United States Patent [19]

Yando

[11] **3,727,719**

[45] **Apr. 17, 1973**

[54] **SOUND REPRODUCING SYSTEM**

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[22] Filed: **June 19, 1969**

[21] Appl. No.: **840,117**

[52] **U.S. Cl.** .....**181/31 B**

[51] **Int. Cl.**.....**G10k 13/00**, H04r 1/28

[58] **Field of Search**.....181/31.1

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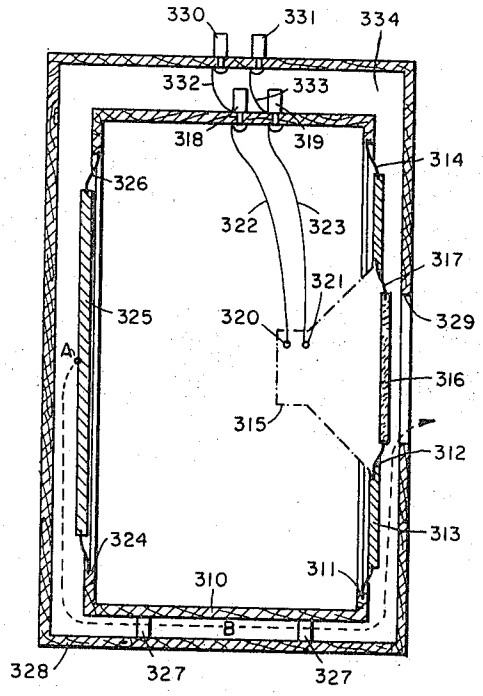
Primary Examiner—Stephen J. Tomsky

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[57] **ABSTRACT**

A dynamical system for the reproduction of sound. The system includes a relatively small enclosure with a driven loudspeaker cone and one or more free pistons suspended in airtight fashion in openings in the enclosure. A rigid shell having an opening juxtapositioned to the driven cone, may surround the enclosure, for purposes of increasing the coupling among free pistons and between free pistons and the driven cone.

10 Claims, 7 Drawing Figures



PATENTED APR 17 1973

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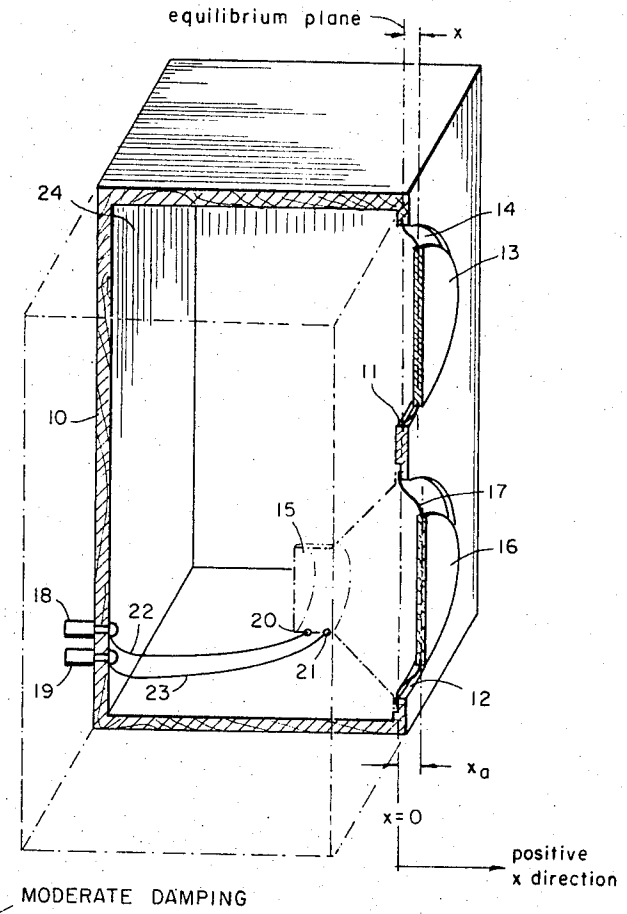


Fig. 1.

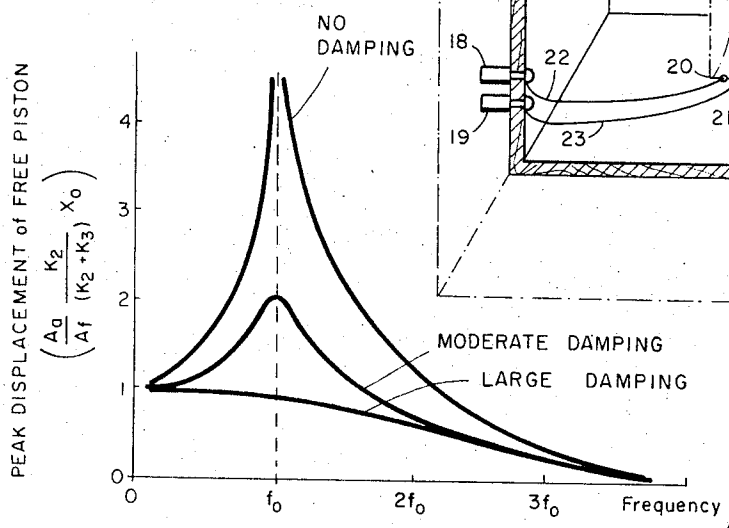


Fig. 2.

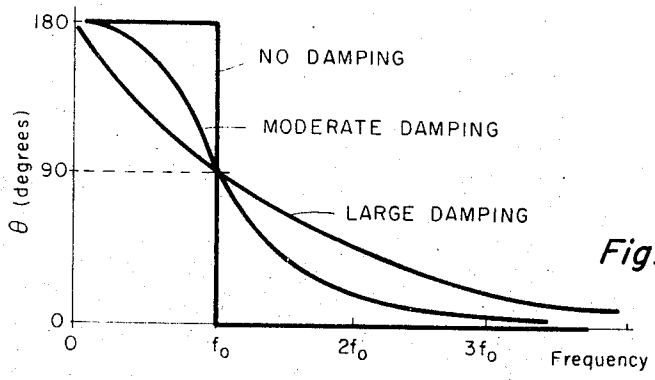


Fig. 3.

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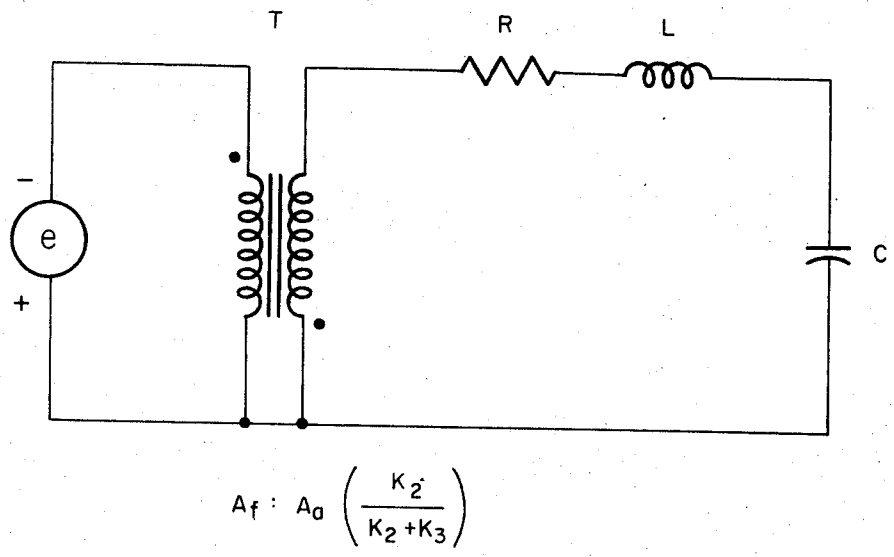


Fig. 4.

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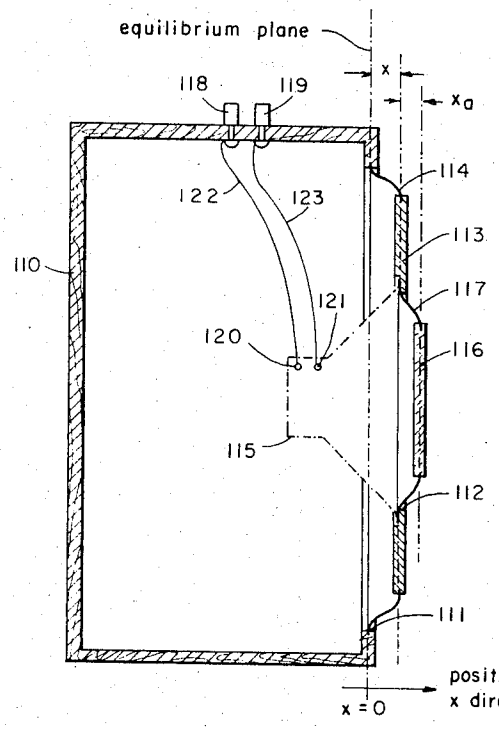


Fig. 5.

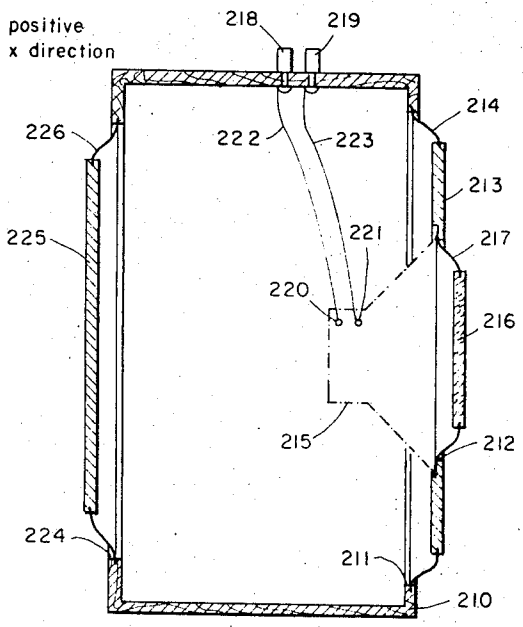


Fig. 6.

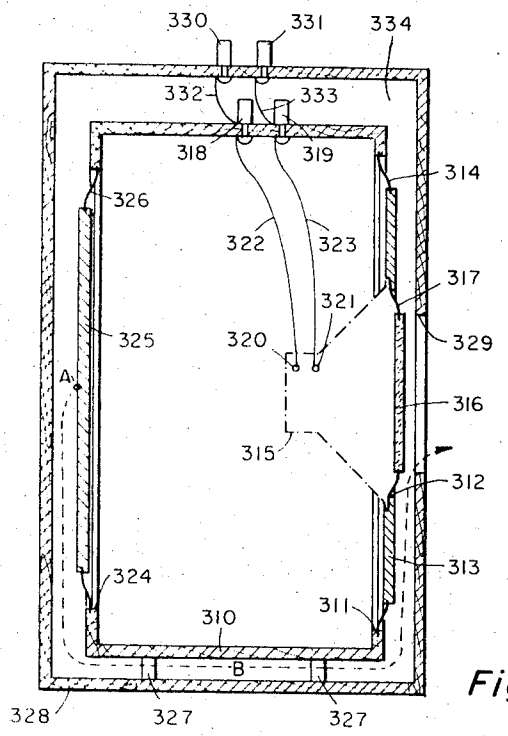


Fig. 7.

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SOUND REPRODUCING SYSTEM

This invention relates generally to loudspeaker enclosures but more specifically to a dynamic means for extending the frequency range and increasing the power output of a loudspeaker.

A loudspeaker is a device which converts electrical energy into acoustical energy via its electromagnetically driven cone. The front and back surfaces of the moving cone radiate sound waves and these constitute the acoustical output of the loudspeaker device. It is the destructive interference between these two waves, especially at low frequencies, which has always constituted the major problem in sound reproduction. Loudspeaker enclosures represent attempts to control these interference effects for the purpose of extending the lower frequency limit of a loudspeaker.

The earliest loudspeaker "enclosure" was based on the infinite baffle concept. According to this concept, the loudspeaker is mounted against a hole in a partition which extends to infinity in all directions. This confines the front and backside radiations to their respective hemispheres thereby eliminating all destructive interference effects. Even though the infinite baffle may be approximated by room partitions in practical situations, this approach was never very important because of its obvious costliness and inflexibility.

By folding a flat baffle into the form of an open backed cabinet a more practical form of speaker enclosure was evolved. The open backed cabinet is the most widely used loudspeaker enclosure today. It is the lowest cost enclosure, especially when the loudspeaker shares the cabinet space with electronic components as in a TV or radio set. The performance of the open backed enclosure is rather mediocre however, and where cost is not the primary consideration more elaborate enclosures are used to obtain improved sound quality.

A popular speaker enclosure in this category is the bass reflex type which is a closed cabinet with a proportioned port or vent located near the loudspeaker diaphragm. Due to its cabinet-vent resonance, the bass reflex enclosure shifts the phase of the rearward speaker radiation as it emerges through the port to reinforce the forward speaker radiation. In good bass reflex designs, the low frequency cutoff may be extended almost one octave below that of an open backed enclosure of the same volume. The main factors which limit the usefulness of the bass reflex enclosure are its relatively large size and its moderately high cost in relation to its performance level.

With the recent trend toward cheaper and higher power audio amplifiers, the relatively inefficient but high performance acoustic suspension speaker enclosure has come into its own. This enclosure is a fully sealed, rigid cabinet, packed with sound absorbing material, which contains and dissipates the backside radiation of the speaker. Such speaker enclosures are relatively compact and are capable of fine performance as is attested to by their wide usage. On the debit side, it can be said that they are rather inefficient and fairly expensive to construct. Furthermore, a special problem exists because the confined air places an elastic constraint on the backside of the speaker cone, thereby raising its natural resonant frequency. The result is that the acoustic suspension cabinet, though smaller than the bass reflex cabinet, nevertheless has its own

minimum volume requirement for any given level of performance.

Other speaker enclosures do exist which provide excellent performance but are not very widely used because they are larger and costlier than acoustic suspension systems. When viewed with respect to this present state-of-the art, the present invention represents an advance which will improve sound reproduction systems in the following ways;

It is an object of this invention to provide a sound reproduction system which is less costly than present types.

Another object of this invention is to provide a sound reproduction system which is more compact than present types.

Yet another object is to provide a sound reproduction system which will provide a higher level of performance than is possible in present types.

Still another object of this invention is to provide a more efficient sound reproduction system which derives useful acoustical radiation from the motion of the back surface of the speaker cone.

And finally, a further object of this invention is to provide a sound reproduction system which acts as an improved acoustic transformer and thereby increases the bass frequency power output of the loudspeaker.

The present invention is not to be narrowly classified as a loudspeaker enclosure because in reality it is a dynamical system of masses and elastances activated by an electrodynamic loudspeaker. By controlling the vibrational energies of the masses and elastances, the dynamical system creates acoustic radiations which augment those of the loudspeaker over a predetermined low frequency range. More specifically, the present invention consists of an airtight chamber with an electrodynamic loudspeaker mounted on one of its sides. At least one of the other sides of the chamber is flexibly suspended so it can move inwardly and outwardly with respect to the enclosed volume. The mass of the suspended side which we shall refer to as a free piston, is chosen to resonate with the effective elastic stiffness of the dynamical system at a predetermined frequency within the low frequency range.

When the voice coil of the loudspeaker is energized, its moving cone radiates acoustic energy directly from its front surface while its back surface, acting as a piston, modulates the air pressure within the chamber. These pressure modulations cause the free piston to vibrate characteristically; the greatest vibration occuring at a frequency where the mass of the free piston resonates with the effective elastic stiffness of the dynamical system.

At frequencies approximately equal to and greater than this frequency the acoustic radiation from the free piston will reinforce the direct loudspeaker radiation, resulting in an increased acoustic output. By a suitable choice of dynamical system parameters of which the system resonant frequency is but one, the acoustic output of the loudspeaker may be significantly enhanced over the low frequency range.

After the foregoing introduction it becomes appropriate to examine the present invention and its objects in more complete detail. This objective will be accomplished by the following detailed analysis and description in connection with the attached drawings wherein:

FIG. 1 is a cross-sectional perspective view taken at the central plane of symmetry which depicts the basic embodiment of my invention.

FIG. 2 is a diagram which shows the free piston vibrational amplitude characteristic as a function of frequency.

FIG. 3 is a diagram which shows the free piston vibrational phase characteristic as a function of frequency.

FIG. 4 shows an electrical circuit whose electrical behavior is analogous to the acoustical behavior of the embodiment of FIG. 1.

FIG. 5 is a cross-sectional view taken at the central plane of symmetry of a second embodiment of my invention.

FIG. 6 is a cross-sectional view taken at the central plane of symmetry of a third embodiment of my invention.

FIG. 7 is a cross-sectional view taken at the central plane of symmetry of a fourth embodiment of my invention.

Referring to FIG. 1 there is shown a rigid walled airtight chamber **10**, typically of wood construction, having two openings **11** and **12** in its front face. Although a wood chamber is suggested, any other construction material such as plastic or metal would be equally satisfactory. A rigid plate **13**, hereinafter to be referred to as the free piston **13** is suspended in opening **11** on an elastic membrane **14**. Said membrane **14** permits the free piston **13** to move to and fro about the equilibrium plane and also acts as seal to prevent the passage of air into and out of the chamber **10** through opening **11**. The mass of the free piston **13**, is so proportioned as to cause said free piston to resonate with the effective elastic stiffness of the dynamical system at a specified frequency within a predetermined low frequency range. Two sources; the enclosed air volume **24**, and the elastic membrane **14** contribute to the elastic stiffness of the dynamical system. Normally, a minimum system stiffness is desired and under such circumstances the use of a supple elastic membrane is indicated. A supple piston suspension, however, is not mandatory since stiff piston suspensions for the adjustment of the free piston resonant frequency are also envisioned within the scope of the invention.

A loudspeaker generally designated by the numeral **15**, and most typically of the electrodynamic type is mounted against and seals opening **12** of the airtight chamber **10**. The loudspeaker cone is represented diagrammatically by the rigid plate **16** with its elastic suspension **17**. The rigid plate **16** will hereinafter be referred to as the actual piston **16**. Two input terminals **18** and **19** passing through the walls of the chamber **10** in a substantially airtight manner are connected to voice coil terminals **20** and **21** with conductors **22** and **23**. Circular shapes were chosen for the openings **11**, **12**, and the free piston **13**, and the actuated piston **16** and all the other embodiments are assumed to have circular pistons as well. These choices are based on convenience rather than necessity and are not to be construed as a limitation on the geometry of the actuated or free pistons because other geometrical shapes would serve equally well.

In operation, an electrical current is applied to terminals **18** and **19** and this will produce a displacement x_a, of the actuated piston **16** from its equilibrium plane. This displacement will produce a pressure change within the airtight chamber which in turn will cause the free piston **13**, to be displaced a distance x from its equilibrium plane. These displacements result in a change of the enclosed volume **24**. At any given instant in time the volume of the chamber **10** may be expressed as,

$$v = V + (x_a A_a + x A_f) \tag{1}$$

where v = the instantaneous volume of the chamber

V = the equilibrium volume of the chamber when

$$x_a = x = O$$

A_a = effective area of the actuated piston

A_f = effective area of the free piston

In order to accomplish the objectives of this invention, the dimensions of the chamber are chosen to be small compared with the shortest acoustic wavelength in the predetermined low frequency range. Within this frequency range this chamber will be substantially devoid of pressure gradients and its enclosed volume can be described as isobaric. Under this condition the pressure at all points within the enclosed volume is given by:

$$p = (PV^n)/(v^n) \tag{2}$$

where p = the instantaneous pressure within the chamber

P = chamber pressure at equilibrium volume = atmospheric pressure = 14.7 psi.

The exponent n can be between unity for an isothermal process and 1.4 for an isentropic process. In practice, n will be between these extremes and will be dependent upon the frequency of the pressure cycle and the rate at which the enclosed air can exchange heat with its surroundings.

The instantaneous pressure changes within the chamber result in a pressure differential applied over the cross section of the free piston **13**. This pressure differential produces a force on the free piston which under typical circumstances is very closely given by:

$$F_d = (P - p) A_f = -(K_1 x_a + K_2 x) \tag{3}$$

where

$K_1 = (n P A_f A_a)/V$ and $K_2 = (n P A_f^2)/V$

In response to the force F_d, the free piston **13**, moves in accordance with the equation.

$$-K_1 x_a = m (d^2x)/dt^2 + r (dx)/dt + K x \tag{4}$$

where

m = the effective mass of the free piston

r = damping factor of the free piston

$K = K_2 + K_3$

K_3 = effective stiffness factor of the free piston suspension.

If a sinusoidally varying current is applied to the loudspeaker voice coil, then the displacement x_a of the actuated piston will also be a time varying sinusoidal function.

In particular, if we assume that:

$$x_a = X_o \operatorname{Cos} wt. \tag{5}$$

where $W = 2\pi f$

and f = *frequency of the displacement*

then solution of equation (4) reveals that the displacement x of the free piston will be;

$$x=\frac{K_1X_0\cos(wt-\theta)}{\sqrt{r^2w^2+(w^2m-K)^2}} \quad (6)$$

where the phase angle, θ, is defined by the implicit relationship:

$$\theta=\pi-\tan^{-1}(rw)/(K-w^2m) \quad (7)$$

Equations (6) and (7) reveal that the amplitude and the phase of the free piston motion are frequency dependent. An examination of equation (6) shows that the displacement of the free piston will be a maximum at the frequency f_o where

$$f_0=\frac{1}{2\pi}\sqrt{\frac{K}{m}}$$

The frequency f_o, shall hereinafter be referred to as the dynamical system resonant frequency. The special significance of this frequency becomes apparent upon examination of FIGS. 2 and 3.

FIG. 2 shows the relative magnitude of the displacement of the free piston in terms of the actuated piston displacement as a function of frequency. FIG. 2 shows that the motion of the free piston is profoundly influenced by the "damping" factor. By damping is meant the ratio of the energy lost from the dynamical system per cycle of vibration to the total energy stores in said dynamical system. The major fraction of this energy "loss" is in fact represented by the useful sound energy which is radiated from the outer face of the free piston. In an ideal case where no damping exists the free piston displacement increases without limit at the resonant frequency f_o and then gradually becomes smaller and smaller as the frequency increases. This resonant peak reduces to a finite value for moderate degrees of damping and actually vanishes as shown for large damping factors.

FIG. 3 shows the phase angle θ, of the free piston displacement with respect to the actuated piston displacement. This figure reveals that θ is equal to 180° at very low frequencies. This means that an inward or negative free piston displacement will result from an outward or positive actuated piston displacement. That this should be so is obvious when we realize that an outward movement of the actuated piston creates a low pressure in the chamber which in turn causes the free piston to be pushed inward by the external atmospheric pressure. As the frequency increases, the free piston mass causes its displacement to lag the chamber pressure excursions so that θ decreases to 90° at f_o, and approaches zero as the frequency increases beyond f_o. The acoustic radiations from the outer surfaces of the actuated and free pistons bear the same relative phase relationships as do their respective displacements. Thus, the acoustic radiation from the free piston will significantly reinforce that from the actuated piston at all frequencies higher than the dynamical system resonant frequency. In accomplishing this result, this dynamical system extends to the output of a loudspeaker to lower frequencies than has heretofore been possible with loudspeaker systems of comparable volume. FIG. 3 reveals another important characteristic of the present invention. Because the actuated and free piston displacements are substantially in phase above the dynamical

system resonant frequency, large pressure variations are produced in the airtight chamber which oppose the motion of the actuated piston. This restraining action loads the actuator motor and enables the system input power to be increased without driving the actuated piston beyond its limits of linearity. This unusual power handling capability stems from the isobaric specification for the enclosed volume of the airtight chamber, a specification which tightly couples the free piston to the actuated piston over the entire low frequency range. As a result, this dynamical sound reproducing system can obtain considerably more undistorted low frequency power from a given loudspeaker than is possible in any existing loudspeaker system.

FIG. 4 shows an electrical circuit whose electrical behavior is analogous to the kinematical behavior of the dynamical system of FIG. 1. The circuit parameters of FIG. 4 are related to the parameters of the dynamical system by the relationships:

$$e=x_a$$

$$R=rV/(n\,P\,A_f^2+K_3V)$$

$$L=mV/(n\,Pf^2+K_3V)$$

$$C=1$$

In this circuit the voltage source e, which is the analog of the actuated piston displacement, x_a, is coupled to the series RLC circuit by way of an ideal transformer, T, having a turns ratio of $A_f:A_a\,(K_2)/(K_2+K_3)$. By analogy with its known behavior as an electrical element, the ideal transformer, T, confirms the role that the assumed isobaric condition of the dynamical system plays in creating tight coupling between the actuated and free pistons over the low frequency range. The electrical energy dissipated in the resistance R represents the acoustic energy which is radiated from the free piston plus the small frictional losses in the dynamical system, and the electrical charge on the capacitor C represents the displacement, x, of the free piston. The inductance, L, is seen to be related to the proportions of the free piston and the enclosed volume of the dynamical system. Together the R, L, and C elements form a series circuit which resonates at f_o, the dynamical system resonant frequency.

Dynamical systems more complex than the embodiment of FIG. 1 are also envisioned within the scope of the present invention. For example, several free pistons proportioned to resonate at several frequencies could be employed in the dynamical system. Under such circumstances, a network more complex than the series circuit of FIG. 4 would be necessary to simulate the broader band behavior of the several free pistons.

FIG. 5 shows a second embodiment of my invention. In this figure there is shown a substantially rigid airtight chamber **110** having a large opening **111** in its front face. A rigid plate **113**, hereinafter to be referred to as the free piston **113**, is suspended in opening **111** on an elastic membrane **114**. Said membrane **114** permits the free piston **113** to freely move to and fro about its equilibrium plane and also acts as a seal to prevent the passage of air into and out of the chamber **110**. An opening **112** is provided in the free piston **113**. A loudspeaker **115** most typically of the electro dynamic type is rigidly mounted against and seals the opening **112** of

the free piston 113. The cone structure of this loudspeaker is represented diagrammatically by the rigid plate 116 and the mounting membrane 117. The rigid plate 116 will hereinafter be referred to as the actuated piston 116.

Two terminals 118 and 119 passing through the chamber 110 wall in an airtight manner are connected to the loudspeaker voice coil terminals 120 and 121 with electrical conductors 122 and 123 respectively. In operation an audio power amplifier connected to terminals 118 and 119 would supply the electrical power needed to energize the dynamical system.

The kinematics of operation of the embodiment of FIG. 5 are similar to that of FIG. 1 with an exception due to the mounting of loudspeaker 115 upon the free piston 113. Thus the frame and magnetic structure of the loudspeaker become an integral part of the free piston while the speaker cone or actuated piston, 116, suspended within the loudspeaker frame, retains its capacity for an independent motion relative to the free piston 113. The actuated piston displacement, x_a, relative to its own frame represents only a portion of its total displacement. The free piston displacement, x, is added to the relative displacement, x_a, to give the actuated piston, 116, a total displacement of $x + x_a$. This result serves to effectively increase the displacement capability of the loudspeaker thereby further improving its capability to produce bass frequency acoustic power. The embodiment of FIG. 5 will often times be preferred over that of FIG. 1 because it can provide improved performance at an equal or smaller cost. It may not always be possible however, to create a dynamical system based on the embodiment of FIG. 5 due to limitations imposed by the mass or other structural or operational features of the loudspeaker used. In such a case the embodiment of FIG. 1 is to be preferred.

Under some circumstances, when the free pistons of the embodiments of FIGS. 1 and 5 are relatively massive, objectionable vibrations will be induced in the body of the airtight chamber and transmitted to the surroundings. These objectionable vibrations are dealt with and substantially eliminated in a third embodiment of my invention which is shown in FIG. 6. The designating numerals 210 through 223 have their counterpart in numerals 110 through 123 respectively in FIG. 5. Thus the embodiment of FIG. 6 is very similar to that of FIG. 5 but with the addition of another opening 224, on the chamber wall opposite to that containing opening 211. A rigid plate 225, hereinafter to be referred to as free piston 225 is suspended within the opening 224 with the elastic membrane 226. The elastic membrane 226 permits the free piston 225 to move freely to and fro about its equilibrium plane and also acts as a seal to prevent the passage of air into and out of the airtight chamber 210. The mass and cross sectional area of free piston 225 is adjusted to be substantially equal to that of free piston 213. This adjustment assures that free pistons 213 and 225 will resonate with the elastic stiffness of the dynamical system at one and the same predetermined frequency. Under this circumstance, the momenta of free pistons 213 and 225 will be equal but oppositely directed thereby creating a dynamic balance which will leave the body of chamber 210 quiescent and free of all objectionable vibrations.

The embodiment of FIG. 6 represents a very simple dynamical system which is a highly satisfactory sound reproducer. A somewhat more complex embodiment with an even more enhanced low frequency output is shown in FIG. 7. This embodiment achieves its improved capability by increasing the acoustical interaction or coupling between the several pistons of the dynamical system. As is evident in FIG. 7, this important result is accomplished by mounting the embodiment of FIG. 6 on standoffs, 327, within an outer shell generally designated by the numeral 328. The numerals 310 through 326 represent the same details which were identified with the numerals 210 through 226 respectively in FIG. 6. The outer shell, 328, typically of wood construction, consists of substantially rigid non-movable surfaces and is provided with a port, 329, in a position preferably juxtaposed with the actuated piston, 316. Although a wood outer shell is suggested, any other construction material such as plastic or metal would be equally satisfactory. Two input terminals 330 and 331 are mounted in a substantially airtight manner in the outer shell, 328, and are electrically joined to terminals 318 and 319 of the airtight chamber, 310, with conductors 332 and 333, respectively. In operation an audio power amplifier connected to terminals, 330 and 331, would supply the electrical power needed to energize the dynamical system.

Typically, the dimensions of the airtight chamber, 310, and the outer shell, 328, are sufficiently small so that the distance from the most remote point, A, on free piston 325, taken along dotted line B to the port, 329, is small compared to the acoustic wavelengths in the prescribed low frequency range. This being so, the space, 334, between the chamber, 310, and the outer shell, 328, can be regarded as a conduit for communicating the acoustic pressure modulations created by free pistons, 313 and 325, to the actuated piston, 316, and the port, 329. The establishment of this short conduit has the effect of increasing the mutual acoustical coupling between pistons 313, 316, and 325 thereby causing an increased loading on the actuated piston, 316, and resulting in an increased power output over the prescribed low frequency range. In the mid and high frequency ranges, free pistons, 313 and 325 are quiescent and so make no contribution to the sound output and none is needed however, since the actuated piston, 316, can generate adequate amounts of acoustic power in these ranges.

The foregoing specifications have described a dynamical system for extending the low frequency range of a loudspeaker and for increasing its power output capability in this frequency range. The embodiments of FIGS. 1, 5, 6, and 7 were chosen to facilitate the explanation of the fundamental ideas upon which the present invention is based. Accordingly, the specifications shall be interpreted merely as illustrative and not limiting in any sense.

What is claimed as new is:

1. A dynamical system for the reproduction of sound which consists relatively small substantially airtight chamber having a plurality of openings, with rigid plates compliantly suspended in an airtight manner in each of the said openings, an electrodynamic loudspeaker having a cone rigidly mounted in an airtight manner within an opening in one of said plates, the

cone of said electrodynamic speaker being vibrated by the passage of electrical current through the voice coil of said electrodynamic loudspeaker, the mass and area of each of the said plates being proportioned so that at least one of said plates will be vibrating substantially in unison with the said speaker cone at each interval within a prescribed low frequency range, the plurality of the said plates being spatially arranged so as to minimize their combined momentum and a substantially rigid outer shell enclosing the airtight chamber for increasing the acoustical power output of the electrodynamic speaker, said outer shell provided with an opening juxtaposed to the loudspeaker cone.

2. A dynamical system for the reproduction of sound according to claim 1 and whose airtight chamber is proportioned so that its enclosed volume is substantially isobaric over said prescribed low frequency range.

3. A dynamical system for the reproduction of sound according to claim 2 where the mass and area of the plurality of the said plates are proportioned to vibrate at one and the same characteristic frequency, and substantially in unison with the said loudspeaker cone over the said prescribed low frequency range.

4. A dynamical system for the reproduction of sound, comprising:

a relatively small substantially airtight enclosure having a first opening on one side thereof;

a free piston in the form of a first rigid plate suspended in airtight fashion in said first opening by compliant means sealing the space between said plate and first opening; and

an actuated loudspeaker cone compliantly suspended in a second opening within said first rigid plate by compliant means sealing the space between said cone and said second opening.

5. A system in accordance with claim 4, further including at least an additional free piston compliantly suspended in airtight fashion in an opening formed in the wall of said enclosure, the spatial arrangement of the totality of said free pistons being such that the momenta of the several free pistons substantially cancel one another.

6. A system in accordance with claim 5, wherein said additional free piston comprises a second rigid plate mounted in a third opening at the wall of said enclosure opposite that bearing said cone and said first plate, said second plate being suspended in said third opening by compliant means sealing the space between said plate and said third opening.

7. A system in accordance with claim 5, further including a substantially rigid shell enclosing said dynamical system for increasing the acoustical coupling among free pistons and between free pistons and cone and thereby increase the power output of said system over its low frequency range, said shell being provided with a port juxtaposed to said driven cone for radiating sound energy from said system.

8. A dynamical system for the reproduction of sound, comprising:

a relatively small enclosure having at least one actuated loudspeaker cone and at least one free piston suspended in airtight fashion in openings in the walls thereof; and

a substantially rigid shell enclosing said small enclosure for increasing the coupling between said piston and cone and thereby increasing the power output of said dynamical system over the low frequency range of said system, said shell being provided with an opening in a position juxtaposed to said cone for radiating the sound energy output of said dynamical system.

9. A system in accordance with claim 8, including a plurality of said free pistons, the spatial arrangement of said pistons being such that the momenta of the several pistons substantially cancel one another.

10. A system in accordance with claim 9, wherein said free pistons comprise rigid plates.

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