

May 11, 1937.

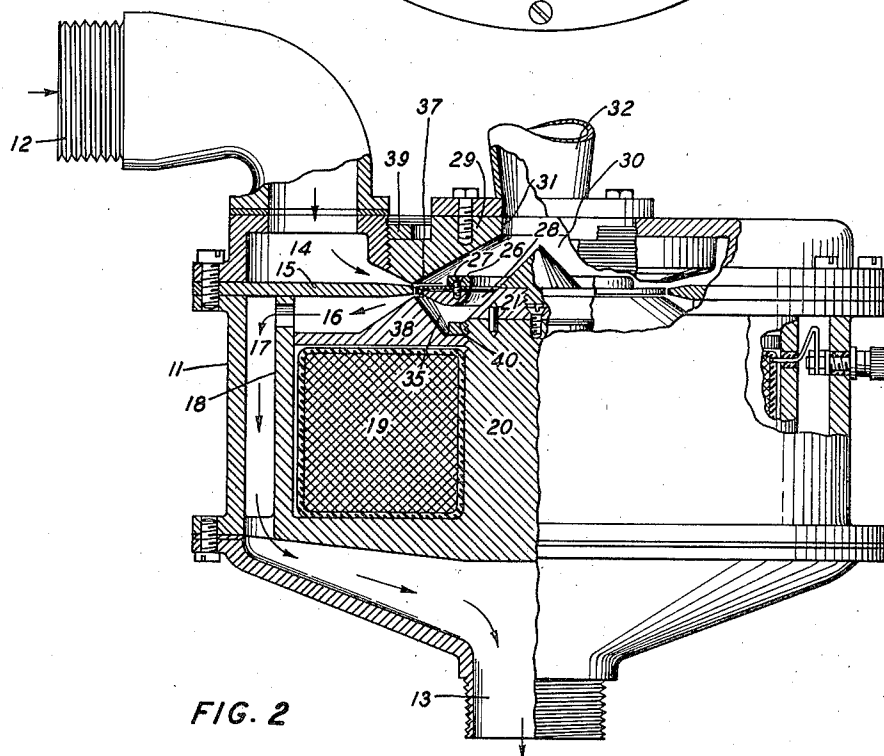
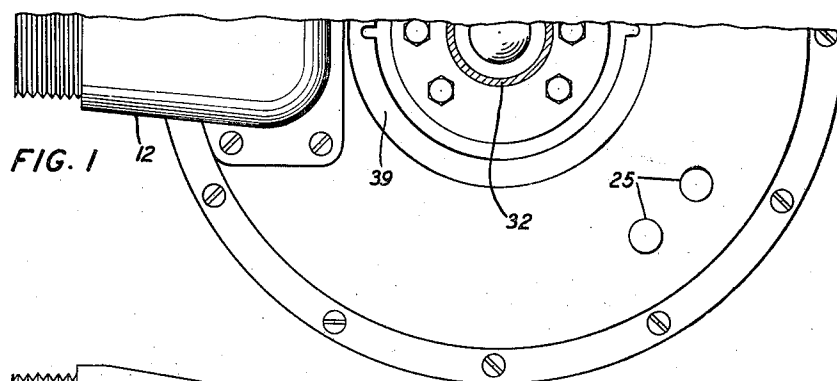
C. A. LOVELL

2,079,693

SOUND REPRODUCER

Filed Jan. 17, 1935

2 Sheets-Sheet 1



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FIG. 3

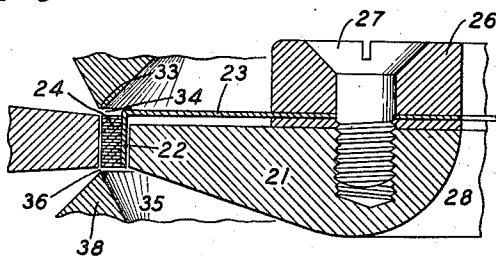


FIG. 4

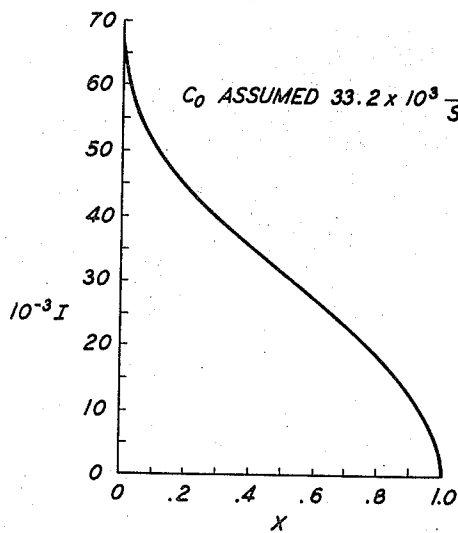
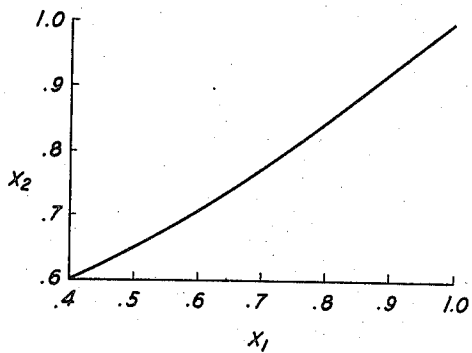


FIG. 5



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SOUND REPRODUCER

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Application January 17, 1935, Serial No. 2,307

9 Claims. (Cl. 179—108)

This invention relates to improvements in sound reproducing devices and particularly to such devices employing vibratory elements to modulate fluid streams for producing large volumes of sound. Sound reproducing devices of this type make use of a fluid stream such as air under pressure which is modulated by means of a non-sound radiating valve and which is usually passed out through a sound opening into the atmosphere.

The object of this invention is to produce sound with great volume and purity of tone and to accomplish this result in an efficient manner by means of a structure which converts a high percentage of the energy of compressed air or other fluid into sound without the distortion which would ordinarily occur with a high percentage energy conversion.

A loud-speaker or sound amplifying device according to the invention comprises in general a chamber having ducts for incoming and outgoing fluid streams, valving or modulating means for varying the cross-sectional area of orifices in the ducts in accordance with the sound to be produced and a separate sound radiating opening through which the fluid may or may not pass during the radiation of the sound depending on the choice of operating conditions.

In most cases of practical interest, the fluid used is compressed air and the sound radiating opening is the throat of an exponential horn. Such a horn will radiate sound frequencies within its operating range without appreciable distortion and it is therefore said to be a linear device. Applicant has found, however, that when such a horn is used with a sound amplifying device according to this invention, an appreciable steady flow of air through the horn causes it to become non-linear in its operation. According to an important feature of this invention the device is designed to generate alternating pressures of great magnitude at the sound opening or horn throat with no appreciable steady flow of air to the horn. This is accomplished by connecting the outgoing air duct to the intake of the compressor supplying the compressed air and proportioning the normal area of the orifices to the absolute pressures of the incoming and outgoing fluid streams so that the average flows through the orifices are substantially equal and no appreciable steady flow through the horn can occur.

In these loud speakers or amplifying devices, the modulating or valving means does not, itself, radiate sound to any extent and the sound output is proportional to the square of the displacement

of the modulator whereas the output of a radiating device is proportional to the square of its velocity. A feature of this invention, therefore, is a modulator vibratory system which has such low mass and mechanical resistance to vibration that its impedance is substantially a pure elasticity over the range of frequencies for which the frequency is to be constant. In the preferred structure the valve is an annular member of any suitable light material such as duralumin or a light magnesium alloy and has a short cylindrical portion adapted to carry the actuating means such as a coil, the narrow annular flange projecting inwardly and being rigidly secured to suitable mountings to provide proper support and impedance to vibrations of the valve under the influence of the driving coil. The cylindrical portion of the valve member may be of metal of good conductivity in which eddy currents are induced when the member is set in vibration to provide all or a part of the damping necessary for the proper frequency response of the device. This construction has the further advantage that it provides a leakage path between the incoming and outgoing fluid streams in shunt relation to the orifices so that the difference in pressures of the two fluid streams has no appreciable biasing effect on the modulator.

For minimum distortion in the sound produced by the device of this invention, it has been found that the amplitudes of the alternating components of the flow of fluid at the two orifices should be equal. This involves a particular proportioning of the orifice areas with respect to the fluid pressures used and in most cases results in the outlet orifice being larger than the inlet orifice.

When operating with no steady flow through the horn, maximum efficiency is obtained by a proper proportioning of the areas of the inlet orifice and the sound radiating opening. The numerical value of this ratio for a particular structure will depend on the choice of operating pressures and also on the area of the outlet orifice.

These and other features of the invention will be more clearly understood from the following detailed description and mathematical analysis of the factors underlying the design of these devices and the accompanying drawings in which Fig. 1 is a top or plan view of the device, Fig. 2 is a medium section and Fig. 3 an enlarged view of the modulator and air stream constriction and Figs. 4 and 5 are curves for facilitating the choice

of constants to meet the requirements of a particular case.

In the embodiment of the the invention shown in Figs. 1 to 3, the casing 11 is provided with an inlet duct 12 for connection with the discharge line of an air compressor and an outlet duct 13 for connection to the intake line of the compressor. The inlet duct terminates in a high pressure chamber 14 separated by an annular magnetic plate 15 from the low pressure chamber 16 which opens in passages 17 leading to the outlet duct. Beneath the plate 15 there is disposed a magnetic cup member 18 containing a magnetizing winding 19 and having a central pole 20 on which is mounted the pole-piece 21 which with the plate 15, defines an annular gap 37 in the circuit of the flux set up by the winding 19. Mounted in this gap on the vertical portion 22 of the annular metallic diaphragm 23 is a signal current coil 24 which may be connected to a sound pick-up circuit, or other source of currents to be amplified, by means of the terminals 25.

The diaphragm is secured to the pole-piece 21 by a clamping ring 26 and screws 27 and the pole-piece is provided at intervals with slots 28 to provide an air path between the upper and lower faces of the diaphragm to equalize the air pressure acting on it in accordance with the invention more fully disclosed in the copending application of C. A. Lovell and R. L. Wegel, Serial No. 2308, filed January 17, 1935. This equalization of the pressure very greatly reduces the stresses which the diaphragm must withstand and permits it to be made very thin and light so that its impedance to vibratory motion is small and is predominantly a stiffness over the operating range of frequencies.

Threaded into the upper part of the casing is an annular brass piece 29 defining the sound outlet chamber 30 and having a central radiating opening 31 leading into the throat of an exponential horn 32. The piece 29 is streamlined in accordance with well-known principles of design and tapers to an edge 33 above the coil to define an orifice 34 for the incoming air stream which passes from the chamber 30 into the chamber 35 through the slots 28 to the lower side of the coil where a similar orifice 36 leading into the chamber 16 is defined by the coil and the brass piece 38.

Since the orifices are the sections of greatest constriction of area in the air stream, most of the pressure drop occurs at the orifices so that the pressure is positive or above atmospheric in the chamber 14 and negative or less than atmospheric in the chamber 16. The direction of flow, however, can be reversed without changing the manner of operation except that the orifices must be readjusted, in accordance with the requirements explained below, to keep the average flow the same through each orifice and prevent a steady flow through the horn. It will be noted that the pieces 29 and 38 are both threaded and provided with clamping rings 39 and 40 so that the orifices can be adjusted to any relative size required for a particular operating condition.

When current flows in the coil 24, the coil is deflected from its equilibrium position and the area of one orifice is increased and the area of the other orifice decreased. This disturbs the equality of flow and causes an instantaneous flow through the horn equal to the difference of the flows through the two orifices. Hence, when

currents of the sound frequencies traverse the coil, the coil will vibrate about its position of equilibrium causing reversals of air flow in the horn corresponding to the current variations and producing sound radiations of great intensity from the horn mouth.

Since the acoustic resistance of the orifices is linear only for a limited range of areas, vibrations of the modulating coil at large amplitudes would ordinarily introduce distortion, but the two orifices of this device operate analogously to two vacuum tubes in push-pull relation and cancel out all even order distortion products thereby making possible a much higher percentage modulation with satisfactory purity of tone than can be used in single orifice constructions. This greatly improves the efficiency and power capacity of the device and makes the invention particularly well adapted to applications requiring very large volumes of sound.

The design of a loud-speaker according to the invention and the factors underlying the adjustment of the orifices for best results will be more clearly understood from the following mathematical discussion.

For a clearer understanding of the references we define the following symbols:

r = radius in centimeters of the modulator edge (one-half the diameter of driving coil 24)

$S_{(1)}$ = effective area of orifice 34 in square centimeters

$S_{(2)}$ = effective area of orifice 36 in square centimeters

$I_{(1)}$ = linear discharge velocity of air through orifice 34 in c.c./sec.

$I_{(2)}$ = linear discharge velocity of air through orifice 36 in c.c./sec.

ρ_1 = density of air discharged through orifice 34 in grams/c.c.

ρ_2 = density of air discharged through orifice 36 in grams/c.c.

S_L = area of sound opening 31 in square centimeters

p_1 = absolute pressure in chamber 14 in

$\frac{\text{dynes}}{\text{cm.}^2}$

p_2 = absolute pressure in chamber 16 in

$\frac{\text{dynes}}{\text{cm.}^2}$

p_o = absolute average pressure at sound opening 31 in

$\frac{\text{dynes}}{\text{cm.}^2}$

q_o = amplitude of sinusoidal displacement of the modulator in centimeters

k = adiabatic constant of gas (about 1.405 for air)

$$m = \frac{k-1}{k} = (.287 \text{ for air})$$

C = velocity of sound in gas in $\frac{\text{cm.}}{\text{sec.}}$

$$X_1 = \frac{p_o}{p_1}$$

$$X_2 = \frac{p_2}{p_o}$$

R_L = acoustic resistance of sound opening 31

The equation for the velocity of the steady flow from the chamber 14 through orifice 34 is

$$I_{(1)} = C\sqrt{\frac{2}{k-1}}\sqrt{1-X_1^m} \quad (1)$$

while that through orifice 36 is

$$I_{(2)} = C\sqrt{\frac{2}{k-1}}\sqrt{1-X_2^m} \quad (2)$$

If we develop Equations (1) and (2) in Taylor's series about arbitrary initial points and retain only the first two terms in each series, that is, the terms representing the steady flow and the fundamental vibrations, we will have equations showing the effect on $I_{(1)}$ and $I_{(2)}$ respectively of causing small changes in pressure at the sound opening. We then have

$$I_{(1)} = I_1 \left[1 - \alpha_1 \left(\frac{\Delta X_1}{X_1} \right) \right] \quad (3)$$

$$I_{(2)} = I_2 \left[1 - \alpha_2 \left(\frac{\Delta X_2}{X_2} \right) \right] \quad (4)$$

where

$$I_1 = C\sqrt{\frac{2}{k-1}}\sqrt{1-X_1^m} \quad (5)$$

$$I_2 = C\sqrt{\frac{2}{k-1}}\sqrt{1-X_2^m} \quad (6)$$

$$\alpha_1 = \frac{m}{2} \frac{X_1^m}{1-X_1^m}, \quad (7)$$

$$\alpha_2 = \frac{m}{2} \frac{X_2^m}{1-X_2^m}. \quad (8)$$

Consider the effect of causing the areas of the orifices to undergo the sinusoidal variations given by

$$S_{(1)} = S_1[1 + \delta_1 \sin \omega t] = S_1[1 + \delta_1 \sin \theta] \quad (9)$$

$$S_{(2)} = S_2[1 - \delta_2 \sin \theta]$$

These variations will cause a pressure variation at the sound opening which we define as

$$\frac{\Delta p}{p_0} = \beta \sin \theta \quad (10)$$

It follows from definitions of X_1 and X_2 that

$$\frac{\Delta X_1}{X_1} = \beta \sin \theta \quad (11)$$

$$\frac{\Delta X_2}{X_2} = -\beta \sin \theta \quad (12)$$

hence (5) and (6) respectively become

$$I_{(1)} = I_1[1 - \alpha_1 \beta \sin \theta] \quad (13)$$

$$I_{(2)} = I_2[1 + \alpha_2 \beta \sin \theta] \quad (14)$$

The volume velocity through the orifice area 34 is

$$\dot{\Phi}_1 = S_{(1)} I_{(1)} = S_1 I_1 [1 + (\delta_1 - \alpha_1 \beta) \sin \theta - \alpha_1 \delta_1 \beta \sin^2 \theta] \quad (15)$$

while that through orifice area 36 is

$$\dot{\Phi}_2 = S_{(2)} I_{(2)} = S_2 I_2 [1 - (\delta_2 - \alpha_2 \beta) \sin \theta - \alpha_2 \delta_2 \beta \sin^2 \theta] \quad (16)$$

The discharge pressure of the orifice 34 is p_0 which is greater than p_2 , the discharge pressure of orifice 36. Hence ρ_1 is greater than ρ_2 and in accordance with the adiabatic theory of gases

$$\rho_2 = \rho_1 X_2^{(1-m)} \quad (17)$$

The volume velocity through orifice 36 measured at the density ρ_1 would be

$$\frac{\rho_2}{\rho_1} \dot{\Phi}_2 = \frac{\rho_2 S_2 I_2}{\rho_1} [1 - (\delta_2 - \alpha_2 \beta) \sin \theta - \alpha_2 \delta_2 \beta \sin^2 \theta] \quad (18)$$

The volume velocity through the sound opening due to the orifice variation is

$$\dot{\Phi} = \dot{\Phi}_1 - \frac{\rho_2}{\rho_1} \dot{\Phi}_2 = S_1 I_1 - \frac{\rho_2}{\rho_1} S_2 I_2 + \left[(\delta_1 - \alpha_1 \beta) S_1 I_1 + \frac{\rho_2}{\rho_1} (\delta_2 - \alpha_2 \beta) S_2 I_2 \right] \sin \theta - \left[S_1 I_1 \alpha_1 \delta_1 - \frac{\rho_2}{\rho_1} S_2 I_2 \alpha_2 \delta_2 \right] \beta \sin^2 \theta. \quad (19)$$

The condition that the first order distortions from the two orifices cancel each other is that the coefficient of the $\sin^2 \theta$ term in Equation (19) vanish. The first term in (19) represents a steady flow through the horn and since appreciable steady flow will make the horn non-linear, it is desirable that this term vanish also. Under these conditions

$$\rho_1 S_1 I_1 - \rho_2 S_2 I_2 = 0 \quad (20)$$

and

$$\rho_1 S_1 I_1 \alpha_1 \delta_1 - \rho_2 S_2 I_2 \alpha_2 \delta_2 = 0 \quad (21)$$

Since the variation of both orifice areas is due to the displacement of the same modulator we have

$$\frac{\delta_1 S_1}{2\pi r} = \frac{\delta_2 S_2}{2\pi r} = q_0 \quad (22)$$

or

$$\delta_1 S_1 - \delta_2 S_2 = 0 \quad (23)$$

From the foregoing conditions, it follows that

$$\delta_1 \alpha_1 - \delta_2 \alpha_2 = 0 \quad (24)$$

$$\rho_1 I_1 \alpha_1 - \rho_2 I_2 \alpha_2 = 0 \quad (25)$$

Conversely if Equations (23), (24) and (25) are satisfied than (20) and (21) are satisfied. This is interesting since Equation (25) merely imposes a relation (Equation 27 below) between X_1 and X_2 , which can always be satisfied. Then if S_1 and S_2 are adjusted to satisfy Equations (23) and (24), first order distortions from the two orifices cancel each other. Using the definitions for α_1 and α_2 and Equation (17) we get from Equation (25)

$$\frac{X_1^m}{\sqrt{1-X_1^m}} = \frac{X_2}{\sqrt{1-X_2^m}} \quad (26)$$

which when solved for

$$X_1^m$$

gives

$$X_1^m = \frac{X_2^2}{2(1-X_2^m)} \left[\sqrt{1 + \frac{4(1-X_2^m)}{X_2^2}} - 1 \right] \quad (27)$$

The graph of Equation (27) is given by the curve of Fig. 5.

When these conditions are satisfied the volume flow through the sound opening given by (19) becomes

$$\dot{\Phi} = \frac{S_1 I_1 (1+R)}{R} [\delta_1 - R \alpha \beta] \sin \theta \quad (28)$$

where

$$R = \frac{\alpha_2}{\alpha_1} = \frac{S_2}{S_1} = \frac{\delta_1}{\delta_2} \quad (29)$$

The conversion efficiency of the speaker is defined as the ratio of the acoustic power radiated, to the compressed air power dissipated in the ori-

fices. The power dissipated in orifice 34 when the modulator is at rest is

$$\frac{dW}{dt} = \frac{1}{2} \rho_1 S_1 I_1^3$$

and that of the two orifices is

$$\frac{dW}{dt} = \frac{1}{2} \rho_1 S_1 I_1^3 + \frac{1}{2} \rho_2 S_2 I_2^3 \quad (30)$$

which can be written when Equation (20) is satisfied

$$\frac{dW}{dt} = \frac{1}{2} \rho_1 S_1 I_1^3 \left[1 + \left(\frac{I_2}{I_1} \right)^2 \right] \quad (31)$$

The average power radiated through the sound opening is

$$\frac{dw}{dt} = \frac{1}{2\pi} \int_0^{2\pi} \bar{R}_L \dot{\phi}^2 d\theta \quad (32)$$

where $\dot{\phi}$ is given by Equation (28) and

$$\bar{R}_L = \frac{\rho_1 C}{S_L} \quad (32a)$$

We get from Equation (32)

$$\frac{dw}{dt} = \frac{\bar{R}_L (1+R)^2 S_1^2 I_1^2 (\delta_1 - R\alpha_1 \beta)^2}{R^2} \quad (33)$$

From the relation

$$\Delta p = \bar{R}_L \dot{\phi} \quad (34)$$

we get

$$\frac{\Delta X_1}{X_1} = \beta = \frac{\rho_1 C S_1 I_1}{S_L P_o} \frac{1+R}{R} (\delta_1 - R\alpha_1 \beta) \quad (35)$$

From Equation (35) we have

$$\delta_1 - R\alpha_1 \beta = \frac{\delta_1}{1 + \frac{\rho_1 C I_1 (1+R) \alpha_1}{P_o} \frac{S_1}{S_L}} \quad (36)$$

and

$$\frac{dw}{dt} = \frac{\rho_1 C S_1^2 I_1^2 (1+R)^2}{2R^2 S_L} \frac{\delta_1^2}{\left[1 + \frac{\rho_1 C I_1 (1+R) \alpha_1}{P_o} \frac{S_1}{S_L} \right]^2} \quad (37)$$

Hence we have

$$\frac{dw}{dt} = \eta = \frac{C}{I_1 R^2} \frac{(1+R)^2}{\left[1 + \left(\frac{I_2}{I_1} \right)^2 \right]} \frac{\left(\frac{S_1}{S_L} \right) \delta_1^2}{\left[1 + \frac{\rho_1 C I_1 (1+R) \alpha_1}{P_o} \frac{S_1}{S_L} \right]^2} \quad (38)$$

If η be considered as a function of the ratio it can be shown to have a maximum, when

$$\frac{S_1}{S_L} = \frac{P_o}{\rho_1 C I_1 (1+R) \alpha_1} \quad (39)$$

and the value of the maximum is

$$\eta_{(max)} = \frac{(1+R) \delta_1^2}{4R^2 \left[1 + \left(\frac{I_2}{I_1} \right)^2 \right]} \frac{P_o}{\rho_1 I_1^2 \alpha_1} \quad (40)$$

Making use of the relation

$$\frac{P_o}{\rho_1 C^2} = \frac{1}{k} = (m-1) \quad (41)$$

we have

$$\eta_{(max)} = \frac{(1+R) \delta_1^2}{4R^2 \left[1 + \left(\frac{I_2}{I_1} \right)^2 \right]} X_1^m \quad (42)$$

Equation (39) gives the relation between the area of the sound opening and orifice 34 for maximum conversion efficiency. It can be rewritten to give the ratio of the sum of the orifice areas to that of the sound opening thus

$$\frac{S_1 + S_2}{S_L} = \frac{P_o}{\rho_1 C I_1 \alpha_1} = \frac{\sqrt{\frac{2(1-m)}{m}} (1 - X_1^m)}{X_1^m} \quad (43)$$

The Equation (37) becomes, when equation (39) is satisfied.

$$\left(\frac{dw}{dt} \right)_{max} = \frac{\rho_1 S_1 I_1^3 (1+R) \delta_1^2}{X_1^m 8R^2} \quad (44)$$

The method of adjusting the pressure and dimensioning the structure to operate according to the relationships developed in the above mathematical discussion will now be outlined briefly. Suppose we wish to construct a speaker which will radiate 100 watts of sound power. First we choose X_1 , say $X_1 = .58$. From Fig. 5 we get the corresponding value of X_2 , i. e., $X_2 = .70$. Then from Fig. 4 we get $I_1 = 2.82 \times 10^4$ cm./sec., $I_2 = 2.30 \times 10^4$ cm./sec. Then from Equation (7) and (8) respectively we get $\alpha_1 = .836$, $\alpha_2 = 1.32$. From Equation (29) we have

$$R = \frac{S_2}{S_1} = \frac{1.32}{.836} = 1.59$$

Choose $\delta_1 = .707$ then from Equation (44) we get, when we substitute for

$$\frac{dw}{dt} = 100 \text{ watts} = 10^9 \frac{\text{ergs}}{\text{sec.}}, S_1 = 1.31 \text{ sq. cm.}$$

Hence $S_2 = 2.06$ sq. cm. and $S_1 + S_2 = 3.37$ sq. cm. From Equation (43) we get $S_L = 3.34$ sq. cm. and all the essential constants of a loud-speaker according to the invention are then determined.

The above mathematical discussion is based on the use of a compressible gas but the Equations (20) and (21) are equally applicable to cases in which water or other so-called incompressible liquids are used as the transmitting medium. With an "incompressible" liquid, however, the densities at the two orifices are equal and the orifices are identical in both dimensions and operating pressures so that the equations are greatly simplified.

The invention is particularly well adapted for use as submarine signaling device, since the whole structure can be immersed and a stream of water modulated to radiate large volumes of sound through surrounding water. Most submarine signaling systems in use at present, due to their inherent mechanical properties are capable of radiating only high frequencies but the speaker of this invention is inherently more efficient at low frequencies than at high frequencies since its output is proportional to the square of the amplitude of the modulator vibrations. Moreover, due to the fact that the high static pressures of the water on the modulator are always equalized the modulator can be of relatively low mechanical impedance and hence of high efficiency.

What is claimed is:

1. In a sound amplifying device, an outlet chamber having a sound radiating opening, orifices in the chamber for continuous incoming and outgoing fluid streams and means for modulating both streams simultaneously at the orifices in accordance with sound to be produced.

2. In a sound amplifying device, an outlet chamber having a sound radiating opening, a stream-line passageway to the chamber for an incoming fluid stream, a stream-line passageway from the chamber for an outgoing fluid stream, and a single vibrating member constricting both passageways and modulating both streams in accordance with sound to be produced.

3. In a sound amplifying device, an outlet chamber having a sound radiating opening, orifices in the chamber for incoming and outgoing fluid streams, a coil disposed between and constricting the orifices, means for producing a mag-

netic flux through the coil and a metallic member supporting the coil for vibration and extending into the flux for damping the coil vibrations.

4. In a sound amplifying device, an outlet chamber having a sound radiating opening, incoming and outgoing fluid stream passageways for the chamber, a modulating member defining an orifice in each passageway, means for supporting the member, means for maintaining equal static pressures on the opposite sides of the supporting means, means for driving the member in accordance with sound to be produced and a fluid leakage path between the passageways adjacent the modulating member externally of the outlet chamber.

5. A sound amplifying device according to claim 1 in which the pressures of the continuous fluid streams and the areas of the orifices are proportioned to produce equal average flows of fluid through the orifices.

6. A sound amplifying device according to claim 1 in which the pressures of the continuous fluid streams and the areas of the orifices are proportioned to produce equal instantaneous amplitudes in the alternating components of the flow of the fluid through the two orifices.

7. A sound amplifying device according to claim 1 in which the area of the orifice for the outgoing stream is larger than the area of the orifice for the incoming stream.

8. A sound amplifying device according to claim 1 in which the pressure in the fluid streams

and the areas of the orifices are so proportioned that the ratio

$$\frac{p_2}{p_0}$$

is as large as the ratio

$$\frac{p_2}{p_1}$$

where p_0 is the pressure at the sound opening, p_1 is the pressure of the incoming stream and p_2 is the pressure of the outgoing stream, all of said pressures being in pounds per square inch absolute.

9. A sound amplifying device according to claim 1 in which the pressures of the fluid streams and the areas of the orifices are proportioned to produce equal average flows of fluid through the orifices and in which the ratio of the sum of the areas of the orifices to the area of the sound opening is substantially equal to

$$\frac{S_1 + S_2}{S_L} = \frac{2.23 \sqrt{1 - \left(\frac{p_0}{p_1}\right)^{.287}}}{\left(\frac{p_0}{p_1}\right)^{.287}}$$

where S_1 , S_2 and S_L are the areas in square inches of the incoming and outgoing orifices and the sound opening respectively, p_0 is the absolute pressure in pounds per square inch at the sound opening and p_1 is the absolute pressure in pounds per square inch of the incoming stream.

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