A THEORY OF THE ACOUSTIC EFFICIENCY OF THE TELEPHONE RECEIVER

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This brief progress report combines the general procedure of two previous researches, the motional-impedance of the telephone receiver,[1] and sound absorption by the flue method.[2] The plan is as follows: I. To determine the total energy absorption of the telephone receiver diaphragm from the electrical input; II. Of this total absorption, to determine that part which is lost as heat; III. The difference between the energy absorption of I and II gives the acoustic output of the diaphragm.

I. The essential features of the telephone receiver, the vibrating plate and the magnet and coils, are shown at end A of the sound flue in Plate I, a. Closing the end of the flue is the plate or diaphragm, behind which are the polepieces, with coils connected to an impedance bridge for determining the motional-impedance of the receiver (that part of the impedance due entirely to the vibratory motion of the diaphragm). When the resistance and reactance components of the motional-impedance for frequencies in the resonance region of the diaphragm are plotted as coordinates, the resulting graph is the motional-impedance or velocity circle (plate I, b). Its principal diameter (through the origin) marks the natural frequency f_0 of the diaphragm, and the quadrantal points f_1 and f_2 mark the positions which divide the circle into quadrants.

The equation of motion of the diaphragm is

$$md^2x/dt^2 + rdx/dt + sx = F \sin \omega t \qquad (1)$$

where m, r, and s are its inertia, resistance, and elastic constants respectively; F is the impressed force on it; t is the elapsed time; and $\omega = 2\pi f$. The solution of the equation for vibrational velocity is

$$dx/dt = (F \sin \omega t)/\sqrt{r^2 + (m\omega - s/\omega)^2}$$

Because of its vibratory motion, the diaphragm absorbs energy, the amount absorbed (omitting reactance) being rdx/dt^2. The resistance constant r includes frictional heat in the material of the diaphragm (r_f), the eddy current loss (r_e), and absorption of energy as sound radiated into the flue (r_p) and into the receiver chamber (r_c). For a small, smooth chamber r_c may be neglected. Then the total energy absorbed by the diaphragm is given by:

$$rdx/dt^2 = (r_f + r_p + r_e)(dx/dt)^2 \qquad (I)$$

II. At open end B of the sound flue is a loud speaker, connected to an electric

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[1] The Motional-Impedance of the Telephone Receiver. A. E. Kennelly and G. W. Pierce. Proc. Am. Ac. of Arts and Sciences, 48, 1912.

[2] A Direct Method of Finding the Value of Materials as Sound Absorbers. H. O. Taylor. Phys. Rev. Oct., 1913.

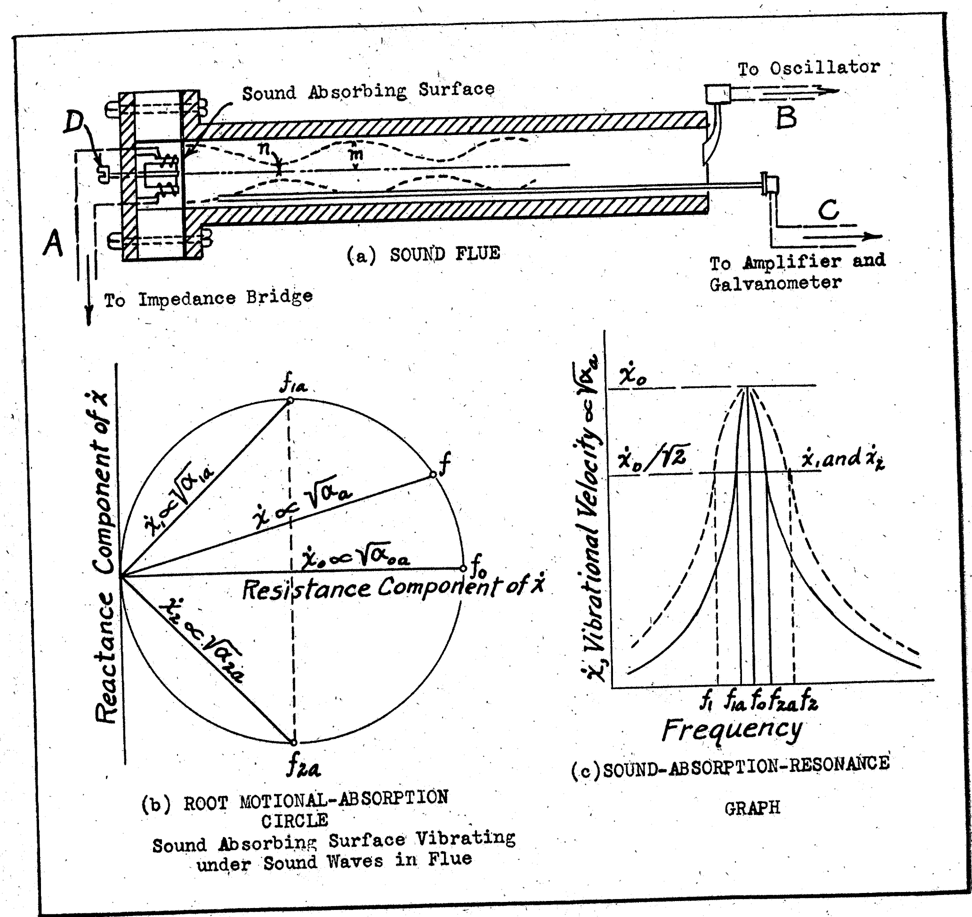

Fig. 1

oscillator, which delivers sound of pure sine-wave form to the flue. The progressive waves combine with those reflected from the plate at A to form a standing wave pattern. The sound intensities, m and n, at the maximum and minimum regions of this pattern are found by means of the exploring tube connected to telephone receiver C associated with an amplifier and galvanometer circuit. For a smooth interior flue surface, which absorbs practically no sound, the coefficient of absorption α of the diaphragm at end A is given by the relation:

$$\alpha = \frac{4}{(m/n)^{1/2} + (n/m)^{1/2} + 2} \qquad (2)$$

When the walls of the flue absorb sound appreciably, a formula for α is used which involves the attenuation of sound by the flue walls.[3]

When the diaphragm is excited by sound waves in the flue (rather than by the receiver coils) sound energy is absorbed by it because of both its porosity and its vibratory motion. The motional-absorption α_a of the diaphragm (that part of sound absorption due entirely to the motion of the diaphragm and not at all to porosity) is the difference between the free and damped coefficients of absorption, $\alpha - \alpha_d = \alpha_a$, where α is the free absorption, and the subscripts, d and a, refer to damped-absorption and motional-absorption, respectively. The

[3] Sound Absorption and Attenuation by the Flue Method. H. O. Taylor and C. W. Sherwin. Jour. Acoustical Soc. of Am., April, 1938.

damped-absorption is obtained when the motion of the diaphragm is damped by means of the contact screw D which, tipped with wax, is made to adhere to the center of the diaphragm. When these motional-absorption coefficients are determined for frequencies in the resonance region of the diaphgram, a sound-absorption-resonance graph may be plotted (diagram c) using dx/dt (proportional to $\sqrt{\alpha_a}$) as ordinates against frequency f as abscissas. dx/dt_1 and dx/dt_2 (each of which are equal to $dx/dt_0/\sqrt{2}$) are vibrational velocities corresponding to the quadrantal points. Thus a velocity circle similar to the motional-impedance circle may be constructed, which may be called the Root Motional-Absorption Circle (plate I, b).

The motional-absorption coefficient α_a corresponds to energy absorbed by the diaphragm from the standing waves in the flue given by $r_a x^2$,[2] where r_a is the resistance constant of the diaphragm for standing-wave excitation; therefore,

$$\alpha_a = r_a (dx/dt)^2$$

Then, when excited by the standing wave in the flue (with the telephone receiver coils on open circuit), the energy absorbed by the diaphragm is:

$$r_a (dx/dt)^2 = (r_f + r_e)(dx/dt)^2 \ldots (II).$$

The term involving r_p does not appear because sound reflected from the diaphragm is not absorbed by it.

III. The difference between (I), and (II), is $r_p (dx/dt)^2$ the energy radiated from the diaphgram into the flue; and the fraction that this energy bears to the total energy absorbed by the diaphragm from the electrical input is the acoustic efficiency e of the telephone receiver; that is,

$$e = r_p/r \ldots\ldots\ldots\ldots\ldots (III).$$

The value of e may be determined if the resistance constant r is evaluated in terms of the quadrantal points of the velocity circle, thus:[4]

$$r/(2m) = (\omega_2 - \omega_1)/2$$

from which $r = m(\omega_2 - \omega_1) = 2\pi m (f_2 - f_1)$, where m is the equivalent mass[5] of the diaphragm. Then from the motional-impedance circle, $r = 2\pi m (f_2 - f_1)$; and from the motional-absorption circle, $r_a = 2\pi m (f_{2a} - f_{1a})$. Combining these values of r and r_a with (III). gives:

$$r_p/r = (r - r_a)/r = 1 - r_a/r = 1 - (f_{2a} - f_{1a})/(f_2 - f_1) = e,$$

the efficiency of the telephone diaphragm as a radiator of sound waves.

The efficiency from electrical input to diaphragm absorption may be given as $(dx/dt)^2 r / i^2 R = e'$, where i is the effective current in the coils and R is their electrical resistance. Then the overall acoustic efficiency E would be:

$$E = ee' = 2\pi m (dx/dt)^2 (f_2 - f_{2a} - f_1 + f_{1a})/(i^2 R)$$

NOTES: This method (omitting the impedance bridge and receiver coils at end A of the flue) may be used to determine the coefficients of sound absorption over various frequency ranges for thin plates of metal or fabric used in the adjustment of the acoustics of rooms.

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[4] The Mechanics of Telephone Receiver Diaphragms, as Derived from their Motional-Impedance Circles. A. E. Kennelly and H. A. Affel, Proc. Am. Ac. of Arts and Sciences. Nov., 1915.

[5] Explorations over the Vibrating Surfaces of Telephonic Diaphragms under Simple Impressed Tones. A. E. Kennelly and H. O. Taylor. Proc. Am. Ac. of Arts and Sciences. April, 1915.