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REVIEW OF TRANSDUCERS USED IN AIR

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Acoustic transducers operating in air are concerned with the conversion of electrical energy into sound waves or vice versa.

In general, these devices may be required to perform over the audible range of frequencies from about 20 Hz to 20,000 Hz, comprising ten octaves, though often the response need not be as broad as this.

Devices may be divided into loudspeakers, microphones and earphones, the first two of these have to deal with three dimensional propagated waves, while the last has effectively a short one dimensional transmission line, being not required to produce generally radiated sound. Apart from a few exceptions to be mentioned presently all transducers involve some solid material capable of vibration which is coupled to the acoustic medium, the air and to the electric transducer element. Hence transducing devices may be analysed in terms of these three parts:-

(1) Coupling e.g. Horn, baffle, enclosure.
(2) Solid e.g. Membrane, cone, ribbon.
(3) Element (a) Electromagnetic (b) Electrostatic
(c) Piezo-electric (d) Variable resistance.

It is highly desirable that all parts of the solid should vibrate in a common phase and that the response of the system should be as nearly independent of frequency as possible, over the required band width.

Much skill and ingenuity has been spent in transducer design in trying to achieve the equivalent of a rigid body, with very little mass for the vibrating solid. The low mass requirement is dictated by the coupling condition to a wave in air which has a density of about 10^{-3} of that of any solid.

Because of the difficulties of constructing a vibrating mass system, considerable thought has been given to alternatives in which there is no problem of resonances or deformation, but none has so far achieved much success.

One of the more promising of the non-mechanical vibrational systems which makes its appearance from time to time at the Audio Fair is the ionophone. This is a loudspeaker in which an amplitude modulated high frequency voltage is applied to a pair of electrodes about 1 cm apart in the throat of a horn made of Pyrex, or other insulating material.

The R.F. signal causes ionisation of the air between the electrodes, and current flow occurs proportional to the imposed audio frequency modulation.

This current gives rise to rapidly varying heating of the air with consequent expansion and contraction, thus pressure waves are set up which resemble the original sound. The system has never proved popular because of the need for an oscillator, low efficiency and inability to cover the lower part of the acoustic range without

2. a very large horn. Also it gives a slight hiss in the absence of a modulating signal, and some distortion.

A system long rejected as a microphone is the hot wire, heated by a small constant current, and cooled when in a sound wave by an amount approximately proportional to the instantaneous particle velocity. The electrical signal from the wire depends on its resistance variation with temperature. While the system is free from resonance its high frequency response is limited by thermal inertia, and a polarising air stream is required to prevent frequency doubling due to cooling in both half cycles. The sensitivity of the device is very poor.

An idea I once tried for a microphone depended on the attenuation of 1 MHz ultrasonics in air being a function of instantaneous pressure. One quartz crystal acted as a transducer of ultrasonics, and another as a detector. Acoustic, or sound waves between the two crystals gave rise to modulation of the ultrasonic beam. The sensitivity of the arrangement was, unfortunately, rather poor.

It would seem that so far the vibrating mass system must be accepted as the basis for all types of transducer, and in both electroinductive and so called electrostatic instruments an electrical conductor may form, or contribute to the mass.

The requirement of uniform frequency response may be approached in various ways. One way is to arrange that the natural resonant frequency of the mass and its supporting compliance shall be outside the bandwidth which it is desired to reproduce.

In the case of the ribbon microphone, although the mass is small, the compliance is very large (i.e. very small restoring force per unit displacement) so that the natural resonant frequency is about 10 - 40 Hz, while the resonant frequency of a Piezo-electric crystal with no added mass is high, often over 20,000 Hz.

A second approach is the use of multiple transducers, each covering a part of the required range, and linking these by what are known as electrical crossover networks.

A third approach involves the use of acoustic elements (such as pipes, slits and cavities, and also absorbent materials) acoustically, or air-coupled to the vibrating system, whose natural resonance is within the bandwidth to be reproduced. Damping of resonances can also be accomplished by elements in the electrical circuit coupled to the mass of the transducer.

The effect of acoustic elements and the electrical impedance, or the frequency response of a transducer can be determined by equivalent circuit theory, in which a mass or inertance of I Kgm is analogous to 1 Henry, and a compliance permitting a displacement of 1 m per Newton is equivalent to 1 Farad. An acoustic resistance of 1 ohm causes a dissipation of 1 watt due to a volume flow of 1 m^3 sec^{-1} at a pressure difference of 1 N per sq.metre, per metre. Thus the inertance of an air volume V m^3 is ρV, where ρ = density of air 1.2 Km m^{-3} and the compliance of a volume V m^3 is $\frac{V}{\rho c^2}$ where c = 344 m Sec^{-1} velocity of sound in air.

ρc^2 is the adiabatic bulk modulus of air K. These concepts are in agreement with the wave equation for sound in free air.

Magnetic coupling due to a conductor of length ℓm at right angles to a magnetic field B Teslas provides an interesting example of impedance reflection analogous to mutual inductance.

A current I amperes in the conductor causes a force B ℓI N. If the mass is M kgm, and the displacement S and velocity V M Sec^{-1}

$F = M \frac{dv}{dt} = B \ell I$ Induced voltage $B \ell v = V$

hence $\frac{V}{Q} = \frac{B^2 \ell^2}{M}$ or $\frac{V}{I} = \frac{B^2 \ell^2}{j\omega M}$

i.e. the mass M reflects as a capacitance with a multiplication factor of $B^2 \ell^2$.

In the mechanical side the equation of motion due to a resistance R shorting the ends of the conductor is:

$$M \frac{dv}{dt} = B \ell I = B \ell \frac{V}{R} = \frac{B^2 \ell^2 v}{R}$$

which causes mechanical damping proportional to $B^2 \ell^2$, and inversely proportional to R.

. Hence an impedence Z is reflected as $\frac{B^2 \ell^2}{Z}$

While the problems of uniform response of a vibrating system are most easily thought of in terms of frequency, those of coupling to the air are often visualised in terms of wavelength λ.

In general in order to radiate efficiently a structure must be large, or effectively large compared with wavelength. Thus for efficient radiation at 20 Hz a vibrating plate would have to be of the order of $\frac{344}{20} = 17$ m in diameter.

Similarly if a microphone is not to discrimate against certain wavelengths due to the diffraction effect of its casing, it follows that ideally a microphone should create the least disturbance of a sound wave and hence should be small compared with λ. This implies that the casing of a microphone should be less than 0.017 m in diameter (= 1.7 cm) if it is not to cause diffraction at 20,000 Hz. It is clearly not possible to have structures very large compared with the largest wavelengths to be considered, or very small compared with the smallest, hence some compromise must be met in the design of coupling systems.

The effect of diffraction in a coupling system is most easily understood in the case of a circular baffle, with a concentric transducer.

It is found experimentally that there is a marked drop in response at that frequency which corresponds to a path difference of one wavelength from front to back of the baffle at its centre, or approximately λ = diameter. Less marked drops in response occur when the diameter is 2λ 3λ etc.

To avoid these marked drops in response speakers have been asymmetrically mounted in baffles.

A suggestion taken seriously by early enthusiasts giving the effect of an infinite baffle was to mount a loud speaker in a hole in the wall between two large room,s which give efficient radiation into both.

The exponential horn is a coupling device once very popular. This behaves as an acoustic matching transformer. The cross-section of the horn A is given by:

$A = A_o e^{gx}$, A_o throat area, x = distance along axis, g = flare constant.

The radiation efficiency of horn coupling can exceed 90% at frequencies above a lower limit referred to as cut off given by:

$$fc = \frac{gc}{4\pi}$$

The transformer ratio for a horn is roughly the ratio of outlet area to throat area, so that effective horns with low frequency cut off have a small value for g, and hence must be very long.

Good horns must be very rigid in the wall so that no vibration can be set up by relatively high sound pressures.

Some ambitious horns have been constructed of concrete, built out 60 feet into the garden.

Horns tend to be directional at high frequencies, and also produce distortion due to non linearity of the air, if the sound energy density exceeds about 25 watts per sq.metre.

Providing the throat area is not too small, horns can, however, improve the performance of a loudspeaker by increasing the air loading which smoothes out resonances, and by reducing vibration amplitude for a given sound energy output.

Nowadays the trend is to small enclosures, high efficiencies being not so important as amplifier outputs of 60 to 100 watts are readily available. The principle of the small enclosure is to absorbe as completely as possible all the radiation from the back of the speaker vibrating system. The technique involves the use of porous material in layers with air spaces in a box with rigid walls.

We come now to considering the electrical element in more detail and with examples of complete units.

The earliest electromagnetic system referred to as moving iron had an edge-clamped disc of ferromagnetic alloy as diaphragm. The disc was attracted to the pole pieces of a permanent magnet, and the magnetic field strength varied by means of signal current flowing in the coils round the pole pieces.

This system was used in the Gecophone with a metal horn in the early 1920's.

An improvement in moving iron systems was devised by Farrand, called the balanced armature speaker, in about 1926 the iron actuator being coupled to a cone of paper. Second harmonic distortion is greatly reduced by the symmetrical arrangement.

A major step in high quality reproduction was brought about by the moving coil loud-speaker in which a coil attached to a cone moves in the direction of its axis due to forces imposed by the interaction of current in the coil with a strong radial magnetic field.

Early models of this were "energised" by a coil carrying D.C. surrounding the central soft iron pole.

Most radio sets, or should I say wireless sets, used the coil as a smoothing choke, or inductance in the high tension supply, but this resulted in hum being produced. High quality speakers had a separate D.C. supply, and used separate inductances to remove the ripple from the amplifier high tension supply. The performance of many of these was remarkable, large amplitude of movement being possible with little wave form distortion, due to constancy of the current flux linkage with displacement.

The flux densities in energised or electromagnet speakers could be of the order of 2 Teslas being nearly that of the saturation value for soft iron. With improvement in permanent magnet materials these became used in moving coil speakers and flux densities are now around 1.5 Teslas (15,000 gauss). Many modifications of cone systems have been produced such as multiple cone and multiple coil to give a wide frequency response.

Two of the more successful departures from cones of organic materials have been the G.E.C. metal cone of aluminium alloy and the recent Jordan Watts cone of titanium, which result in a light, but rigid vibrating system, with excellent frequency response.

The vibrating mass in the K.E.F. low frequency speaker is a thick slab of polystyrene foam.

An alternative system to the rigid mass is found in the electrostatic speaker, in which a very light membrane made conducting by evaporated gold or aluminium, is caused to move by the electric field between it and a rigid perforated metal plate. The field is produced by the applied voltage which is the sum of the signal voltage and a constant polarising voltage. The membrane is not

5. rigid, but all parts of it vibrate in phase as the driving force is distributed all over it. The driving force in the electrostatic system would approach the ideal linear relation to the signal with the circuit shown. The equation of motion is then:-

$$M\ddot{x} + R_m\dot{x} + \frac{1}{C_m}x = Q\frac{V}{S}$$

R_m is the radiation resistance which outweighs the quantities M and $\frac{I}{C_m}$ due to the mass and compliance in this type of speaker.

Q is kept constant by having R of several megohms

$R_m \simeq$ 420 acoustic ohms $m^{-2} = \rho c = 1.2 \times 344$

$M \simeq 10^{-3}$ Kgm m^{-2}. $\frac{1}{C_m} \simeq$ 4 Farads^{-1} m^{-2}

Loudspeakers have been made using the reverse Piezo-electric effect, whereby an applied voltage to a crystal such as that of Rochelle salt results in forces tending to give rise to a deformation either of re-twisting, or bending.

Systems in which the crystal is directly coupled to a cone have been used as "tweeters" for reproduction of high notes, but large amplitudes of displacement cause crystal fracture, hence these are not applicable to a wide range of reproduction.

Coming now to microphones, we consider first a non-reversible transducer mechanism, that of variable resistance, in the carbon granule instrument. A diaphragm coupled to a capsule containing some form of graphite, causes a varying compression of the particles, when sound acts on the instrument. The resistance variation modulates the current from a D.C. supply in a somewhat non-linear manner. High class instruments have used carbonised poppy seeds as the graphite granules, but even with this botanical source of carbon, the reproduction is far from Nature.

The system is highly sensitive and can give about 1 watt of output with moderately loud speech as acoustic input and using a 12 volt accummulator as D.C. supply. Carbon microphones directly coupled to earphones have been used to provide power for loudspeakers and may hence claim to be the first semi-conductor amplifiers.

Piezo-electric microphones consist of a light alloy cone directly coupled to a crystal. The sensitivity is increased by a large cone, but this tends to bring the resonance into the audio frequency band. The major advance in these instruments is the use of ceramics such as barium titanate instead of Rochelle salt or quartz. Rochelle salt crystals are damaged by moisture and extreme temperatures, while the Piezo E.M.F. due to quartz is small.

Microphones provide interesting examples of the way in which acoustic coupling can be used to control not only the frequency response, but also the directional sensitivity.

Moving coil microphones are like miniature loudspeakers, but usually have only a light spherical cap across the coil, and no cone. If the case of the instrument excludes the external sound from the inside of the device the instrument is pressure operated and its sensitivity is independent of the direction of sound travel for large wavelengths.

Variation of response with frequency due to diffraction of sound at the surface of the case is minimised if the case is spherical and the direction of the incident sound is perpendicular to the coil axis. This form of construction has been used in the Weston-Electric ball microphone and in a similar one made by S.T.C.

The ribbon microphone of which a popular form is made by Reslo consists of a thin corrugated strip of aluminium or duralumin about 2×10^{-2} mm in thickness and 3 mm in width, free to vibrate

6. in the magnetic field between the pole pieces of permanent magnet system. These pole pieces also form the acoustic baffle and the ribbon driving force is provided by the pressure difference resulting from the acoustic diffraction at the baffle.

It can be shown that for what is essentially a mass controlled system over the audible range that the velocity and hence the magnetically induced output signal is independent of frequency.

The directional response of the ribbon has a polar diagram of the form $r = A\,|\cos\theta|$ i.e. output voltage proportional to the cosine of the sound angle of incidence on the baffle.

If the general sound field is excluded from one face of the ribbon the microphone becomes omnidirectional. Further if this face is presented with an acoustic impedance similar to that of free air the frequency response of the instrument will remain uniform. This is achieved by coupling one side of the microphone to a long tube in which there are at intervals tufts of felt, or other acoustic absorbing material. This tube is the acoustic analogue of the critically damped transmission line, and as such I consider fulfils a long felt want.

The development of the electrostatic or condenser microphone is almost entirely due to a modification of acoustic coupling and to the provision of amplifiers with high input impedance.

Early condenser microphones of the form of a flat plate electrode and a metal foil separated by a thin insulating ring were very insensitive, as the very small volume of air between the plate and membrance presented a high reactance to the motion of the membrane. At a suggestion due to Wente small perforations through the metal plate were made allowing air flow in and out of a larger cavity, thus presenting a large compliance. The electrical equation assuming vibration at a single frequency is:-

$$\frac{Q}{C} + R\frac{dQ}{dt} = E \qquad C_o = \frac{\epsilon A}{x_o} \quad C = \frac{\epsilon A}{x_o + \alpha e^{j\omega t}}$$

$$\frac{Q}{C_o}(1 + \beta e^{j\omega t}) + R\frac{dQ}{dt} = E \qquad \beta = \frac{\alpha}{x_o}$$

$$Q(1 + \beta e^{j\omega t}) + R\,C_o\frac{dQ}{dt} = EC_o = Q_o \quad \text{non-linear 1st order}$$

$$\text{let } Q = \Sigma A_n e^{j\omega n t}$$

$$(1+\beta e^{j\omega t})\,\Sigma A_n e^{j\omega n t} + RC_o\,\Sigma\, j\omega n A_n e^{j\omega n t} = Q_o$$

whence

$$A = Q_o, \quad A_n = \frac{-\beta\, A(n-1)}{1 + j\omega n\, RC_o}$$

Distortion in the electrical output signal is kept low by making R as large as possible using either a cathode follower of an F.E.T. source follower. This preamplifier must be well shielded electrically and must be close to the microphone to avoid electrical interference.

An interesting form of condenser microphone which has variable directional properties was devised by Braunmuhl and Weber and produced by Neuman. In one mode of operation with omnidirectional properties the electrical signals from the two membranes are added, giving a resultant due to displacements in opposite directions i.e. both towards each other, or both away from each other.

Bidirectional, or figure of eight polar response like that of the simple ribbon is obtained by subtracting the electrical outputs from each membrane. The resultant signal is now dependent on displacements in the same direction. The amplitude of the nett signal in the two cases for a given intensity sound field will be the same if the directional response due to one membrane alone is of cardioid form $r = \alpha\ (1 + \mathrm{Cos}\ \theta)$

Thus for membrane (1) $V_1 = \alpha(1 + \mathrm{Cos}\ \theta_1)$

(2) $V_2 = \alpha(1 + \mathrm{Cos}\ \theta_2) = \alpha(1 - \mathrm{Cos}\ \theta_1)$

$V_1 + V_2 = 2\alpha \quad V_1 - V_2 = 2\alpha\ \mathrm{Cos}\ _1$

Condition (1) for a single membrane implies no displacement for a sound wave coming from the rear $\theta_1 = \pi$ or 180°.

This is achieved by making the time of passage of sound to the two faces of membrane (1) equal, for sound at this angle.

The electrical analogue shows how this is done.

L replaces the mass of membrane (2) C & C the cavity compliance and R the resistance of the perforations.

From the circuit:-

$$E_1 = E_2\ (1 + j\omega CR)\ (1 - \omega^2 LC)$$

$$= E_2\ (1 + j\omega CR - \omega^2 LC - j\omega^3 LC^2 R)$$

for constant time delay τ we require $E_1 = E_2\ e^{j\omega\tau}$

$$e^{j\omega\tau} = 1 + j\omega\tau - \frac{\omega^2\tau^2}{2!} - \frac{j\omega^3\tau^3}{3!}$$

Hence the time constant CR must be equal to τ, but it will be seen that second order constancy of delay can be provided

$$\text{if} \quad L = \frac{R^2 C}{2}$$

The third term requires: $L = \frac{R^2 C}{6}$ which cannot be met, however, the equivalent diffraction path tends to increase with frequency and a good fit can be obtained in practice.

In the complete instrument, the directional pattern is continuously variable by changing the polarising potential on one of the membranes.

A cardioid directional response using a moving coil element, can be obtained by using an acoustic network giving a delay to sound arriving at the inside of the dome. This is done in the Shure microphone.

A recent development in condenser microphones makes it possible to do without the usual polarising voltage. This is the use of an electret which provides an electric field by means of a "frozen in" charge displacement in an insulator. These microphones can be used with transistor amplifiers, run from a low voltage supply.

A field in which I am particularly interested is that of ultra-directional microphones, but must not start on this theme, as to discuss them and systems used would require several hours.

I will, therefore, conclude by showing photographs of two of my own constructions which perform satisfactorily, and embody certain features not used in commercial instruments.