Ultrasonic Transducers for Use in Air

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HINGHAM, MASS.

Reprinted from the PROCEEDINGS OF THE IEEE
VOL. 53, NO. 10, OCTOBER, 1965
pp. 1363-1371

PRINTED IN THE U.S.A.

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***Abstract*—Fewer applications were found for the use of ultrasonics in air than for ultrasonics in liquids or solids. This was primarily because of the inherent limitations of generating high-intensity sound levels in a gaseous medium, and also because of the extremely high attenuation that accompanies in the propagation of ultrasonic energy through air. Several types of transducers are described for the generation and reception of ultrasonic sound in air. Data are presented in the form of engineering design charts which include several quantitative relationships between piston displacements, acoustic power, sound pressure level, beam patterns, attenuation, and additional fundamental information for use in the design of ultrasonic equipment to achieve the transmission of high-frequency sound over a specified range. Due to the natural limitations in the transmission of ultrasonics in air over large distances, the major applications have been in remote control systems, proximity indicators, automatic counting, burglar- and fire-protection systems, and short-range carrier telephony.**

INTRODUCTION

IT IS COMPARATIVELY simple to generate high-intensity ultrasonic sound levels under water; it is equally simple to transmit these sounds over ranges of several miles. This accounts for numerous developments in the utilization of underwater sound for many applications. The relative ease in generating high-intensity sound energy under water is primarily due to the high acoustic impedance of the liquid, which requires relatively small amplitudes of vibration in the medium for the production of high acoustic power levels. The attenuation of ultrasonic sound in water is very much less than the attenuation of sound of the same frequency in air, which makes it feasible to transmit high-intensity underwater sound over very large distances.

The generation of high-intensity sound fields in air is greatly limited because of the relatively low acoustic impedance of the medium which requires relatively large amplitudes of vibration. There are practical limits in the maximum amplitudes of vibration, however, which may be generated by ultrasonic transducers. Two of the most important limitations are imposed: first, by the maximum stress that may be safely permitted in the vibrating element without reaching fatigue failure; and second, by the harmonic distortion which is generated in the air when the peak acoustic pressure is an appreciable fraction of atmospheric pressure. Before discussing several types of ultrasonic transducers which are suitable for use in air, some fundamental design data will be presented to give the reader a quantitative understanding of the various relationships between some of the basic parameters that govern the generation and transmission of ultrasonic sound in air.

DESIGN DATA

Some useful fundamental data will be presented in this section to give the reader some quantitative relationships between piston displacements, frequency, acoustic power, sound pressure level, beam patterns, attenuation, and other basic information to permit the theoretical analysis of a transducer design for generating ultrasonic power of a specified intensity.

Acoustic Power vs. Piston Displacement and Frequency

If a plane surface is set into vibration with uniform phase and amplitude over its entire area such as obtains for a true piston, the radiation resistance of the air against which the piston is vibrating becomes constant for the frequency region in which the piston diameter is greater than $\frac{1}{3}$ wavelength of the sound. In the cgs system, the magnitude of this impedance for normal atmospheric conditions is approximately equal to 42 acoustic ohms per square centimeter of piston area. The acoustic power generated by a vibrating piston under such conditions [1] is given by

$$P_A = \frac{42\omega^2 d^2 A \times 10^{-7}}{2} \text{ watts} \tag{1}$$

where

$\omega = 2\pi f$
f = frequency in c/s
d = peak displacement of piston in cm
A = area of piston in cm^2.

Figure 1 is a design chart derived from (1) showing the relationship between the peak displacement of a vibrating surface and the acoustic power radiated from the surface at various frequencies. It can be seen that for a peak displacement of 0.001 inch, only a few watts per square inch can be generated at the lower ultrasonic frequencies.

Acoustic Power vs. Sound Pressure

Figure 2 shows the sound pressure at a distance of one foot from an acoustic source. This sound pressure is expressed in microbars as a function of the acoustic power in watts being radiated by the source. The chart (Fig. 2) assumes that the source is radiating uniformly into hemispherical space, and neglects attenuation due to viscosity loss in the air.

Manuscript received June 10, 1965.

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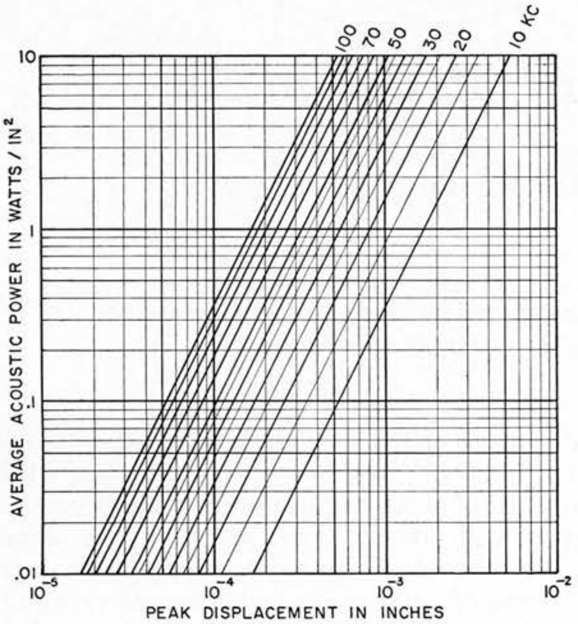

Fig. 1. Relationship between peak displacement of a vibrating surface and the acoustic power generated at various frequencies. (Surface diameter is greater than ⅓ wavelength.)

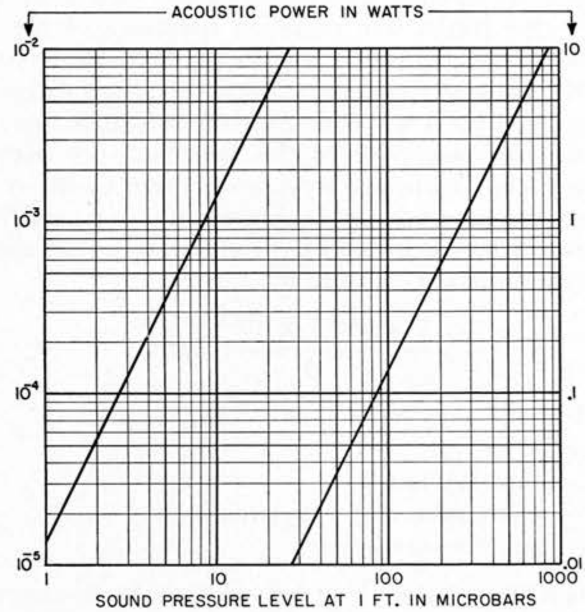

Fig. 2. Sound-pressure level at one foot vs. acoustic power output from an omnidirectional source radiating into hemispherical space.

Increase in Sound Pressure Along Normal Axis of a Large Piston

For the condition in which the vibrating source is a circular piston whose diameter is large compared with the wavelength of sound being generated, the radiation of sound will be confined within a small conical beam which will result in a relative increase in sound-pressure level along the normal axis of the vibrating piston. Figure 3 shows the magnitude of the increase in the axial sound pressure which results from the concentration of the sound as a function of the ratio of the diameter of the piston over the wavelength of sound being radiated.

Beam Pattern vs. Piston Diameter

Figure 4 presents a family of curves which may be used for determining the shape of the main beam into which the sound from a large vibrating piston is confined. The four curves show beam angles at which response is down 3, 6, 10, and 20 dB as a function of piston diameter over wavelength of sound being radiated.

Attenuation of Ultrasonic Sound in Air

The transmission of ultrasonic frequencies in air is greatly limited by the relatively high attenuation that results from the viscosity loss caused by the molecular vibrations. Knudsen [2] investigated the absorption of sound in air and he found that the absorption increases in the presence of water vapor in the air and becomes greater than the Stokes [3] classical absorption which applies for dry air. The maximum attenuation, as reported by Knudsen, occurs in the region of approximately 20 percent relative humidity. Sivian [4] conducted additional experimental investigations on the absorption of high frequency sounds in the atmosphere and his reported data are shown by curve *A* in Fig. 5. Curve *A* represents the experimental absorption as a function of frequency for average atmospheric conditions corresponding to 75°F and 37 percent relative humidity at normal atmospheric pressure. Curve *B* is the attenuation computed from the Stokes classical theory. The dry-air attenuation data, as measured by Sivian, were found to be approximately 50 percent higher than the values indicated by curve *B*.

Acoustic Power Output of Nonpiston Sources

For nonpiston-type sound sources, such as modulated air-flow loudspeakers or sirens, the acoustic power generated by the source [5] is given by

$$P_A = \frac{42U^2 \times 10^{-7}}{2A} \text{ watts} \tag{2}$$

where

U = peak volume velocity of air through port opening in cm³/s.
$U = 2\pi f X$
X = peak volume displacement though opening in cm³
f = frequency in c/s
A = area of opening in cm².

On first inspection, it may appear that (2) is not correct, since it states that for a fixed volume velocity of air flowing through an opening, the acoustic power increases as the opening is made smaller. This is exactly as it should be because, as the area of the opening decreases, the velocity of the fluid flowing through the opening increases in inverse proportion. Since the acoustic power

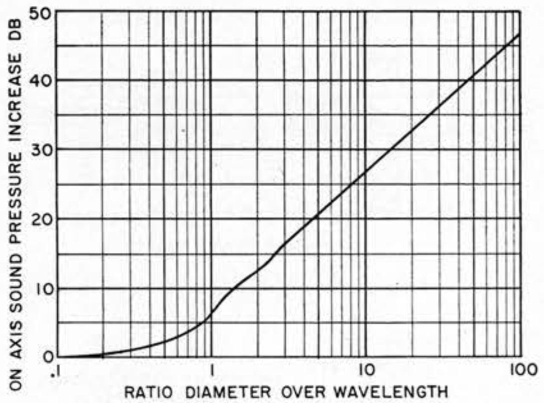

Fig. 3. Increase in sound-pressure level along the normal axis of a piston generating constant acoustic power as a function of the ratio of piston diameter to wavelength of sound.

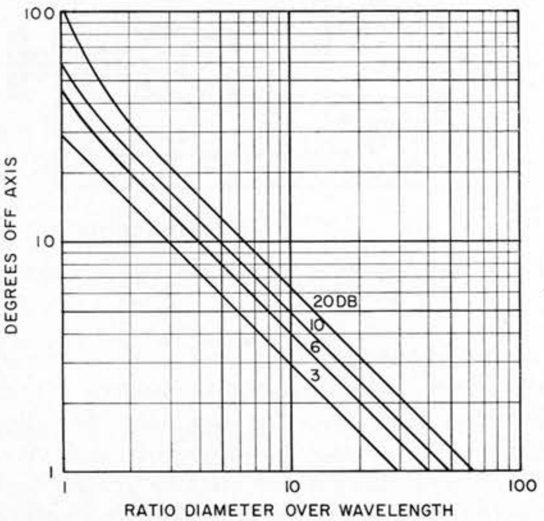

Fig. 4. Directional radiation pattern from a vibrating circular piston showing the degrees off the normal axis at which the attenuation is 3, 6, 10, and 20 dB as a function of piston diameter over wavelength.

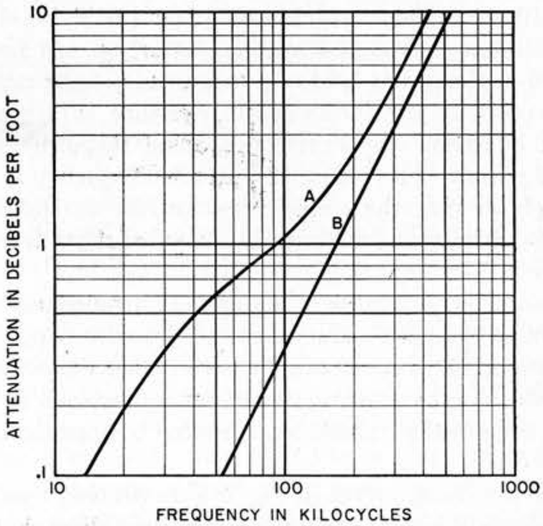

Fig. 5. Absorption of sound in air as a function of frequency. Curve *A* is the average of experimental data for average atmospheric conditions 75°F and 37 percent relative humidity. Curve *B* is the theoretical attenuation for dry air from classical theory.

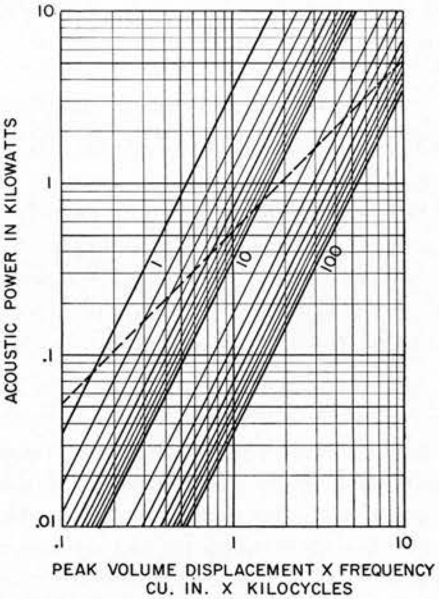

Fig. 6. Relationship between peak volume displacement, frequency, and acoustic power output for modulated air-flow transducers. Area of port opening in square inches is indicated on curves. Dotted line represents upper limit of acoustic power at which peak sound pressure near source becomes equal to 1/10 atmosphere.

radiated per unit area is proportional to the square of the fluid velocity, the relationship in (2) will follow.

There are two limitations, however, that prevent one from simply reducing, without limit, the port opening of a modulated air-flow transducer to increase the power generated for a constant fluid displacement. The discharge opening must have linear dimensions that do not become smaller than approximately $\frac{1}{3}$ wavelength of the sound being generated so that the radiation resistance per unit area of the opening remains constant. Also, as the area is reduced and the acoustic power density increases with a corresponding increase in sound pressure, it is necessary that the maximum sound pressure generated remain a small percentage of the atmospheric pressure; otherwise distortion will be introduced because of nonlinearity in the medium.

Thuras, Jenkins, and O'Neil [6] investigated the generation of extraneous harmonic frequencies in air due to the presence of intense sound waves, and found that the second harmonic distortion, generated in the region of high-intensity sound pressure, is directly proportional to both the frequency and the magnitude of sound pressure. During each cycle of sound pressure oscillation, if equal positive and negative increments of pressure are impressed on a mass of air, the changes in volume of the mass will not be equal; the volume change for the positive pressure will be less than the volume change for the equal negative pressure. From this nonlinear condition in the air, harmonic generation becomes very high when the ac pressure becomes an appreciable part of atmospheric pressure. For a peak sound pressure of the order of 1/10 atmosphere, which is equivalent to +171 dB vs. 0.0002 μbar, a second harmonic distortion will be generated in the sound field of a magnitude of the order of 10 percent of the fundamental pressure within a distance of about one wavelength along the direction of propagation. (This assumes that the frequency is high enough so that the sound pressure has not fallen off significantly over a distance of one wavelength from the source.)

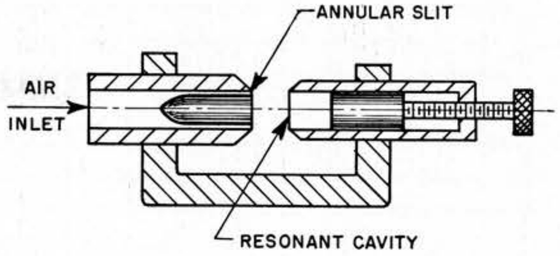

Fig. 7 Construction of Galton ultrasonic whistle.

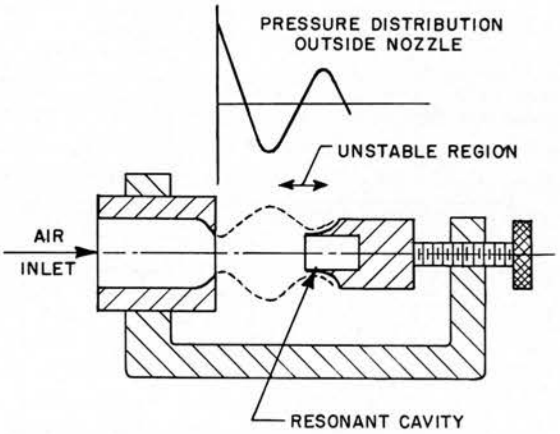

Fig. 8. Construction of Hartmann ultrasonic generator.

If an arbitrary value of about 1/10 atmosphere is assumed as the peak value of sound pressure which is to be generated with maximum permissible distortion, it follows that the acoustic power per square inch of radiating area of the transducer is limited to approximately 77 W/in^2.

The family of curves in Fig. 6 were derived from (2), and shows the relationship between fluid displacement, frequency, and acoustic-power output for various areas of openings in a modulated air-flow loudspeaker. The dotted line drawn across the chart shows the upper limit of acoustic power permissible for various radiating areas to keep the peak sound pressure at the source below 1/10 atmosphere.

ULTRASONIC GENERATORS

The earliest and simplest forms of ultrasonic generators convert mechanical energy directly into sound energy. The mechanical generators may be classified into two general types. One type operates by the conversion of a stream of air into high-frequency modulated oscillations; the other type by a resonant mechanical plate or rod being set into mechanical vibration.

Modulated Air-Flow Transducers

One of the earliest types of ultrasonic generators is the Galton whistle, shown in Fig. 7. Air passes through a nozzle having an annular slit, as shown. The circular stream of air passing through the slit strikes against the circular knife edge of the adjustable resonant cavity which is formed by the hollow tube and the adjustable plug. The position of the plug within the tube determines the resonant frequency of the cavity, which, in turn, determines the frequency of the whistle. This transducer is extremely simple and may be operated by blowing with the mouth. Frequencies as high as approximately 100 kc/s may be generated by this simple transducer; however, the acoustic power generated is quite small.

An improvement on the Galton whistle which permits somewhat higher acoustic powers is the Hartmann generator [7], shown in Fig. 8. If air is supplied through the nozzle at a gauge pressure of approximately 0.9 atmosphere, an external jet stream will be produced beyond the tip of the nozzle which will have a pressure distribution as shown in the graph above the cross-sectional view of the transducer. The region of pressure rise outside the nozzle, as indicated by the arrows, is unstable, and a hollow body placed in this unstable region will oscillate at the resonant frequency of the cavity. The Hartmann generator may be used for generating ultrasonic sound up to about 100 kc/s with a conversion efficiency of the order of 5 percent. Although the acoustic power generated by this transducer can be somewhat higher than the power produced by the Galton whistle, the Hartmann generator is still a relatively low-power ultrasonic-sound source.

For generating relatively high ultrasonic power in the range of several hundred watts, a siren may be utilized. Allen and Rudnik [8] described a siren consisting of 100 conically-shaped ports closely spaced on a 6-inch diameter circle. Each port opening is $\frac{1}{2}$ inch long and has a diameter equal to 0.094 inch at the small end, and 0.188 inch at the large end. A schematic cross-sectional view of the siren is shown in Fig. 9. A circular rotor, having 100 teeth slightly wider than the port openings, is driven by a high-speed motor. At a motor speed of 18 000 rpm, a 30-kc/s sound signal is generated equal to approximately 200 W. The air pressure in the chamber is approximately 0.2 atmosphere gauge. A siren, similar to the unit shown in Fig. 9, with chamber pressures increased to approximately two atmospheres, yielded acoustic outputs up to about 2 kW with a conversion efficiency of 20 percent.

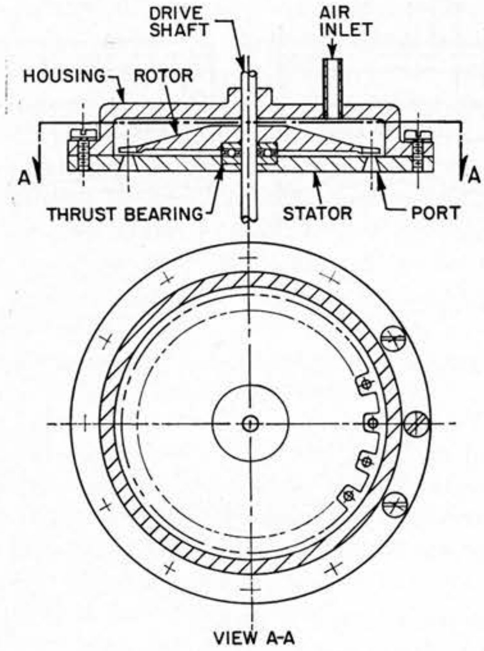

Fig. 9. Construction of an ultrasonic siren.

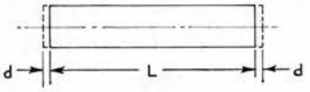

Fig. 10. Vibrating rod at longitudinal resonance.

Mechanical Vibrating Sources

A simple ultrasonic mechanical generator may consist of a small tuning fork, a longitudinally vibrating rod, or a flexurally vibrating plate, any of which may be set into vibration by striking with a mechanical blow. The maximum amount of sound energy that may be generated from such vibrating systems is limited by the maximum stress which may be safely developed in the material. Figure 10 illustrates a cylindrical rod of length L, which, when set into vibration at its fundamental resonant frequency, develops a peak displacement d at each end, as shown. The peak stress developed in the rod is given by

$$\text{peak stress} = \frac{2dE}{L} \text{ psi} \qquad (3)$$

where

d = peak displacement in inches
E = modulus of elasticity in psi
L = length of rod in inches.

For longitudinal resonance of the rod

$$L = \frac{c}{2f} \qquad (4)$$

where

c = velocity of sound in the material in in/s
f = frequency in c/s.

The velocity of sound in steel, nickel, and aluminum is approximately the same, and is equal to about 200 000 in/s, which, when substituted into (4), shows that a one-inch length rod of either of these materials would have a natural resonant frequency in the neighborhood of 100 kc/s.

The maximum stress that can be developed in the vibrating material is limited by the fatigue limit. The fatigue limit is determined not only by the elastic limit of the material, but it is greatly dependent upon the surface finish and heat treatment. As a practical fatigue limit, a maximum safe-working stress which may be achieved, using the best steel alloys heat treated for optimum fatigue, is about 30 000 psi. For a 1-inch length steel rod, the peak displacement d that can be realized at 30 000-psi peak stress, as determined from (3), is equal to 0.0005 inch. For this magnitude of peak displacement at 100 kc/s, which is the resonant frequency of the rod, Fig. 1 shows that the acoustic power radiated from each end of the rod is approximately 9 W/in^2 of area. If the rod is $\frac{3}{8}$ inch diameter, the maximum acoustic power which can be generated is in the neighborhood of 1 W.

If a resonant rod is employed as an ultrasonic generator, only transient pulses can be generated if mechanical excitation is employed. For remote control applications, a single pulse may be used to initiate the operation of a remotely located device. For such applications, an extremely simple ultrasonic source can be a resonant metallic rod, suspended at its midpoint, with a mechanically actuated striker that may be used to impart a blow to one end of the rod. If sustained acoustic signals are required, however, some form of electromechanical excitation of the vibrating element may be used.

Electroacoustic Transducers

Longitudinal Resonant Vibrators

Figure 11 illustrates three basic types of electromechanical transducers which are in general use for the conversion of sustained electrical oscillations into mechanical vibrations to generate acoustic power from the radiating end faces of the structures.

Magnetostriction transducers for use at ultrasonic frequencies generally employ a large number of thin nickel laminations, each a few thousandths of an inch thick, bonded together to form a rigid stack. An efficient construction employs a polarizing magnet and an ac coil surrounding the nickel stack, as illustrated in the top view of Fig. 11. When the frequency of the electrical signal fed to the coil corresponds to the resonant frequency of the stack, maximum amplitude will be developed, and sustained ultrasonic sound will be gen-

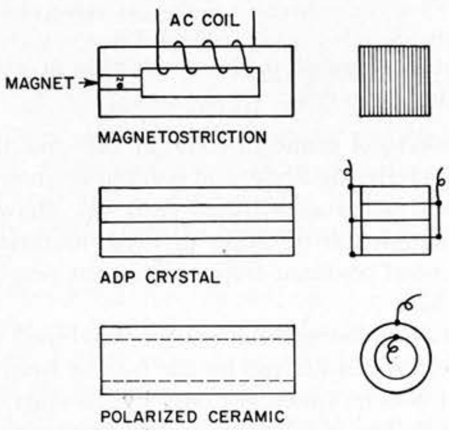

Fig. 11. Examples of electroacoustic transducers for operating at longitudinal resonance.

erated from the end face of the stack.

The center view in Fig. 11 illustrates a piezoelectric ultrasonic generator employing a stack of 45° Z-cut ADP (ammonium di-hydrogen phosphate) crystals cemented together, as shown. Electrodes from the crystal faces are connected to electrical terminals, as illustrated, and upon the application of an alternating voltage at the resonant frequency of the assembly, sustained vibrations will be established, as in the case of the magnetostriction transducer.

The lower view in Fig. 11 illustrates a hollow polarized ceramic tube having inner and outer electrodes, as shown. The ceramic tube may be driven in a similar manner as described for the ADP crystal, and sustained vibrations may be established at the ends of the tube corresponding to its length resonant frequency. One end of the ceramic tube may be capped with a solid disk, if desired, to increase the radiating area of the transducer, and thereby increase the acoustic power which may be generated.

Flexurally Vibrating Transducers

Another class of vibrating structures for generating sound waves makes use of the fluxural vibrations of disks which may be either clamped at the periphery or may have a free edge. Figure 12 illustrates a clamped and a free-edge disk, with an indication of the positive and negative displacements of the surfaces which occur during resonant vibration.

The illustrations in Fig. 12 show a bilaminar assembly comprising two plates of polarized ceramic, arranged such that upon application of a positive potential to the assembly, one disk expands and the other contracts to result in a convex displacement toward the element which develops the expanded dimension. On the reversal of the applied voltage, the displacement reverses in phase to set up transverse vibrations, as illustrated.

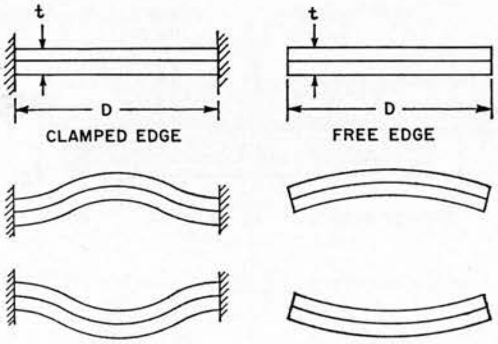

Fig. 12. Examples of electroacoustic transducers operating at flexural resonance.

The fundamental resonant frequency of a clamped circular disk is given by [9]

$$f_r = \frac{0.77t}{D^2}\sqrt{\frac{E}{\rho}}\ \mathrm{c/s} \tag{5}$$

where

t = thickness of disk in inches
D = diameter of disk in inches
E = modulus of elasticity in dynes/cm^2
ρ = density in g/cm^3.

For a clamped steel or aluminum disk, the resonant frequency as computed from (5) becomes

$$f_r = \frac{385t}{D^2}\ \mathrm{kc/s}. \tag{6}$$

For a polarized barium titanate bilaminar assembly

$$f_r = \frac{316t}{D^2}\ \mathrm{kc/s}, \tag{7}$$

and for a polarized lead zirconate-titanate structure

$$f_r = \frac{220t}{D^2}\ \mathrm{kc/s}. \tag{8}$$

For a free disk, the resonant frequency is approximately 88 percent of the frequency indicated for the clamped disk.[1]

Electrostatic Transducers

The illustrations in Figs. 11 and 12 showed some basic types of resonant electroacoustic transducers which may be employed for generating ultrasonic energy in a narrow frequency band near the resonant frequency of the vibrating structure. For applications requiring wide-band acoustic output, such as is needed in a sound source for use in calibration of ultrasonic microphones, it is possible to operate a conventional condenser microphone as an ultrasonic loudspeaker.

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[1] For a more complete analysis of the vibration of a free disk, see R. N. House, Jr., and J. Kritz, An analytic study of the vibrating free disk, *IRE Trans. on Ultrasonic Engineering*, vol. UE-7, pp. 76–84, June 1960.

The construction of a conventional-type condenser microphone employs a thin stretched metallic diaphragm closely spaced from a conducting back plate, as illustrated in Fig. 13(a). When a positive dc potential is applied between the back plate and the diaphragm, an alternating voltage is generated due to the change in capacitance between the diaphragm and back plate when the diaphragm is set into vibration by the presence of sound waves. If the diaphragm is approximately ½ inch in diameter, it is possible to stretch either a stainless-steel or an aluminum membrane to achieve a resonant frequency in the neighborhood of 10 kc/s. Under such a condition, the microphone will have a flat response over the low-frequency range, and will show a peak in the neighborhood of the resonant frequency. Above the resonant frequency, the vibrating system will be mass-controlled so that the condenser microphone becomes a reasonably flat sound source for the ultrasonic frequency region above 10 kc/s. Smaller transducers of this type, working as microphones with undiminished sensitivity up to 100 k/s, have been described by Rasmussen [9a].

A typical value of dc polarizing voltage for a condenser microphone is 200 volts, which means that the unit may be operated as a loud-speaker with ac voltages up to about 50 volts before serious distortion is introduced. Under such conditions, a sound pressure of a few μbars will be generated over the frequency range 10 kc/s to 100 kc/s at a one-foot distance from the transducer. Although this represents extremely small acoustic power, the sound field is adequate for making calibrations of ultrasonic microphones.

Figure 13(b) illustrates a modification of the condenser microphone in which the spaced stretched metallic diaphragm is replaced by a thin plastic film which has a metalized coating on the outside surface. The film is placed in mechanical contact with the backing plate, resulting in an effective resonant frequency of several hundred kc/s with a corresponding flat response over a wide ultrasonic-frequency region. Kuhl, Schodder, and Schröder [10] employed plastic films of vinyl or polyethylene approximately 0.0005 inch thick which produced microphones having resonant frequencies as high as 200 kc/s.

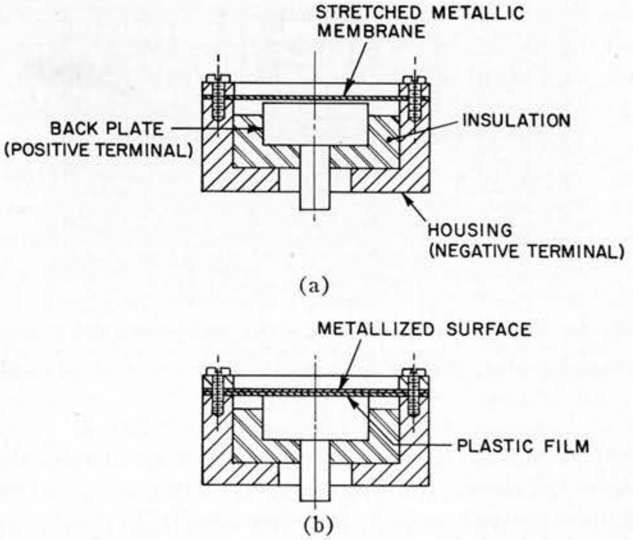


Fig. 13. Construction of electrostatic transducer. (a) Conventional stretched-diaphragm type. (b) "Solid dielectric" type.

A comprehensive study of electrostatic transducers employing metallized 0.00025-inch Mylar plastic films in direct contact with the back electrode was undertaken by Wright [11]. He showed that even for a polished electrode surface over which the Mylar was stretched, a resultant air film of the order of one micron in thickness was responsible for the compliance which established a resonant frequency for the vibrating system in the vicinity of 500 kc/s. The rougher the surface of the backing plate, the larger would be the effective air gap and the lower the resonant frequency of the system. Sensitivities ranging from −85 dB to −95 dB vs. 1 V/μbar were obtained by Wright for diaphragms of approximately ½ inch diameter. These microphones also make reasonably smooth wide-range ultrasonic loudspeakers, which are limited to very low power output by the inherent limitations of the infinitesimal displacements that can be permitted by the design.

The very nature of the "solid dielectric" electrostatic transducer, in which the sensitivity depends on the effective air gap that exists between the two contacting surfaces, makes it difficult to produce a device whose sensitivity can be predicted accurately in advance. The design also results in a degree of variation in characteristics, so that a calibration of the unit becomes necessary where accurate measurements are required. A general limitation of condenser-type microphones is that distortion is introduced at high sound-pressure levels, the distortion being significant when the motion of the diaphragm becomes an appreciable part of the effective air-gap spacing in the structure.

D. Standard Microphone for Ultrasonic Measurements

Standard microphones, whose characteristics are very stable and whose linearity permits the measurement of sound pressures of the order of several hundred lbs/in², employ a tiny stack of ADP crystals similar to the center illustration in Fig. 11. A photograph of a commercial type of such a measurement standard, together with its response characteristic, is shown in Fig. 14. The stability of microphones employing ADP plates is exceptionally high. Numerous ADP transducers have been in widespread active service for over fifteen years without measurable changes in their calibration. Another inherent advantage of this type of microphone is that it has a virtually infinite acoustic impedance which permits accurate calibrations to be made of intense sound fields

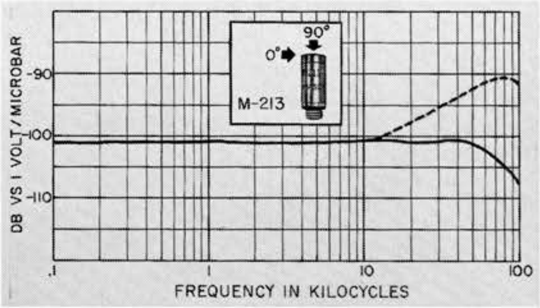


Fig. 14. Photograph and frequency response of commercially available reference standard ADP microphone for making accurate measurements of sound pressure over very large dynamic ranges.

over very wide dynamic ranges. A comprehensive discussion of the engineering design principles for this type of microphone may be found elsewhere [12], [13].

APPLICATIONS

Due to the inherent limitations which restrict the power generating capability of ultrasonic transducers, coupled with the very high absorption encountered during the transmission of ultrasonic sound through air, the applications of ultrasonics in air are necessarily limited to distances between the transmitter and receiver. These distances are in the order of one hundred feet or so, depending on the ultrasonic frequency employed. The most important commercial application of ultrasonics in air has been in remote control systems, an example of which is the remote control of television sets which is accomplished by ultrasonic signals initiated by a viewer seated across the room from the set. One type of control system employs resonant rods, similar to the illustration in Fig. 9; these rods are struck by mechanically triggered hammers actuated in the mechanism held by the individual.

In more sophisticated systems, an ultrasonic electroacoustic transducer is employed which generates steady-state acoustic signals of different predetermined frequencies for accomplishing a variety of functions at the television set. An inexpensive transducer, which has been very widely used in quantities of many hundreds of thousands, employs a free-edge bilaminar disk. This disk is set into flexural vibration by electrical signals supplied to the thin polarized ceramic plate which makes up half the bilaminar assembly [14], [15]. The details of this transducer design are shown in Fig. 15. The efficient operation of the transducer requires that the outer periphery of the bilaminar disk beyond the nodal diameter be shielded from the medium to prevent phase interference between the radiation from the center of the disk and the outer periphery. The cross-sectional view shows how a resilient washer is employed to shield the radiation from the undesired portion of the vibrating disk. For a transducer designed to operate in the 40 kc/s region, a $\frac{7}{8}$-inch diameter bilaminar disk, approximately 0.090 inch thick, was employed in the construction. The frequency response characteristics of the transducer as a transmitter and as a receiver are shown in Fig. 16.

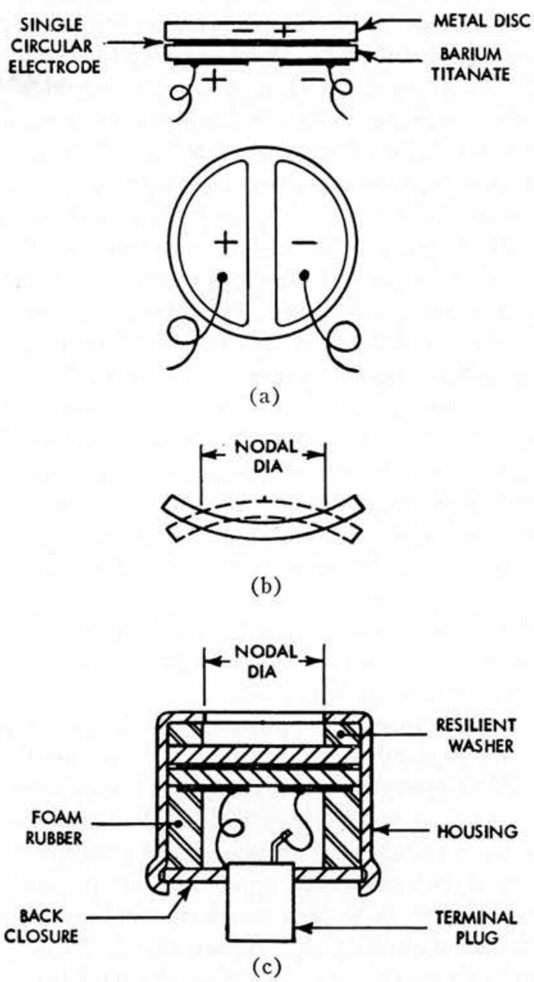
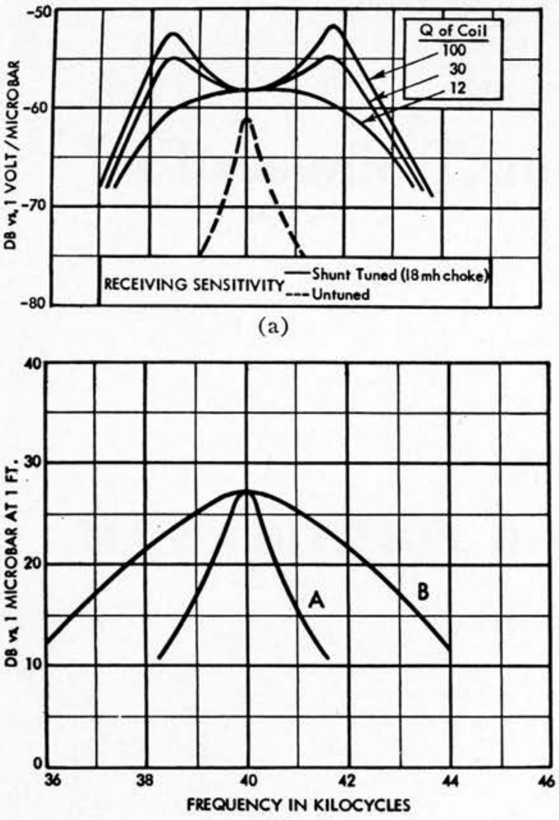


Fig. 15. Design details of low-cost ultrasonic transducer in wide use in ultrasonic remote control systems. (a) Bilaminar assembly showing special polarization of ceramic disk portion. (b) Mode of vibration of transducer element. (c) Cross section through complete transducer.

The radiation pattern from the transducer covers a conical angle of approximately 60° which makes it ideally suited for many remote control applications. If the transducer is required to operate on a more concentrated beam, a very simple conical horn may be attached to the opening in the housing. The concentration of the sound will be confined approximately to the angle of the cone which forms the horn. Upon sharpening the beam angle by this suggested procedure, the acoustic intensity will be increased along the principal axis of the transducer.

In addition to remote control applications, ultrasonic signals have been employed for automatic door-opening systems; for counting in applications where photocells are not practical, and also for short-range quiet communication in which an ultrasonic carrier is modulated



(a)

(b)

Fig. 16. Response characteristics of transducer shown in Fig. 15. (a) Receiving response. (b) Transmitting response curves obtained with 100 mW available power: curve A, untuned, 4000-Ω impedance source, curve B, series tuned with 18 mh, 400-Ω impedance source.

by the speech signals for transmission over a range up to 100 feet or so. This avoids the use of audible P.A. systems which might be a source of disturbance in certain applications.

Ultrasonic sound may be used for short-range proximity indicators, such as, for example, the determination of the last several feet of height of a plane from the landing strip for the possibility of automatic guidance of the plane in the final landing operation. Such a proximity system has also been successfully employed in maintaining a predetermined altitude of a helicopter hovering a short distance above water or land.

A very interesting application of an ultrasonic proximity indicator has been in an experimental blind aid which uses the transducer shown in Fig. 15 in a hand-held case resembling a flashlight. An ultrasonic pulse is emitted at about one-second intervals from the transducer when the operator turns on the equipment. If the ultrasonic beam finds an object in its path, the reflected sound from the object will return to the transducer to automatically trigger off another pulse to establish a steady repetition rate for successive reflections. The repetition-rate frequency is fed to a tiny earphone which permits the blind person to know the relative distances of objects that he intercepts with the ultrasonic beam.

Future applications of ultrasonics in air will probably see an expanded use of control devices and proximity indicators. One interesting application of ultrasonic control has been considered for use as a burglar-alarm system in which an ultrasonic transducer radiates sound in a vacant room and sets up a diffuse standing-wave pattern within the enclosure. A receiving microphone, also placed within the room, picks up the sound, and the frequency of the received signal is compared with the oscillator frequency which drives the transducer. Both frequencies will be identical if everything within the room remains stationary. If a person enters the room, the sound-wave pattern is disturbed and the frequency of the received signal will be changed by the Doppler effect caused by the person's acting as a moving target for the sound reflected from his body. The same system would also act as a fire alarm, since a fire in the room would cause large convection currents of air due to the heat, which, in turn, would shift the frequency because of the Doppler effect due to the motion of the medium transmitting the ultrasonic sound.

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