating in its fundamental mode at 1000 cps, i.e., $\ell = 13.4$ cm. For these conditions, $K = 2.54 \times 10^{-2}$, $\sigma = 8.02 \times 10^{-4}$, and thus $\sigma \ell = 1.08 \times 10^{-2}$, corresponding to $Q \simeq 150$.

Radiation-Driven Resonance Tube

The function of the piston-driver shown in Fig. 1 is to bring about a pressure increase by displacing the gas in the neighborhood of $x = 0$. The pressure amplitude of the sound wave generated in this process is $\rho_0 c U$, so that the magnitude of this pressure depends on the rate of this displacement

⁶ H. Luft, “Concerning a New Method of Performing Gas Analysis using Absorption of Infrared Rays without Spectral Decomposition,” *Z. tech. Physik*, **24**, 1943, 97.

⁷ A. Hadni, “Possibilités Actuelles de Détection du Rayonnement Infrarouge,” *J. de Physique*, **24**, 1963, 694.

⁸ J. G. Parker, “Effect of Several Light Molecules on the Vibrational Relaxation Time of Oxygen,” *J. Chem. Phys.*, **34**, 1961, 34.

and involves a compression of the gas. Generation of sound by radiation absorption, however, involves heating of the gas and can occur with no movement of the gas. Modification of the acoustic resonance tube to permit radiation driving is illustrated in Fig. 2. Here the piston source has been replaced by a rock salt window, transparent to the incident radiation, and a chopper system that permits pulsing the radiation at the desired frequency. The detection system, including the condenser microphone, is essentially unchanged.

Application of thermodynamics to this problem gives for the amplitude of the sound wave generated in an infinitely long tube,

$$P = \frac{(\gamma - 1) I_0}{c} \left(\frac{\alpha^2}{k^2 + \alpha^2} \right). \quad (6)$$

Previously undefined quantities are γ , the ratio of specific heats; I_0 , the Fourier component of the absorbed incident intensity corresponding to frequency f ; α , the radiation absorption coefficient of the gas; and $k = 2\pi f/c$. It is important to emphasize that the radiation intensity I_0 appearing in Eq. (6) is the net radiation absorbed by the gas from an external source. In determining the radiation output of a given source it is therefore necessary to subtract from the absolute radiation intensity at any given temperature the value corresponding to ambient temperature. From Eq. (6) it is clear that the most favorable condition for the generation of sound by radiation absorption occurs when $\alpha \gg k$, or, alternatively,

$$f \ll \frac{c\alpha}{2\pi}. \quad (7)$$

For a gas such as CO_2 , α is of the order of 1 cm^{-1} for the strongly absorbing ν_2 bending mode (15 microns) at a pressure of 1 atmosphere. Thus,

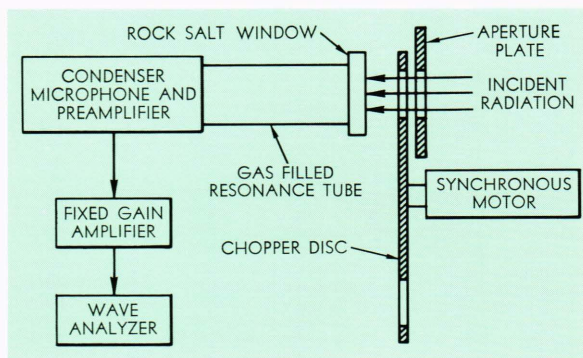


Fig. 2—Schematic representation of radiation-driven acoustic resonance tube. Rock salt window and chopper assembly replace piston shown in Fig. 1.

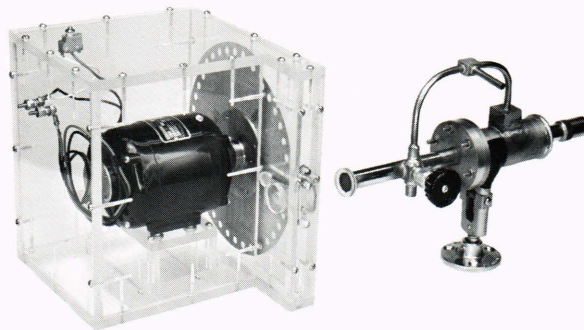


Fig. 3—System used in experiments. Three-inch bolted flange contains 5/8-inch-diameter condenser microphone and joins preamplifier housing to resonance tube.

since $c \simeq 2.5 \times 10^4 \text{ cm/sec}$, we obtain

$$f \ll 4 \times 10^3 \text{ cps.}$$

However, since α increases with increasing pressure, this limiting frequency may be increased simply by raising the gas pressure.

For sound generation by radiation absorption at sufficiently low frequencies that inequality (7) is satisfied, we have then from Eq. (6), for an infinitely long tube

$$P = \frac{(\gamma - 1) I_0}{c}. \quad (8)$$

Considerable amplification of this signal may be obtained at resonance in a tube with closed ends such as that indicated in Fig. 2.

To investigate more fully the coupling of radiation and sound and also the effects of resonance amplification, an experimental resonance tube and chopper assembly was constructed in accordance with the system illustrated schematically in Fig. 2. This apparatus is shown in Fig. 3. The resonance tube was a brass cylinder, with a 0.686 cm inner radius and 12.7 cm long. A 0.2-inch-thick rock salt window was waxed on one end of the tube and an Altec type 21D condenser microphone was used to close the other end. To equalize pressure on both sides of the fragile glass diaphragm of the condenser microphone during evacuation and filling of the tube, it was necessary to enclose the microphone preamplifier in a housing that could be pumped out and filled by an inlet pipe paralleling the line feeding the resonance tube itself. To reduce airborne sound generated by the siren-like action of the chopping disc, the whole chopper assembly was enclosed in a Plexiglas box. Two 0.2-inch rock salt crystals permitted radiation to pass into the box, through the aperture and chopping disc, and finally exit from the box. Variation of the chopper frequency was accom-

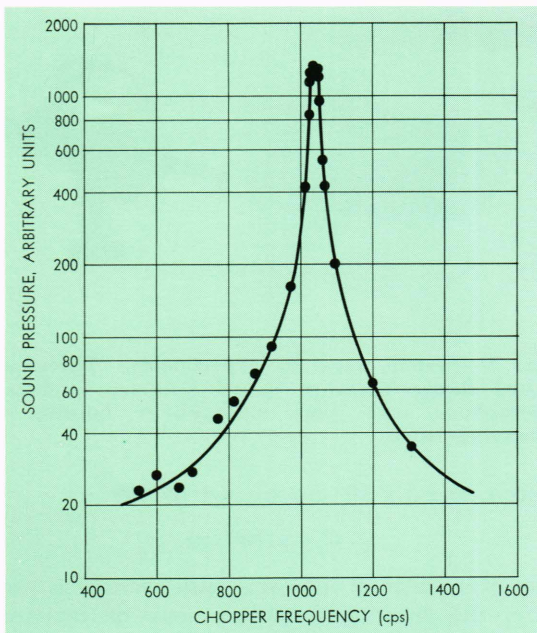


Fig. 4—Experimental data for acoustic resonance tube sound pressure level as a function of chopped radiation frequency in the vicinity of the fundamental resonance.

plished by varying the frequency of the input to the synchronous motor. A light source and photo-cell combination was used to provide output pulses at the chopping frequency which were fed into a counter and displayed as frequency.

Figure 4 shows a plot of the sound pressure versus chopping frequency with the tube filled with 1 atmosphere of CO₂. The resonant frequency was 1045 cps and the overall *Q* of the system turned out to be approximately 70.

To examine the effect of changing radiation level on sound pressure produced and also to check the accuracy of Eq. (6), an experiment was conducted in which a black-body source held at a constant temperature was moved steadily away from the entrance to the resonance tube. The separation of source and tube was sufficiently large in all cases that the point-source approximation could be used with negligible error. The chopping frequency was held constant at 1045 cps, the fundamental resonance frequency of the tube. For this frequency, the conditions leading to Eq. (8) are well satisfied so that the measured sound pressure should vary directly with the incident radiation intensity.

Since this radiation may be considered as emanating from a point source, this means that the sound pressure generated should vary inversely

as the square of the distance *d* from the source to the resonance tube entrance, that is,

$$P = \frac{C}{d^2}.$$

Figure 5 shows a plot of $(P)^{-1/2}$ versus *d* and quite clearly demonstrates the validity of this assumed functional dependence. Numerically, *C* = 0.180, so that

$$P(\text{experimental}) = 0.180/d^2 \text{ dynes/cm}^2. \quad (9)$$

Next we must determine from Eq. (8) the expected sound pressure level. The source temperature was 380°K, the ambient temperature was 296°K, and the aperture was 0.478 cm in diameter. Using the fact that for a pressure of 1 atmosphere the bandwidth of the 15-micron absorption in CO₂ is approximately⁹ 1 micron, we calculate

$$I_o = \frac{1.37 \times 10^{-4}}{d^2} \text{ watts/cm}^2,$$

with *d* in cm. Two factors must be considered which have the effect of reducing *I*_o. The first is that radiation from the source must travel through three rock salt windows, which causes a 50% loss in intensity, and the second is that the pulses of radiation are essentially triangular in form which introduces a factor of $4/\pi^2$. Taking both of these into account gives

$$I_o = \frac{2.78 \times 10^{-5}}{d^2} \text{ watts/cm}^2. \quad (10)$$

Substitution of the appropriate values of γ and *c* into Eq. (8) and using Eq. (10) gives

⁹ D. E. Burch, D. A. Gryvnak, and D. Williams, "Total Absorption of Carbon Dioxide in the Infrared," *Appl. Optics*, **1**, 1962, 759.

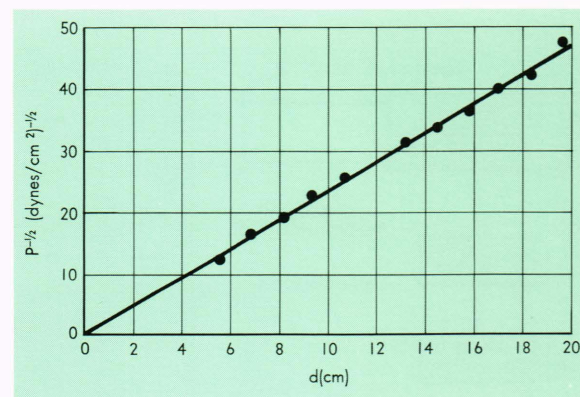


Fig. 5—Plot of sound pressure versus separation of source and resonance tube. Verifies point source assumption used in calculating *I*_o.

$$P \text{ (theoretical)} = \frac{2.80 \times 10^{-3}}{d^2} \text{ dynes/cm}^2. \quad (11)$$

Finally, to account for the increase in sound pressure due to resonance one must multiply by the Q of the tube. From the data presented in Fig. 4, we have $Q = 70$ and thus

$$P \text{ (theoretical)} = \frac{0.125}{d^2} \text{ dynes/cm}^2. \quad (12)$$

which is in reasonable agreement with Eq. (9).

On the basis of the foregoing, it would seem reasonable to accept the validity of Eqs. (6) and (8) and to assume that one may accurately predict the behavior of systems using other gases and possibly resonators of different types than the one considered here.

Future Design Considerations

It is of interest to examine the effect of changing various parameters on the sound pressure amplitude produced at resonance. Thus from Eq. (8), we have for the fundamental resonance

$$\begin{aligned} P \text{ (resonance)} &= \frac{2(\gamma - 1)}{\pi c} I_o Q \\ &= \frac{2(\gamma - 1) I_o a}{c^2 K} \sqrt{f_o P_o} \end{aligned} \quad (13)$$

using Eq. (5). For a given gas, it is therefore clear that large values of P (resonance) are favored by high frequencies and pressures. It is interesting to note from inequality (7), that to make the device workable at high frequencies, high pressures are required, therefore indicating that an important quantity to be considered is gas pressure. If it is desirable to operate the device at high gas pressures, then it is also desirable to make the tube as small as possible, suggesting that a should be small. However, it is clear from Eq. (13) that this tends to diminish P (resonance) if I_o is held constant. If, instead of taking I_o to be constant, it is assumed that the total power, W , of the incident beam is fixed and some means of focusing is used, then

$$I_o = \frac{W}{\pi a^2}$$

and

$$I_o a = \frac{W}{\pi a}$$

which increases as a decreases. Thus, if the problem involves the generation of P (resonance) with fixed total radiation power, the maximum signal

will be generated for the tube of small ℓ and a with high operating gas pressure. It is possible, therefore, to construct a small device with high sensitivity.

In obtaining the data shown in Fig. 4, a Q of 70 or so was obtained with $P_o = 1$ atmosphere. If P_o were increased to 10 atmospheres and f_o to 10,000 cps, the value of Q would be increased to 700 and P (resonance) would increase tenfold.

As regards the ultimate sensitivity of the radiation-driven acoustic resonance tube, several factors must be considered. First, is the sensitivity of the condenser microphone and the noise level against which it must perform; secondly, the high acoustic Q of the gas column, making the device susceptible to pickup of airborne noise of external origin; and thirdly, Brownian motion of the gas molecules.

The device pictured in Fig. 3 was constructed using a commercially available condenser microphone, which, although being one of the more sensitive types, does not represent the ultimate sensitivity attainable. In spite of this and the fact that a rather modest acoustic Q was achieved, the device was sufficiently sensitive to produce a signal which exceeded the background level by a factor of three when exposed to radiation from the human hand. It is believed that an order of magnitude improvement is attainable by redesigning the microphone system. This, when coupled with another factor of 10 from an improved acoustic Q , would produce a device of sufficient sensitivity to warrant consideration as a useful radiation detector.

The experiment described in the preceding section relies on the absorption of radiant energy by the vibrational degrees of freedom of the CO_2 molecule. Methane and ethylene have also been used with equally good results and in general it is possible to use any polyatomic gas having sufficiently strong absorption in one or more vibrational modes. However, as was mentioned at the outset, either vibrational or rotational transitions can absorb radiant energy. Thus, whereas vibrational absorption would utilize the region of wavelengths from roughly 1 to 20 microns, the rotational modes of molecules such as water vapor, ammonia and others would allow the conversion of far longer wavelength radiation to sound, perhaps reaching to 1000 microns or more.

The conversion of radiant energy to sound energy by this system then, is not limited to the experiments performed so far. The system is quite flexible and could probably be applied even to liquids and solids. Different sensors and configurations would be required but the basic physics of the conversion process using acoustic resonance would remain unchanged.