United States Patent

Hance

[15] **3,690,405**

[45] **Sept. 12, 1972**

[54] **LOUDSPEAKER SYSTEM HAVING BASS RESPONSE RANGE BELOW SYSTEM RESONANCE**

[72] Inventor: **Edwin A. Hance,** 3920 Foothill Rd., Santa Barbara, Calif. 93105

[22] Filed: **Feb. 24, 1971**

[21] Appl. No.: **118,482**

Related U.S. Application Data

[63] Continuation of Ser. No. 744,574, July 12, 1968, abandoned, which is a continuation-in-part of Ser. No. 520,277, Jan. 12, 1966, abandoned.

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

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

[58] **Field of Search** ..... 181/31 B, 31 R

[56] **References Cited**

UNITED STATES PATENTS

1,837,755	12/1931	Carlisle et al.	181/31 B
2,766,839	10/1956	Baruch et al.	181/31 B
3,239,028	3/1966	Murray	181/31 B
3,371,742	3/1968	Norton et al.	181/31 B

FOREIGN PATENTS OR APPLICATIONS

1,142,754	4/1957	France	181/31 B

Primary Examiner—Stephen J. Tomsky
Attorney—Warren T. Jessup et al.

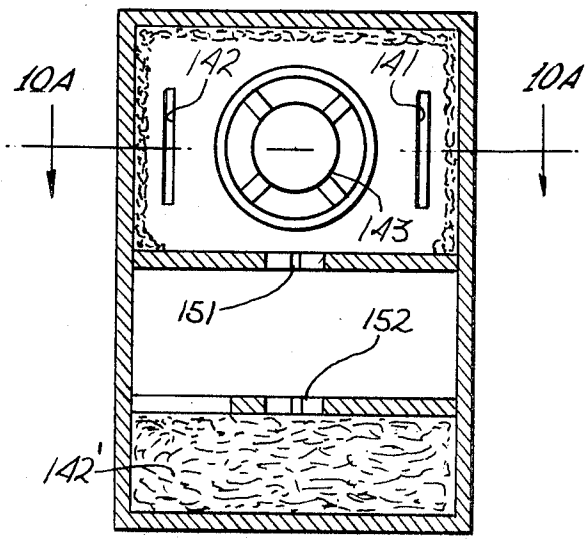
[57] **ABSTRACT**

The subject patent application is concerned with improvements over prior art systems relative to the processing of the speaker back-wave by acoustic networks that include a part, and the use of the back-wave to produce supporting port radiation in a frequency band below the basic resonance frequency of the system.

The structure includes essentially a pair of acoustic cavities, coupled by an aperture. The speaker is mounted in the first cavity. The second cavity may be subdivided and may include damping. A port aperture is included in one of the cavities. The improvements involve relationships between acoustic elements of inertance, capacitance and resistance that result in in-phase port radiation; and in relationships whereby smooth response is obtained while maintaining and improving the phase of port radiation relative to that of the speaker front-wave in the frequency region below system resonance.

The present invention concerns only the bass and lower midrange frequencies, and is intended for operation with 6 db/octave amplifier equalization in the bass range.

22 Claims, 32 Drawing Figures



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SHEET 1 OF 8

Fig. 1A

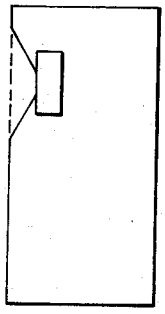


Fig. 2A

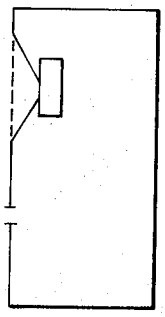


Fig. 3A

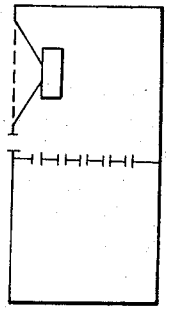


Fig. 3C

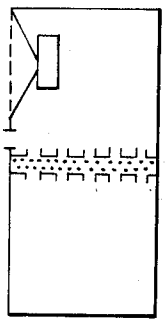


Fig. 4A

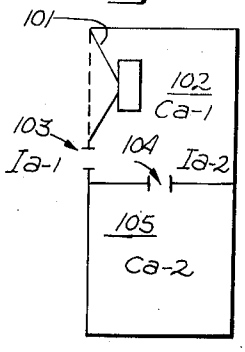
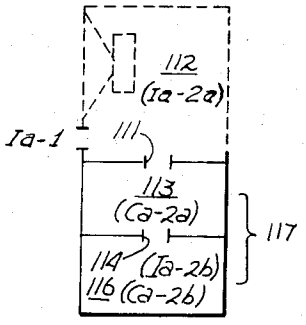


Fig. 5A



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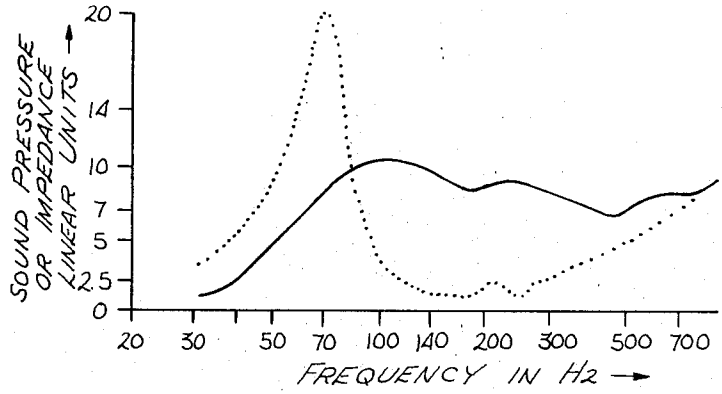


Fig. 1B

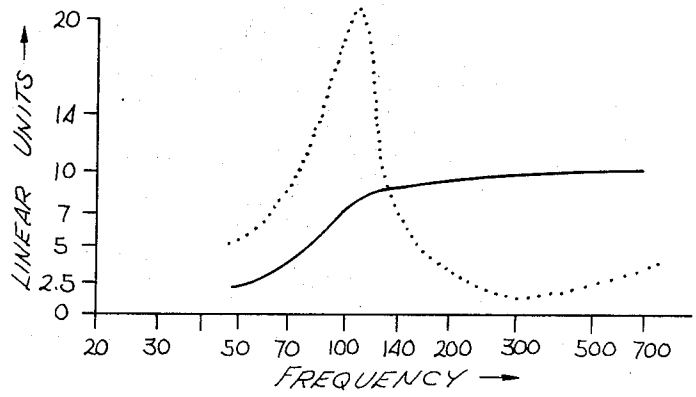


Fig. 1C

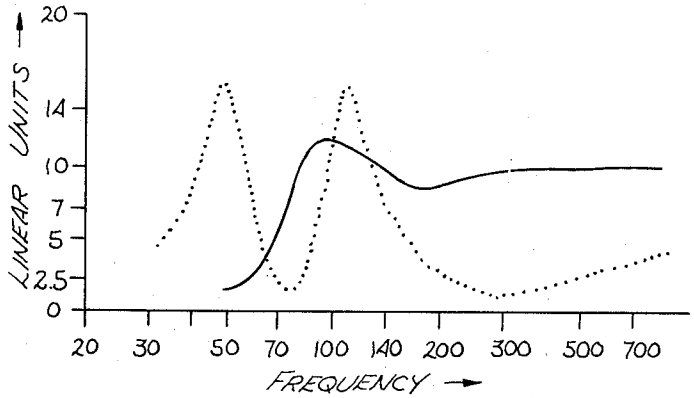


Fig. 2B

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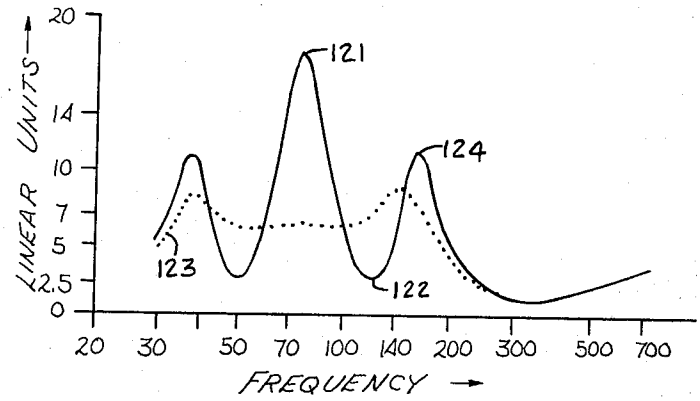


Fig. 3B

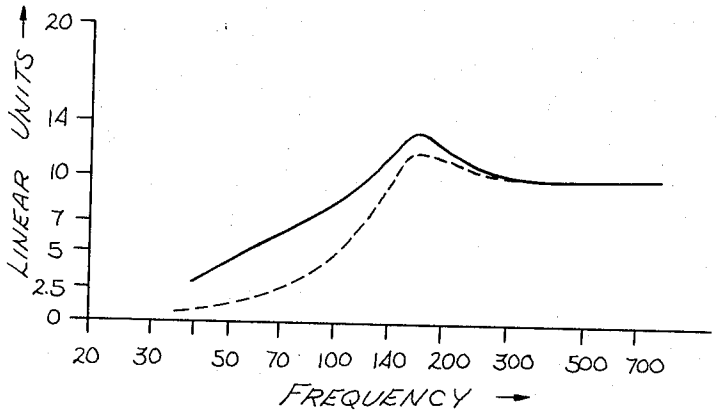


Fig. 3D

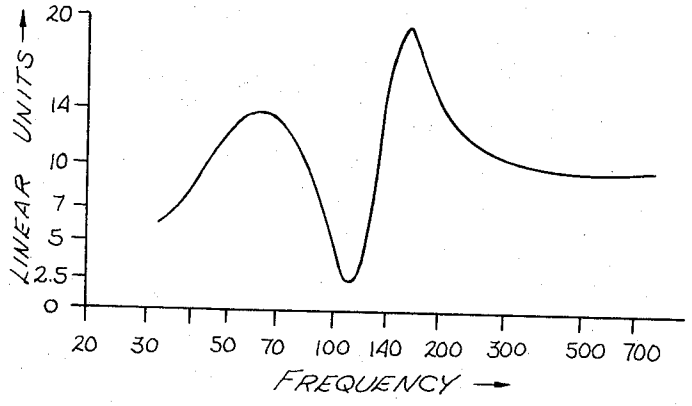


Fig. 4B

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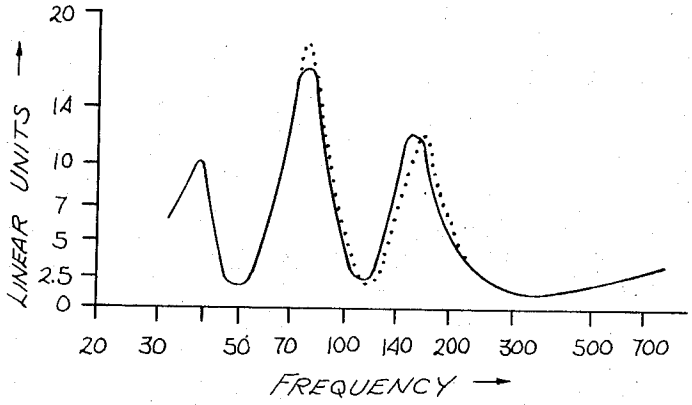


FIG. 5D

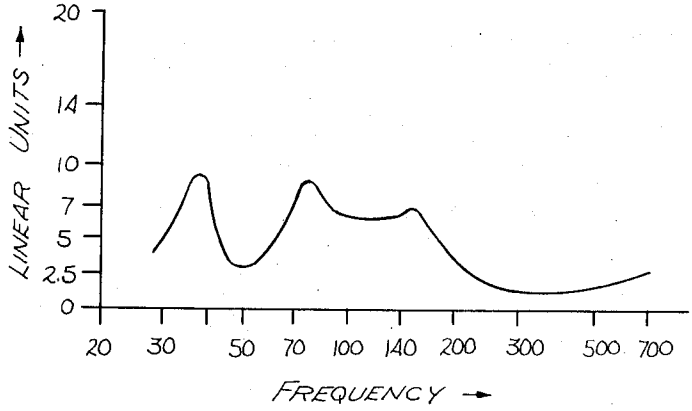


FIG. 6B

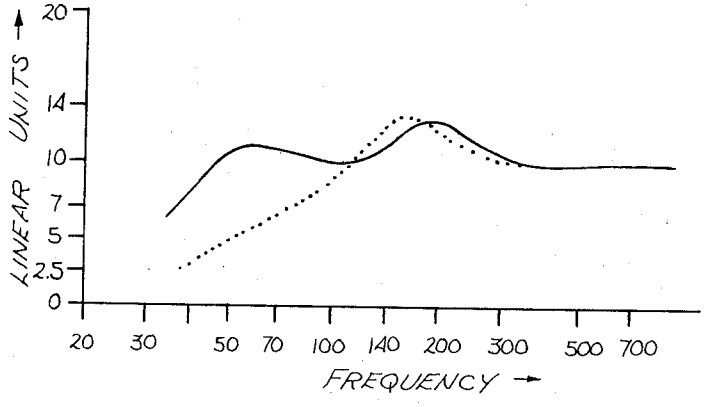


FIG. 6C

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Fig. 5B

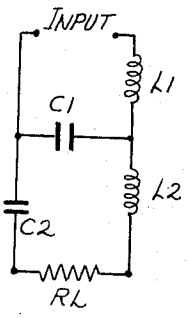


Fig. 6A

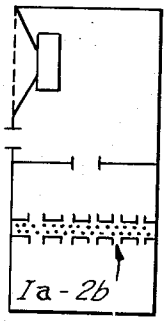


Fig. 6D

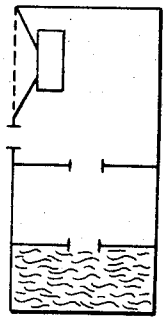


Fig. 8A

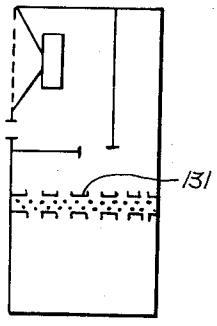


Fig. 9A

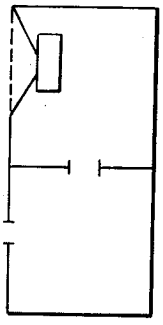
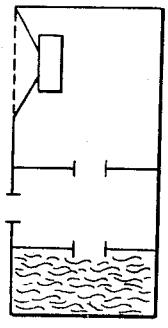


Fig. 9D



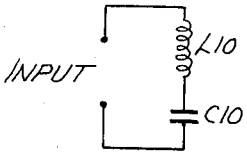


Fig. 4C

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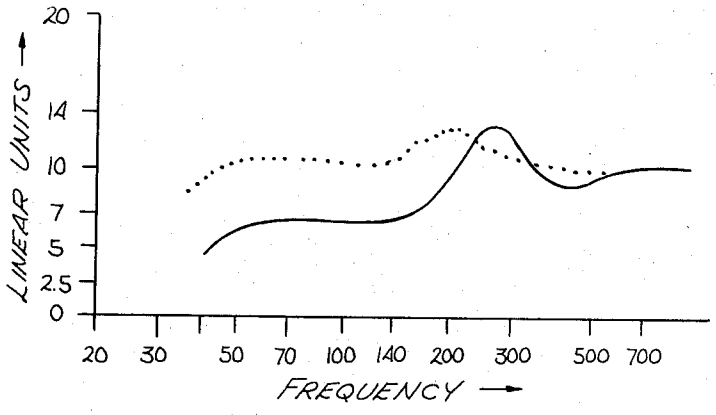


Fig. 7

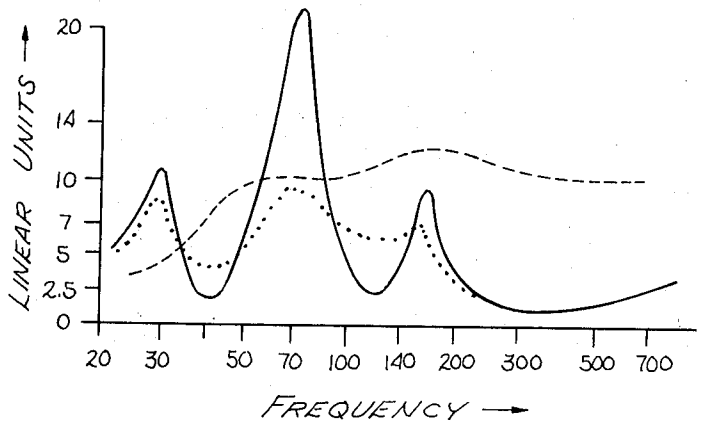


Fig. 8B

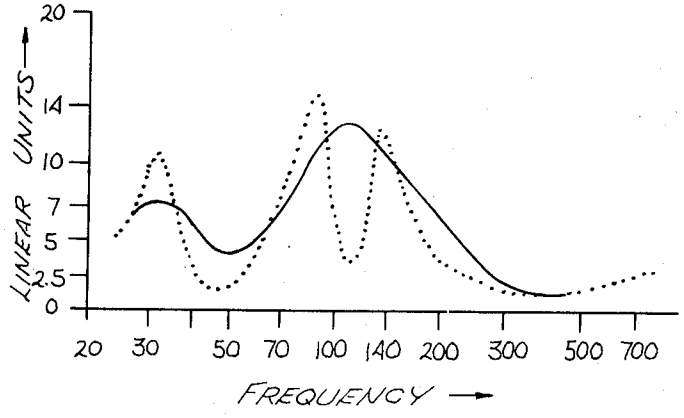


Fig. 9B

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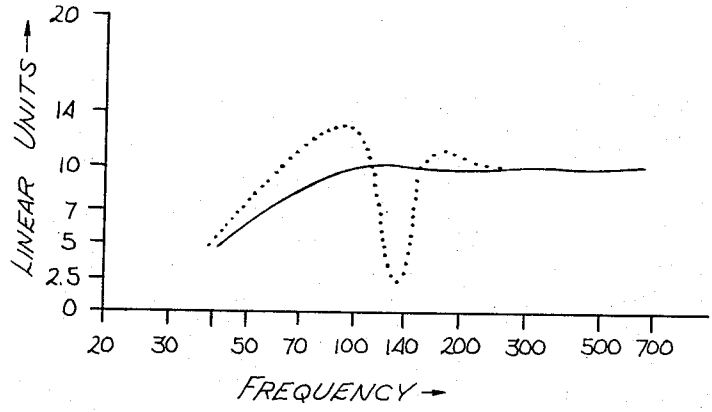


Fig. 9C

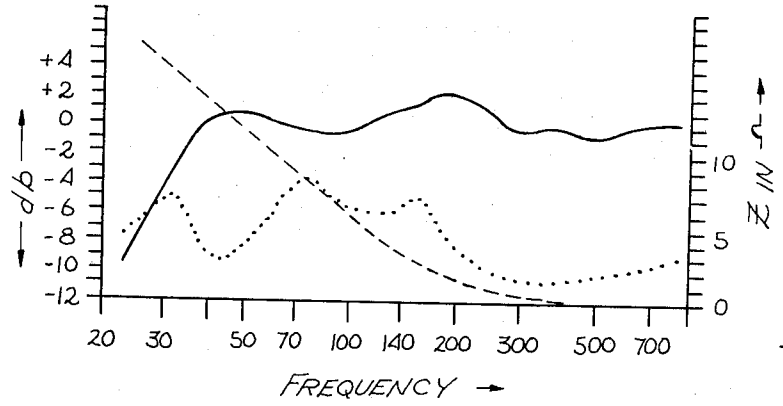


Fig. 10E

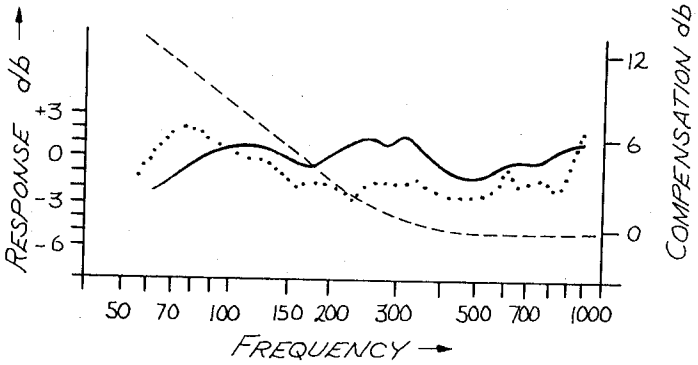


Fig. 11

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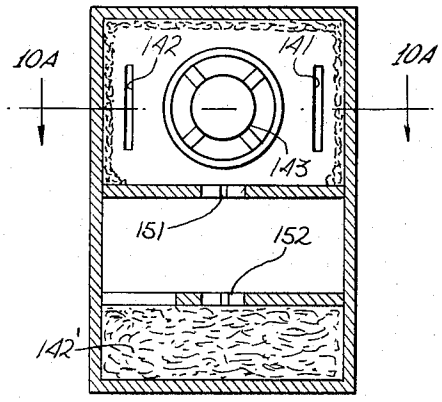


Fig. 10B

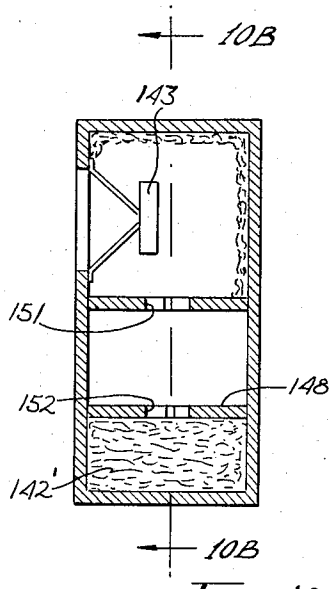


Fig. 10C

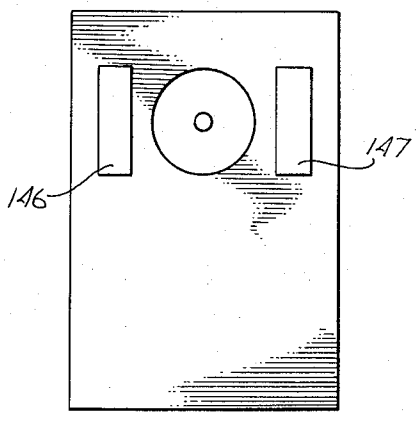


Fig. 10D

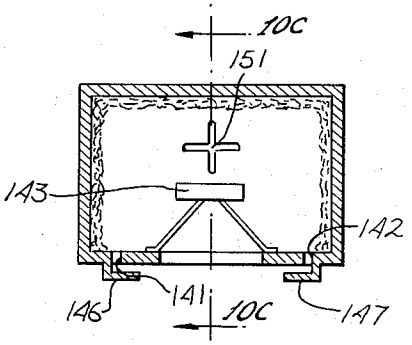


Fig. 10A

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LOUDSPEAKER SYSTEM HAVING BASS RESPONSE RANGE BELOW SYSTEM RESONANCE

This is a continuation of application, Ser. No. 744,574, filed July 12, 1968, now abandoned, which is a continuation-in-part of application, Ser. No. 520,277, filed Jan. 12, 1966, now abandoned. BACKGROUND OF THE INVENTION

The employment of piston-type direct radiator loudspeakers in the frequency region below that frequency for which the equivalent piston diameter is equal to a one-third wave length gives rise to severe problems. This invention relates to the employment of such loudspeakers in systems for the reproduction of sound in such frequency regions and the problems associated therewith.

One such problem arises from the requirement of separation of the speaker back-wave from the front-wave as these two waves originate 180° out of phase and will normally produce radiation cancellation at the lower frequencies. This problem is compounded when the physical requirements of the system are such that its dimensions must be small relative to the longest wavelength of sound to be reproduced.

Another such problem arises from the characteristics of acoustic radiation resistance in this frequency region. This resistance varies inversely as the square of frequency. See Elements of Acoustical Engineering by H. F. Olson, page 82, FIG. 5.1. Thus, a speaker in an infinite baffle must increase its cone excursion by a factor of four for each time the frequency is reduced by a factor of one-half, if flat frequency response is to be attained. This is the condition where the cone velocity is inversely proportional to frequency. See Elements of Acoustical Engineering by H. F. Olson, page 128. The extension of bass range in this type of system is, therefore, limited by the maximum practical excursion attainable.

The natural cone excursion characteristic, which corresponds to that produced when a speaker having constant reflected electrical impedance is driven by a constant current, is one of constant velocity. Under this condition the cone excursion will be proportional to $1/f$ (f=frequency) rather than the $1/f^2$ characteristic required for flat response when infinitely baffled. Hence, a speaker operating in this mode will produce a radiated sound pressure characteristic that is proportional to frequency; and if flat response is to be achieved, the system must be driven by an amplifier having a complementary $1/f$ gain characteristic. This represents a compensation of 6 db/octave. See Elements of Acoustical Engineering by H.F. Olson, pages 135 and 136.

A further problem arises when the back-wave of the speaker is confined by an enclosure that represents one or more acoustic elements having variable impedance characteristics relative to frequency. This problem is compounded when the enclosure includes an aperture or apertures that conduct acoustic volume current from the interior to the exterior. Under the latter circumstance, the reflected electrical impedance characteristic of the system is in no way directly indicative of the actual radiated sound pressure of the system.

Answers to the problems that have been set forth are found in two types of speaker systems that are in widespread current use. These are the "acoustic suspension" type and the "bass-reflex" type; however, each of these prevalent basic types has deficiencies of its own, leaving much to be desired. The deficiencies of systems of the acoustic suspension type lie in their lower efficiency and in their large cone excursion requirements. The deficiencies of systems of the bass-reflex type lie in their enclosure size requirements, being on the order of 2:1 greater than corresponding acoustic suspension types for a given bass range, and in their poor bass transient response characteristic. Although the operational and performance characteristics of these two basic system types are well known to persons skilled in this art, for the sake of clarity, they will be briefly reviewed here.

The name "acoustic suspension" takes its connotation from the concept of substituting the acoustic capacitance of a confined volume of air for the restoring force of the normally employed mechanical speaker cone suspension means. Ideally then, the cone resonance frequency would be the same, with the restoring force supplied by a cushion of air trapped in a cavity totally enclosing the speaker back-wave. When this resonance is optimumly damped, the system operates as a "mass controlled piston" mounted in an infinite baffle and provides flat response for frequencies above cone resonance. Below the cone resonance frequency, the response drops off at a 12 db/octave rate. See Elements of Acoustical Engineering by H. F. Olson, pages 130 and 131.

In actual operation, however, the mechanical compliance of the cone suspension cannot be made infinite, and there is a tendency for the cone to mechanically distort due to the large one-sided acoustic reactance into which it faces. The cone and voice coil, therefore, are made heavier than would normally be required. The efficiency, which is largely inversely proportional to the square of the piston mass, is thereby substantially reduced. See Elements of Acoustical Engineering by H. F. Olson, page 112, formula 7.3, and page 113.

The name "bass reflex" takes its connotation from the employment of the speaker back-wave in such a way as to reinforce the speaker front-wave in the bass frequency region. The utter simplicity of its form tends to belie the subtlty of its operational and performance characteristics. This type of system can respond smoothly and efficiently down to the cone resonance frequency of the speaker employed. Below this frequency both the radiation response and the acoustic cone loading drop very sharply. For approximately one octave above this frequency, the back-wave reinforces the front wave and at higher frequencies the system functions in essentially the same way as the acoustic suspension type. The speaker back-wave is enclosed by a cavity having a port or aperture communicating between the interior and the exterior of the enclosure. The acoustic capacitance of the cavity resonates with the acoustic inertance of the port at the resonance frequency of the speaker cone, The mechanical reactances of the speaker cone and the acoustical reactances of the speaker enclosure are thereby coupled together into a network having the characteristics of a type of "constant k " electrical wave filter. An equivalent electrical circuit of the system, with explanation and comments concerning the phase and impedance relationships and their effects, is given in

Sidelights on Loudspeaker Cabinet Design by D. E. L. Shorter, Wireless World, December 1950, page 487.

The well-known reflected impedance characteristic of the speaker in this type of system shows two sharp peaks, with a deep valley between them which centers on the speaker cone resonance frequency. Good results are achieved when the relationship between the speaker and enclosure volume is such that the peaks are separated by a factor on the order of two to one in frequency. Characteristically, the phase of the port radiation changes abruptly at the cone resonance frequency and is nearly 180° out of phase with the speaker front-wave in the region of the lower impedance peak. See Radiotron Designers Handbook, fourth edition, page 848, and Elements of Acoustical Engineering by H. F. Olson, page 132, which also gives the equivalent electrical circuit. The result of this is the sharp drop off in radiated sound pressure and in acoustic cone loading below the resonance frequency. This point in frequency may be more accurately defined as the frequency of resonance of the enclosure acoustic capacitance with the acoustic inertance of the port, which is normally the same as the cone resonance frequency. There is little, if any, effective response in the region of the lower impedance peak, and the response in the region between the valley center and the upper impedance peak is sustained by port radiation produced from the resonance of the enclosure, resulting in poor bass transient response.

Various efforts have been made to combine the characteristics of these two basic system types, but the results have been largely a matter of trading off the disadvantages of one type against those of the other type. Also various modifications have been taught in prior art. One such modification is taught by R. W. Carlisle, et al., in their U.S. Pat. No. 1,837,755. The speaker cone and suspension are considered to resonate with the speaker cone compartment at a definite frequency. This is in keeping with the concept of the acoustic suspension type of system. The object of the invention is expressed as that of critically damping this aforementioned resonance by acoustical means. In its preferred embodiment, an additional cavity is coupled to the speaker compartment by means of an aperture and substantial damping is employed in relation to the coupling aperture. Also, an aperture or port is shown communicating between the interior of the added cavity and the exterior of the system and having substantial damping associated with it. The preferred damping technique is that of employing "flow resistance" in the region of the apertures. Inasmuch as no mention is made of either useful port radiation, or port radiation phase, it is evident that the intent is one of substantially destroying the speaker back-wave energy before such energy has the opportunity of producing exterior radiation. This being the case, the system operates in essentially the same way as the acoustic suspension type with optimum damping achieved acoustically rather than electrically.

Another modification, shown for example in Baruch Lang, U.S. Pat. No. 2,766,839, is taught wherein a bass reflex system is deliberately reduced below its optimum enclosure volume, and modifications are made to reduce the resulting deficiencies. The system is designed with the intention of being operated at the intersection of three mutually perpendicular surfaces, which would normally be the corner of a room. This placement provides improved radiation resistance at the bass frequencies. Response curves given are made from measurements taken under these conditions.

The undersize enclosure volume results in a strong peak in response in the region of the upper impedance peak which is difficult to suppress. Suppression of this peak is accomplished by dividing off a portion of the enclosure cavity with a partition having an array of holes in it, which constitute an aperture, and flow-resistance damping is employed in conjunction with the holes. The acoustic inertance of the aperture is such as to resonate with the divided-off portion of the cavity at a frequency corresponding to the upper impedance peak. The radiation response curves given show little advantage due to the modification other than suppression of the response peak referred to. The basic system functioning is the same as that of the ordinary bass reflex type.

A still further modification is taught in Leon, French Pat. No. 1.142.754, wherein the normal acoustical configuration of the bass reflex type of system is altered by partitioning the enclosure into two cavities, the second cavity being coupled to the first by one or more openings or slits in the partition, This alteration is also shown in application to a speaker mounted in an unvented enclosure. Reference is made to the curve of reflected electrical impedance as an expression of the acoustic pressure on the speaker cone relative to frequency, and the regulation of this curve in the vicinity of a horizontal line is referred to as being the criterion of improvement of speaker system performance.

The typical two-peak and valley reflected electrical impedance curve of the bass reflex type of system is presented as one in which improvements are made in accordance with the teaching. The alleged improvement resulting from the application of the teaching is shown by an electrical impedance curve wherein the two impedance peaks are merged into one new broad impedance peak centered on the frequency that was formerly that of the valley. No mention is made to either the amount or phase of port radiation, or to the required $1/f^2$ cone excursion characteristic, where no port radiation exists. While Leon alludes to the incorporation of additional partitions to create new cavities, he gives no criteria whatever for their design, nor any hint of what different results would follow. It is significant that Leon shows no measurements of actual radiated sound output relative to frequency. It is evident that he made no such measurements, for had he done so, he would have found that the curve of actual radiated sound output bears little correlation to the impedance curve, shown for example in FIG. 4 of the Leon patent. Thus, Leon's FIG. 4, which neatly optimizes the electrical impedance curve, is associated with a corresponding curve of acoustic output which drops off sharply at frequencies below his original upper peak.

SUMMARY OF THE INVENTION

This invention relates to the application of certain modifications and relationships to the basic acoustic system configuration of two cavities, a speaker, a port

aperture, and coupling aperture means between the two cavities. This configuration bears some simularity to that shown in FIG. 2 of the Leon patent, French Pat. No. 1.142.754. When my modifications and relationships are applied to this acoustic configuration, different basic modes of operation are achieved which have important advantages over systems and techniques taught in the prior art..

These modifications and relationships result in a type of system that functions in the manner of constant impedance over the first two octaves of frequency range, and, therefore, it is intended for operation with amplifier frequency compensation of 6 db/octave over this portion of its range. Unlike other basic system types, this type of system produces substantial and effective radiated sound pressure in the octave below system resonance, and the speaker front-wave is supported by strong in-phase port radiation in this frequency region. The port radiation is effective in increasing both the frequency range and the power handling capability of the system. This is achieved without detriment to the frequency response characteristic above system resonance.

The system efficiency has a rising characteristic over the first two octaves that complements the amplifier frequency compensation. The mid-range efficiency tends to be correspondingly greater than that of other systems having the same frequency range and size of speaker and enclosure. The net result is one of substantially greater effective overall efficiency.

With the proper amplifier frequency compensation, this type of system will produce a substantially flat radiated sound pressure characteristic over the frequency range of concern. The system may be conveniently characterized by a unique relationship between speaker cone area, enclosure internal volume, and system resonance frequency. By the means of analysis and experimental investigations, I have determined what this relationship is and have incorporated it into a generalized formula from which the necessary basic design parameters can be determined.

In the preferred form of the invention, the loudspeaker is incorporated with an enclosure having an overall volume similar to that required for optimum performance in the normal bass reflex type of system. The enclosure is divided into two main compartments or cavities comprising acoustic capacitances which are coupled together by an aperture or ducting means comprising an acoustic inertance. The speaker compartment cavity is also coupled to the exterior atmosphere by an aperture or porting means comprising an acoustic inertance. These acoustic inertances are maintained as low in loss at the frequencies of primary concern as is reasonably feasible. The values of the acoustic inertance elements are so adjusted that together with the acoustic capacitances and the reactive mechanical elements of the speaker cone, they produce a short circuit terminated acoustic band-pass filter. The system thus far described corresponds to an electrical "constant k" band-pass filter.

The short-circuit terminated end of the acoustic filter is the second cavity. The reflected electrical impedance curve of this system is now characterized by three impedance peaks, one in the region of $1/2F_r$, one in the region of F_r, and one in the region of $2\ F_r$, where F_r represents the speaker cone resonance frequency. Thus, the three impedance maxima may be said to delineate a first and a second frequency band, each on the order of one octave in width, with the second sequentially following the first in frequency. Also, the frequency region between the uppermost impedance peak and the frequency above which the radiation resistance becomes constant may be considered as a third frequency band. Very important phenomena are produced by the reflected sound energy from the second cavity in the first and second frequency bands, resulting in port radiation characteristics that are inverted from those of the normal bass reflex system. This radiation maximizes in the lower frequency portion of the first band and in the upper region of the second band. The phase of this radiation is substantially the same as that of the speaker front-wave in the mid region of the first band, and strong supporting radiation occurs. In the second band, the phase of port radiation is such as to interfere with the speaker front-wave and this, combined with a high acoustic back-wave impedance, produces a deep valley in radiated sound output in the mid-band region. In the third band the system functions essentially the same as the acoustic suspension type.

In this invention the reflected energy that produces the deep valley of response in the second band is selectively absorbed in a way that does not appreciably alter the system operation in the first and third bands. This is accomplished by altering the second cavity in such a way as to produce an acoustic band-pass filter subsystem whose pass-band encompasses the region between the center and upper impedance peaks, and whose lower cut-off frequency coincides with the center reflected impedance peak, producing an acoustic impedance minimum at this point in the short-circuit terminated condition so that the reactance characteristic and acoustic functioning of the system remain essentially undisturbed. The filter sub-system is then provided with an acoustic resistance termination, thus absorbing the energy as stated. The out-of-band rejection of the sub-system filter increases rapidly beyond its theoretical cut-off frequencies, hence, the effect on the first and third bands is minimal.

The operational characteristics of the system are different in each of the three frequency bands. The basic acoustic band-pass network has a characteristic acoustic impedance (the electrical counterpart is equal to $\sqrt{L/C}$) which is reflected in the electrical impedance of the speaker. The dynamic source resistance of the driving amplifier is coupled to the acoustical network through the electroacoustical transductance of the speaker. In keeping with network theory, it is desirable that this source resistance be matched to the network characteristic impedance. Under this condition, in the first band the system operates in the manner of a band-pass filter that is terminated in a short circuit, but is driven by a generator of matching impedance. In the second band the operation is similar, but the filter is terminated in a resistance representing a matched load. In the third band, the system is unmatched as there is no characteristic impedance as such in this region and its operation is substantially that of a mass-controlled piston in an infinite baffle or acoustic suspension system.

Thus, in the first and second bands the operation is essentially that of a matched system and, therefore, has a radiated sound pressure response characteristic that rises at a rate of 6 db/octave with frequency through the two-octave range. Flat response is attained by incorporating a reverse frequency slope in the driving amplifier which can be done with a simple resistance-capacitance network. The system operated in this way provides relatively uniform frequency response down to one-half F_r. In the lower portion of the first band the acoustic power output for a given cone excursion is on the order of four times that of an equivalent acoustic suspension system so that only about one-half the cone excursion is required.

Also, the efficiency in the region of one-half F_r is essentially the same, and rises at the 6 db/octave rate, becoming on the order of 12 db greater in the region of the third band. In comparison with a corresponding bass reflex system, the third band efficiency is the same, but the efficiency drops off in the second and first bands. An additional octave of useful response is gained for a given enclosure size, and the bass transient ringing is substantially eliminated through a more gradual "roll-off" and phase rotation.

To gain the same response range from a corresponding bass reflex system would require an increase in cone assembly mass of four times so as to produce an octave drop of the cone resonance frequency. The effect on mid-range efficiency would be a loss of 12 db.

This invention also includes an additional modification that further improves the speaker acoustic loading in the region of one-half F_r, thereby further reducing the required cone excursion. This improvement is effected by deflecting the air particle velocity of the acoustic port current in the direction of the speaker cone. In this frequency region the port volume current phase in reference to that of the cone motion is such as to augment the radiation impedance. In this way the effective radiation resistance is increased at the lower frequencies.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a diagram of the "acoustic suspension" type of system.

FIG. 1B (dotted curve) is reflected electrical impedance characteristic of an acoustic suspension type of system. (Solid curve) illustrates the radiated sound pressure characteristic of an acoustic suspension type of system.

FIG. 1C (dotted curve) illustrates the reflected electrical impedance characteristic of an "infinite baffle" type of system. (Solid curve) illustrates the radiated sound pressure characteristic of same.

FIG. 2A is a diagram of a bass reflex type of system.

FIG. 2B (dotted curve) illustrates the reflected electrical impedance characteristic of a bass reflex system. (Solid curve) illustrates the radiated sound pressure characteristic of a bass reflex system.

FIG. 3A is a diagram of a bass reflex system divided into two cavities with multiple-hole coupling.

FIG. 3B (solid curve) illustrates the reflected electrical impedance characteristic of the system of FIG. 3A. (Dotted curve) illustrates the reflected electrical impedance characteristic of the system of FIG. 3A after adding optimum flow resistance to the inter-cavity coupling aperture.

FIG. 3C is a diagram of the system of FIG. 3A after adding flow resistance to the inter-cavity coupling aperture.

FIG. 3D (dash curve) illustrates the uncompensated radiated sound pressure characteristic of the system of FIG. 3C. (Solid curve) illustrates the compensated radiated sound pressure characteristic of the system of FIG. 3C.

FIG. 4A is a diagram of a basic two-cavity and port system (undamped).

FIG. 4B illustrates the compensated radiated sound pressure characteristic of the system of FIG. 4A.

FIG. 4C is the equivalent electrical circuit of the second cavity.

FIG. 5A is a diagram of the modified second cavity without termination and referencing acoustic elements.

FIG. 5B is the equivalent electrical circuit of the lower half of the system shown in FIG. 5A, including the coupling aperture from the speaker compartment to the lower half of the system.

FIG. 5D (solid curve) illustrates the reflected electrical impedance characteristic of the system of FIG. 4A with second cavity modified, but unterminated. (Dotted curve) is deviation of impedance characteristic from unmodified system in FIG. 4A.

FIG. 6A is a diagram of modified system with flow-resistance termination.

FIG. 6B is the reflected electrical impedance characteristic of system in FIG. 6A.

FIG. 6C (solid curve) illustrates the radiated sound pressure characteristic of the system in FIG. 6A. The dotted curve is the same as the solid curve in FIG. 3D.

FIG. 6D is a diagram of the system of FIG. 6A, except with sound absorbing material within the second sub-cavity for the termination.

FIG. 7 (dotted curve) illustrates the radiated sound pressure characteristic of the system in accordance with the invention and having the correct internal volume in accordance with formula. The solid curve is the characteristic with one-half correct volume.

FIG. 8A is a diagram of a modified system with unequal cavity volume.

FIG. 8B (dotted curve) illustrates the reflected electrical impedance characteristic of an unequal cavity, unmodified system. The solid curve illustrates the reflected electrical impedance characteristic of the system in FIG. 8A. The dash curve illustrates the radiated sound pressure characteristic of the system of FIG. 8A.

FIG. 9A is a diagram of the two-cavity system with port in second cavity, referencing acoustic elements.

FIG. 9B (dotted curve) illustrates the reflected electrical impedance characteristic of the system in FIG. 9A. The solid curve illustrates the impedance for the system in FIG. 9A, after modification.

FIG. 9C (dotted curve) illustrates the radiated sound pressure characteristic for the system in FIG. 9A. The solid curve illustrates the radiated sound pressure for the system in FIG. 9A with modifications.

FIG. 9D is a diagram of a modified system with port in second cavity.

FIG. 10A is a plan section taken on line 10A—10A in FIG. 10B of the preferred system with all improvements.

FIG. 10B is a sectional elevation taken on line 10B—10B in FIG. 10C of the preferred system with all improvements.

FIG. 10C is a cross section in elevation taken on line 10C—10C in FIG. 10A of the preferred system with all improvements.

FIG. 10D is a front elevation of the preferred system with all improvements.

FIG. 10E (solid curve) illustrates the radiated sound pressure of the preferred system. The dotted curve illustrates the reflected impedance of the preferred system.

FIG. 11 (solid curve) illustrates the response of the system with 5-inch speaker, following formula. The dash curve illustrates the amplifier equalization curve for the above. The dotted curve illustrates the relative response of an 8-inch acoustic suspension system, for comparison.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In the process of pursuing and evaluating the invention various other systems were investigated and their reflected electrical impedance characteristics were measured, as well as their radiated sound output response characteristics. Some of these measurements are pertinent to the presentation and understanding of the invention. These measurements have been made in the same manner and with the same equipment in each case. The reflected electrical impedance measurements have been made with a resistance bridge by balancing out the D.C. voice-coil resistance component of impedance and calibrating the balance error signal. These measurements, therefore, include the blocked voice-coil winding inductance which is a negligible factor at the bass frequencies. Relative sound output phase measurements have been made with a microphone that is sensitive to the pressure ingredient of the wave only, so that near field sound velocity effects were eliminated which otherwise could give erroneous results.

Radiated sound output measurements were made with the microphone and speaker placed adjustment to the earth's surface as a ground plane, so that the wavefront emanated perpendicular to the ground plane, thus eliminating reflections in the frequency region of concern. Possible error from waveform distortion or stray signal pickup was eliminated by monitoring the microphone output with a Lissajou oscilliscope pattern. Also, these measurements were made well away from major sound reflecting obstacles. See E. W. Kellogg, Journal Acoustical Society of America, Vol. 2, No. 2 Oct. 1930, pages 175, 185–187.

With the exception of an acoustic suspension type of system, the measurements were made of systems employing the same loudspeaker in an enclosure having the same overall internal volume. With this exception, the speaker employed throughout was an Altec Model 400B, which is an 8-inch cone-type speaker of professional quality and good efficiency. The cone functions essentially as a piston on the frequency range involved. The cone resonance frequency is 74 H_z when mounted on a small flat baffle. The same enclosure was used, being altered in each instance to produce the type of system under investigation, and the effective internal volume was held constant at 1.2 cubic feet.

I have used the same speaker and enclosure conditions for evaluation of some of the embodiments of this invention, thereby enabling direct and meaningful comparisons to be made. In each case presented, a limited amount of sound-absorbing material was employed on the walls of that part of the enclosure that comprised the speaker compartment. This was necessary to prevent internal reflections from causing peaks or valley in the 250- to 1,000-cycle region. The amount employed was insufficient to produce any noticeable effect on the low-frequency operation with the exception of a bass-reflex system wherein additional damping was required to produce optimum smoothness of low-frequency response. Where the enclosure consisted of more than one compartment or cavity, the sound absorption was limited to the speaker compartment only.

The simplest form of loudspeaker and enclosure system is that of the "acoustic suspension" type. My observation is that good quality acoustic suspension systems rely heavily on electrical damping to produce the desired cone excursion vs. frequency characteristic for flat radiated sound output. I have measured the reflected electrical impedance and the radiated sound pressure vs. frequency of a high quality, well-known and accepted system of this type, employing an 8-inch speaker. An acoustic diagram of the system appears in FIG. 1A. FIG. 1B shows the electrical reflected impedance and the radiated sound pressure output in relative linear units. Sound power output is proportional to the square of sound pressure. The dotted curve represents the reflected impedance and the solid curve represents the sound pressure output. It is obvious that there is little resemblance between the two curves. The resonance frequency of the system is indicated by the peak of the reflected impedance curve. Below this frequency the response falls off at a rate of 12 db/octave. This particular system is slightly underdamped, giving rise to the peak in response just above the resonance frequency. See Radiotron Designer's Handbook, 4th Ed., page 845, FIG. 20.12. The damping factor of the amplifier employed was very high. The internal volume of the enclosure is approximately 10.65 cubic feet.

Although it is in reverse order as to the historical sequence of development, the next logical step in complication of a loudspeaker and enclosure system is that of adding stiffness to the cone suspension, thus creating the "infinite baffle" type of system. This stiffness adds to the stiffness of the air trapped in the cavity behind the speaker and thus increases the resonance frequency of the system, resulting in a reduction of bass response range. However, an optimum amount of stiffness can aid the mid and and upper mid-range efficiency and smoothness of response. I have measured the reflected electrical impedance and the radiated sound pressure characteristic of such a system using the speaker and enclosure which I have described.

The basic structural form was essentially the same as that shown in FIG. 1A. The dotted curve in FIG. 1C shows the reflected electrical impedance. The solid curve in the same figure shows the radiated sound pressure. The same driving amplifier was used as was for the acoustic suspension system measurements.

Again, there is little resemblance between the radiated sound pressure output and the reflected electrical impedance curves. The cone resonance frequency of the speaker was increased from 74 to 95 cycles by the enclosure. Although the reflected impedance at 95 cycles is on the order of 20 times that which it is at 300 cycles, the actual response is down at least 6 db. This is

due to excessive electrical damping. Again, see Radiotron Designer's Handbook, 4th Ed. page 845, FIG. 20.12.

The apparent loss of bass is only relative. Actually, it is not so much a loss of bass as it is an increase in mid-range efficiency. This can be countered by the use of a lower amplifier damping factor or by compensation of the amplifier frequency response. The results clearly indicate that, with the electrical efficiency available in modern speakers, adequate damping of the resonance of the speaker cone and its compartment is readily achieved electrically and that special techniques for additional acoustic damping as taught by Carlisle, U.S. Pat. No. 1,837,755, are not necessary where the enclosure is essentially an infinite baffle.

I have altered this infinite baffle system to produce operation as a bass reflex type by providing an aperture opening between the interior and exterior of the enclosure. The area of the aperture was adjusted to produce the correct value of acoustic inertance to resonate with the acoustic capacitance of the enclosure cavity at the speaker cone resonance frequency. A diagram of the acoustic configuration is shown in FIG. 2A. The dotted curve in FIG. 2B shows the reflected electrical impedance, and the solid curve in the same figure shows the radiated sound pressure.

Here there is even less resemblance between the reflected electrical impedance curve and the actual radiated sound output curve. The valley minimum point between the two reflected impedance peaks represents the resonance frequency of the system. Although the impedance rises and reaches a strong peak below this frequency, the sound output breaks sharply at this point and continues to drop. My measurements indicate that the phase of port radiation relative to that of the speaker front-wave reverses abruptly at this frequency, below which it is largely 180° out-of-phase with the speaker front-wave. Hence, not only does the response drop abruptly, but so also does the acoustic cone loading, resulting in a correspondingly sharp drop in power handling capability. The increased bass response of this system over that of the infinite baffle system shown by the solid curve in FIG. 1C is the result of supporting port radiation augmented by strong acoustic resonance in the frequency region encompassing system resonance and the upper impedance peak.

Also, in the course of evaluating the invention, I have modified this speaker and enclosure bass reflex system in accordance with the teaching of Leon, French Pat. No. 1.142.754, for the purpose of damping the acoustic resonances that produce the reflected impedance peaks and evaluating the resulting radiated sound output vs. frequency characteristic. I partitioned the enclosure into two cavities, as shown in FIG. 3A, the speaker and port being in the first, and the second being coupled to the first by a plurality of ½-inch holes through the partition wall. The number of coupling holes was adjusted to produce resonance with the second cavity acoustic capacitance at the speaker cone resonance frequency. The area of the port aperture was likewise adjusted to resonate with the acoustic capacitance of the first cavity at the speaker cone resonance frequency. The resulting reflected electrical impedance is illustrated by the solid curve **121** in FIG. 3B. As shown, it is characterized by three major peaks, a characteristic that had not been noted by Leon in his patent. Also, there is little evidence of acoustic damping.

Leon refers to the use of openings or "fentes" which can be interpreted as "slits." Whatever Leon used, it appears to have produced substantially more acoustic damping (resistance) that the holes which I employed. For this reason, I added "flow-resistance" damping in a manner similar to that taught by R. W. Carlisle in U.S. Pat. No. 1,837,755, and by J. J. Baruch, U.S. Pat. No. 2,766,839.

Using the same configuration, I clamped layers of cloth between the dividing panel and an additional member containing a group of corresponding and aligned holes, as illustrated in the diagram FIG. 3C. After much experimenting with different materials I was able to produce the reflected electrical impedance characteristic shown by the dotted curve **123** in FIG. 3B, which represents the most uniform characteristic that I was able to attain. I then measured the radiated sound-pressure output which is shown by the dash curve in FIG. 3D. It is obvious that, although the reflected electrical impedance characteristic of this system is far more uniform that that of the simple bass reflex system, its performance is very inferior. Also, it is evident that this was not foreseen by Leon, as he taught in his patent that the performance of such systems could be evaluated from the "curve of impedance," referring to reflected electrical impedance, and that the criterion of improved performance is the regulation of this curve more in the vicinity of a straight and horizontal line.

It can be seen from the dotted reflected electrical impedance curve **123** in FIG. 3B that the impedance is relatively uniform over a nearly 4:1 frequency range commencing in the region of one-half the cone resonance frequency. Therefore, the cone excursion vs. frequency can be expected to largely follow a $1/f$ (f=frequency) characteristic. As previously noted, such a characteristic, when associated with an infinite plane baffle or total enclosure, results in a radiated sound pressure response that is proportional to frequency, and the required $1/f^2$ excursion characteristic for flat response may be realized through the employment of frequency response compensation in the associated amplifier system.

The required frequency slope of 6 db/octave over the necessary frequency range is obtainable by the employment of a simple R/C network at the amplifier input terminal. When this equalization is employed with the system of FIG. 3C, the resulting sound pressure radiation response is as shown in the solid curve in FIG. 3D. There is still severe loss of response in the region of speaker cone resonance and below, and the bass power handling capability is correspondingly poor.

I have found that this drop-off of response is directly attributable to the amplitude and phase differential of port radiation, relative to that of the speaker front-wave, and that the phase differential is primarily the result of dissipation of the speaker back-wave energy in the intercavity coupling means (the flow resistance associated with the holes between the two cavities in FIG. 3C.)

It was the investigation of this basic two-cavity and port type of system acoustic configuration that lead to my invention. I found that when a relatively low-loss coupling aperture means was employed between the two cavities, the system took on new characteristics that were basically different from the other systems and from the normal bass reflex system. To minimize losses, I used a single aperture to couple the cavities.

A diagram of the acoustic arrangement appears in FIG. 4A. The speaker **101** was mounted to and as a portion of the exterior wall of the first cavity **102** (C*a*–**1**). The inertance of the port aperture **103** (I*a*–**1**) was adjusted so as to resonate with Ca-**1** at the resonance frequency of the speaker cone. The inter-cavity coupling aperture **104** (I*a*-**2**) was likewise adjusted so as to resonate with the second cavity **105** (C*a*-**2**) at the speaker cone resonance frequency.

For convenience of reference, I will hereafter refer to the speaker-cone resonance frequency as F_r, the frequency of resonance of the port aperture with the first cavity as Fr-C**1**, and the frequency of resonance of the coupling aperture with the second cavity as $F_{r\text{-}C2}$.

The reflected electrical impedance curve of this system is characterized by three major impedance peaks instead of the two associated with the normal bass reflex system. The impedance curve of the speaker in the enclosure as described is essentially identical to the solid curve in FIG. 3B. However, the prime difference between this system and the bass reflex system lies in the phase vs. frequency characteristic of port radiation relative to the speaker cone front-wave. I found that the phase of the port radiation is substantially the same as that of the speaker front-wave in the region of the lower impedance valley and that it gradually rotates toward a 180° differential as the frequency was lowered, passing through 90° in the region of the lower impedance peak. Thus, in the frequency region below F_r, the port aperture radiation is substantially in-phase with the speaker cone front-wave and provides substantial supporting radiation down to approximately one-half F_r. In the region above F_r, the port radiation phase is such as to be destructive, and this, combined with a region of high acoustic back-wave impedance, results in a severe valley in the radiated sound pressure response, located between the center and the upper reflected electrical impedance peaks. Using the 6 db/octave amplifier frequency response compensation as described, the radiated sound pressure characteristic of this system is as shown by the curve in FIG. **4B**.

This basic two-cavity undamped system showed several important advantages over other systems. These included effective radiation with port radiation support in the octave frequency band below F_r, as well as comparatively small size. However, these advantages were unimpressive unless the valley in the radiated response could be eliminated, and unless a comparatively smooth transition in response between the compensated low frequency region and the uncompensated upper frequency region could be effected. I have devised certain modifications and relationships that overcome these problems and provide some further improvement in low frequency range.

I have found that the source of both the extended bass frequency range below F_r and the valley in response above F_r is in the reflected energy from the second cavity. Therefore, any damping that would normally or undiscriminatingly dissipate this energy would destroy both phenomena. The problem then is how to dissipate the energy in the response valley region without seriously interfering with the lower frequency response. This I have accomplished in a unique way.

I have devised a technique for modifying the second cavity in such a way that its reactance characteristic is essentially unaltered in respect to frequencies below F_r, while above F_r the cavity behaves as a band-pass filter and termination sub-system that effectively dissipates the energy in the response valley region without substantially affecting the energy in the lower frequency region.

The functioning of the unmodified second cavity is analogous to that of the series resonant electrical circuit shown in FIG. **4C**. In both cases, the input impedance approaches zero at the frequency of resonance.

The theory of operation of the band-pass filter is essentially the same as that of the equivalent electrical wave filter. A diagram of the acoustic configuration with zero acoustic terminating resistance is shown in FIG. **5A**. A circuit diagram of the equivalent electrical filter appears in FIG. **5B**. This circuit when short-circuit terminated, produces resonance at four frequencies, two of which can be referred to as "cut-off" frequencies. At the filter input terminal, the first or lower of these two frequencies appears as a point of near zero impedance, and the third appears as a point of near infinite impedance. Their location can be predetermined by proper calculation of circuit element values. Part of my technique is the substitution of the lower cut-off frequency for the unmodified second cavity resonance frequency Fr-C**2**.

The acoustic and electrical elements shown in FIGS. **4A**, **4C**, **5A** and **5B** are analogous as follows:

Acoustic capacitance, which is produced by cavity volume, is analogous to electrical capacitance.

Acoustic inertance, which is produced by the reactance of aperture openings and any ducting associated with them, is analogous to electrical inductance.

Acoustic resistance, which is produced by sound-absorbing material or flow-resistance, is analogous to electrical resistance.

In general, and for the purpose of this presentation, the following relationships may be considered to be essentially correct.

Where the physical dimensions are small relative to the wavelengths involved,

Acoustic capacitance is proportional to cavity volume;

Acoustic inertance is inversely proportional to aperture area where the path-length through the opening is held constant, and where the aperture is of a slot-type and the area is varied by changing the slot length.

Referring to FIGS. **4A** and **4C**, the specific analogue counterparts are as follows:

I*a*–**2** = intercavity coupling aperture **104**, corresponds to L**10**.

C*a*–**2** = second cavity **105**, corresponds to C**10**.

Referring to FIGS. **5A** and **5B**, the specific analogue counterparts are as follows:

Ia–$2a$ = coupling aperture **111** from the speaker compartment cavity **112** to the first sub-cavity **113**, corresponds to **L1**.

Ia–$2b$ = coupling aperture **114** between the first sub-cavity **113** and the second sub-cavity **116**, corresponds to **L2**.

Ca–$2a$ = first sub-cavity **113**, corresponds to **C1**.

Ca–$2b$ = second sub-cavity **116**, corresponds to **C2**.

As shown in FIG. **5A**, the second cavity **117** is divided into two coupled sub-cavities **113** and **116**, the sum of their volumes being equal to that of the original second cavity **105** in FIG. **4A**.

The band-pass filter consists of a "constant *k*" type of transmission arm, **L1** and **C1**, followed by a series resonant terminating arm, consisting of **L2**, **C2** and RL. In the acoustic case the transmission arm is represented by **111** (Ia–$2a$) and **113** (Ca–$2a$) ,and the series resonant terminating arm is represented by **114** (Ia–$2b$) and **116** (Ca–$2b$). Since no damping or flow resistance is shown in conjunction with Ia–$2b$ or Ca–$2b$ in FIG. **5A**, RL in the equivalent electrical circuit **5B** would be equal to zero.

Let it be assumed that the system of FIG. **4A** is constructed with optimum parameters to produce the response of FIG. **4B**. An arbitrary reference value of one will be assigned to Ia–2 and an arbitrary value of 1 will be assigned to Ca–2 in such optimum system. If the system is now modified to the system of **5A**, by dividing Ca–2 into Ca–$2a$ and Ca–$2b$ cavities of equal volume, then Ca–$2a$ plus Ca–$2b$ must equal Ca–2. Thus, each will have a value of 0.5.

I have found that the apertures **111** and **114** should each have an area on the order of 1.25 times the area of aperture **104** (FIG. 4A) for optimum performance of the modified system shown in FIG. **5A**, where a slot type of aperture is used and the area increased by lengthening the slot. By mathematical analysis of an optimum electrical system constituted per the a analogy of **5B**, I have found that **L1** and **L2** should each be 0.765 times **L10** in FIG. **4C**. Since inertance I is essentially proportional to the reciprocal of aperture area in this case, it follows that the corresponding calculated optimum area for Ia–$2a$ (**111**) and Ia–$2b$ (**114**) would be 1/0.765 or 1.31, very close to the actual area noted. Exact correlation is not possible because of the partially distributed nature of Ca–2, Ca–$2a$, and Ca–$2b$. Also, the relative distributed effect is altered by the division of Ca–2.

In reference to the electrical analogue system in FIG. **5B**, when the value of 0.765 is assigned to **L1** and **L2**, and the value of 0.5 is assigned to **C1** and **C2**, which corresponds to the acoustic case, the following unique relationships exist.

1. The lower cut-off frequency of the filter is the same as that of the resonance of **L10** with **C10** in FIG. **4C**, which corresponds to the unmodified second cavity.

2. In the octave below the lower cut-off frequency, the input impedance of the filter when RL=0 is essentially identical to that of the series resonant circuit of **L10** and **C10** in FIG. **4C**.

3. The resonance frequency of **L1** with **C1**, and **L2** with **C2** is at 1.62 times the resonance frequency of **L10** with **C10** ($F_{r\text{-}C2}$.)

4. The frequency of resonance of **L2** with **C1** and **C2**, which may be referred to as the upper cut-off frequency of the filter, is at 2.29 times the frequency of resonance of **L10** with **C10** ($F_{r\text{-}C2}$).

These relationships hold substantially the same for the acoustical case. As a result, the modified second cavity **117** in FIG. **5A** functions essentially the same acoustically as the unmodified second cavity **105** in FIG. **4A**.

The solid curve of FIG. **3B** represents the electrical impedance of the system of FIG. **3A**. The systems of **3A** and **4A** are the same, except that **3A** employed 16 one-half-inch holes between the cavities, whereas **4A** employed a pair of crossed slots, each arm being approximately 3 by ½inches. The impedance curves were very similar, as may be seen by comparing the solid curve of FIG. **3B**, with the dotted curve of FIG. **5D**, the latter represents the impedance of the system of FIG. **4A**.

Referring again to the solid curve in FIG. **3B**, it can be seen that the valley **122** between the middle and upper reflected impedance peaks is at essentially 1.6 times the frequency of the middle peak **121** ($F_{r\text{-}C2}$) and that the upper impedance peak **123** is at slightly more than twice this frequency. Hence, the frequency of resonance of the filter arms comprised by the modified second cavity (**117** in FIG. **5A**) substantially coincides with the valley frequency, while the lower cut-off frequency coincides with the middle impedance peak **121**, and the upper cut-off frequency falls somewhat above the upper impedance peak.

A simple way to show that the function of the band-pass filter modification of the second cavity is essentially the same as that of the unmodified second cavity before the incorporation of terminating resistance is to calculate the relative reactance produced by each at a significant series of relative frequencies. This can be readily done by substituting the reference values of electrical inductance and capacitance that I have previously assigned to the analogue electrical circuit elements in FIGS. **4C** and **5B** in the formulas governing reactances in series and reactances in parallel. RL in FIG. **5B** is set equal to zero. The formula for series inductive and capacitive reactance (Zs) is as follows:

$$Zs = \omega L - (1/\omega C)$$

where: $\omega = 2\pi$ frequency = 6.28 frequency

For simplification and convenience, an arbitrary value of 0.159 will be assigned to $F_{r\text{-}C2}$, resulting in a value of 1.0 for ω at this frequency. It is obvious from the formula that where the values of L and C are both equal to 1.0 as in FIG. **4C**, the series reactance is equal to zero, thereby producing series resonance at $F_{r\text{-}C2}$.

The 2π factor being a constant and ω being equal to 1.0 at $F_{r\text{-}C2}$, the other relative frequencies can be represented by varying the value of ω. For example, one-half ω would represent one-half $F_{r\text{-}C2}$, and 2ω would represent twice $F_{r\text{-}C2}$. The resulting values of series reactance for the different frequencies can thus be calculated for **L10** and **C10** in FIG. **4C**, and for **L2** and **C2** in FIG. **5B**.

The values of reactance produced by the paralleling of **C1** with **L2** + **C2** can then be calculated by the use of the general formula for parallel resistance or parallel reactance (Zp), which is:

$$1/Z_P = 1/Z_1 + 1/Z_2$$

In this case:

Z_1 = the reactance of C1

Z_2 = the reactance of L2 + C2

Having determined the value of *Zp* for the different frequencies, the values of reactance presented at the input terminal of the band-pass filter circuit in FIG. 5B can be calculated by adding the reactance of L1 to the reactance *Zp*.

Using this method, I have made up the following chart of reactances vs. frequency as represented by various values of ω:

	Reactance of FIG. 4C Circuit Input	Reactance of FIG. 5B Circuit Input
$\omega = 0.25$	−3.75	−3.74
$\omega = 9.375$	−2.29	−2.3
$\omega = 0.5$	−1.5	−1.49
$\omega = 0.75$	−0.68	−0.56
$\omega = 1.0$ ($F_{r\text{-}C2}$)	0.0	0.0
$\omega = 1.62$	+1.0	+1.24
$\omega = 2.0$	+1.5	+2.42
$\omega = 2.29$		∞

As can be seen from the foregoing chart, the reactances produced by the circuit of FIG. 4C and those produced by the circuit of FIG. 5B are essentially identical in the frequency region of 0.25 $F_{r\text{-}C2}$ up through $F_{r\text{-}C2}$. Above $F_{r\text{-}C2}$ a rising characteristic is evident for the circuit of FIG. 5B, which is due to the proximity of the upper cut-off frequency.

As this frequency represents a parallel resonance condition, the reactance is increasingly pushed up as it is approached. Under actual operating conditions, this phenomenon has little, if any, practical effect as will be evidenced by curves made from measurement of the acoustic system operation. Also, there is a series resonance at 2.62 $F_{r\text{-}C2}$. Although this resonance generally has no appreciable effect on the overall reflected impedance curve, it apparently is associated with a characteristic "hump" in radiated sound output in this frequency region. Under some conditions of adjustment, this resonance may result in an additional reflected electrical impedance peak.

In this particular application, however, the purpose of the filter shown in solid lines in FIG. 5A is to absorb the energy in its pass-band rather than to transmit it on. A terminating resistance or "load" is, therefore, required to absorb the energy. While the low-loss requirement holds true for I*a*–2*a* and C*a*–2*a*, certain losses in conjunction with I*a*–2*b* and C*a*–2*b* may function in the correct manner of load resistance. Specifically, flow resistance in conjunction with I*a*–2*b* and loss from sound-absorbing material within C*a*–2*b* can be used for the required resistive termination. Any loss in I*a*–2*a* will dissipate a proportionate amount of the reflected energy required to produce the extended bass range. Such loss should, therefore, be minimized.

It is difficult to define just how much loss can be tolerated in respect to the coupling aperture between the first and second cavities, and in respect to the first sub-cavity, as the effect is relative and, therefore, dependent on the system performance requirements. The effective loss due to the coupling aperture is doubled as

the reflected energy must make the transit twice. However, such loss as was associated with the 16 one-half-inch holes, used as the aperture means in the system of FIG. 3A, would not seriously derogate system performance. The phase of port radiation relative to that of the speaker front-wave in the frequency region below $F_{r\text{-}C2}$ is the best criterion in this respect. Failure of port radiation to support the speaker front-wave is a prime indicator of inadequate efficiency.

I have found that the use of flow-resistance in conjunction with I*a*–2*b* is analogous to the terminating resistance RL in the electrical filter circuit shown in FIG. 5B. In the electrical case, the correct value of terminating resistance is equal to $\sqrt{L/C}$. There is a correspondingly correct criterion for the acoustic terminating resistance. I have successively employed the same mechanism of flow-resistance that I have described previously herein. I increased the number of holes so as to provide the required reduction of total aperture inertance. A diagram of the acoustic configuration is shown in FIG. 6A. The effective absorption of energy in the response valley region is evident from the resulting reflected electrical impedance characteristic which is illustrated by curve in FIG. 6B. It can be seen that the effect on the lower frequency region is relatively minor. The resulting radiated sound pressure characteristic is illustrated by the solid curve in FIG. 6C. The dotted curve is shown with it for reference, as it is a duplication of the solid curve in FIG. 3D, which is the radiated sound pressure characteristic of the coupling aperture damped two-cavity system modeled after Leon. The same 6 db/octave low-frequency amplifier compensation was employed in both cases. As shown by the solid curve of FIG. 6C, the response valley of FIG. 4B is eliminated by the modifications of the second cavity, and the lower frequency response is essentially unaltered.

The use of sound-absorbing material within the second subcavity as shown in FIG. 6D produces results that are substantially the same as the incorporation of flow resistance in I*a*–2*b* (FIG. 6A). However, this type of damping is distributed and may have an effect on the tuning of the sub-cavities. The effect I have encountered is one of decreasing the effective capacitance of the first sub-cavity, while increasing the effective capacitance of the second. While this effect will vary with different types of material, I have found that it can generally be countered by making the first subcavity **113** 10 percent larger in volume than the second **116**, the sum of the two volumes being the same as before, and the first coupling aperture **111** being the same. The second coupling aperture **114** can usually also be the same, but some alteration may be required to optimize the tuning frequency. I prefer this type of termination because I have found it easier to work with and it can provide additional low-frequency selectivity.

The approach that I have used is to fill the entire second sub-cavity **116** with sound-absorbing material. I have found that shredded cotton batten and similar materials work well. The inter sub-cavity coupling aperture must be so shaped as to retain the material. For example, it may be composed of one or more slots, separate or crossed, or it may consist of a group of holes. Also, screening may be used to retain the material. The material packing density is important. The op-

timum packing density may be determined empirically, using the reflected impedance characteristic as a guide. A diagram of this type of enclosure configuration is illustrated in FIG. 6D.

The radiated sound pressure curves that I have shown in FIGS. 3D, 4B and 6C are all based on the use of the same given size of speaker, enclosure internal volume and second cavity resonance frequency, as described. Where the second cavity is modified into a band-pass filter, the lower cut-off frequency is the same as the resonance frequency of the unmodified second cavity. This resonance frequency, which I have referred to as $F_{r\text{-}C2}$, is generally the same as the speaker cone resonance frequency F_r. This relationship, however, is not at all critical, as the basic phase and amplitude relationships that extend the bass range are primarily a function of the enclosure configuration and adjustment. That is, the movement of the speaker cone at any given instance is the initiating phenomenon for the action and reaction of energy within the enclosure. Therefore, such action and reaction as occurs is automatically phase referenced to the speaker cone movement.

The important relationships are those between $F_{r\text{-}C2}$, the effective piston area of the speaker cone and the enclosure internal volume. I have found it necessary to hold these relationships within reasonable limits if a smooth transition between the response in the base frequency region and the response to the upper frequencies is to be realized. These relationships have been optimum in the examples that I have so far described. If the internal volume of the enclosure is too small relative to the cone area and $F_{r\text{-}C2}$, the acoustic back-wave impedance will interfere with the ability of the cone to respond at the lower frequencies, resulting in low relative bass efficiency and uneven response in the transition region. If the enclosure volume is larger than optimum, the bass efficiency will be too high and the bass response level will appear as a plateau lifted above the level of the upper frequencies. These effects tend to be independent of the hinge point used for the amplifier frequency response compensation, and find their source in the ratio of acoustic back-wave impedance to the front-wave radiation impedance. I have found that the back-wave impedance is inversely proportionate to $F_{r\text{-}C2}$ where the overall effective enclosure volume is held constant.

In accordance with this invention, I have discovered an optimum relation among enclosure sizes, speaker sizes, and frequency ranges, and I have developed a generalized formula for optimizing these relationships. By the use of this formula, speaker enclosures of this type can be scaled in respect to internal volume for speakers of different cone areas and for different frequency ranges. The formula is as follows:

$$V = 2.9\,A/F_{r\text{-}C2} + 80\% - 40\%$$

Where:

V = total effective volume of the internal air space in the complete enclosure in cubic feet

A = effective piston area of the speaker cone in square inches

$F_{r\text{-}C2}$ = frequency at which the reactance of said coupling aperture means is equal to and of opposite sign to that of said second cavity

The above value of V may vary from ±80% to −40%, while still retaining satisfactory and acceptable results within this invention.

In other words, $F_{r\text{-}C2}$ is the frequency at which the value of reactance resulting from the combination of the capacitance of the first sub-cavity with the effective inertance of the inter sub-cavity coupling aperture means, and the effective capacitance of the second sub-cavity, is equal in value to and of opposite sign to the value of reactance produced by the inertance of the coupling aperture to the first cavity (the intercavity coupling aperture). $F_{r\text{-}C2}$ may also be defined as the lower cut-off frequency of the band-pass filter subsystem.

My use of the word "aperture" is intended to include any means for accomplishing an acoustical inertance function equivalent to that disclosed above. For example, the acoustical inertance function may be performed by more than one opening and the opening or openings may include ducting or the function might be performed by one or more diaphragms which perform the coupling and inertance function. Also, as in the case of the inter sub-cavity coupling aperture, the acoustical inertance function may in some instances be physically combined with an acoustical resistance function and cavity division function through the employment of a porous or breathing type of dividing wall material. In such a case, the function is nonetheless accomplished, and the reactive component of the impedance thus produced should be considered in the determination of $F_{r\text{-}C2}$.

The same type of considerations apply to my use of the words "cavity" and "sub-cavity." For example, a block of porous material having such physical properties as to perform in the manner of a lossy resonant dielectric could function as the second sub-cavity in the second cavity modification. In such a case the inertance, capacitance and resistance would be inseparably distributed throughout the block. A portion, or one or more, of the block surfaces could function both as the means of division of the second cavity into sub-cavities and as the inertance coupling the two sub-cavities together. Although some of the acoustic elements may in some instances be physically inseparable, essentially the same basic relationships between the effective reactances must exist and should be taken into account in the determination of $F_{r\text{-}C2}$.

The permissible amount of down-side deviation in enclosure volume from that dictated by the formula is largely a matter of how much performance derogation the designer can tolerate. For example, the solid curve in FIG. 7 shows the typical effect of selecting a volume of only one-half that of optimum per the formula, the dotted curve being the characteristic with optimum enclosure volume. In most instances this much derogation would not be tolerable. However, where the system is to be operated at the intersection of two perpendicular planes, the radiation resistance is improved at the lower frequencies and the problem is partially alleviated. Therefore, a tolerance of −40 percent is representative of the maximum that could typically be tolerated under this condition.

Under the theoretical condition where the driving impedance of the speaker is matched to the acoustic impedance of the enclosure at optimum volume, a decrease of 40 percent in bass radiated sound power or −2.2 db. Likewise, under the same theoretical condition, an increase in enclosure volume of 80 percent

over optimum will result in an increase of radiated bass sound power of 66 percent or +2.2 db. Under practical conditions where a matched driving impedance is not realized, the loss or gain from deviation from optimum enclosure volume may be substantially greater as the solid curve in FIG. 7 indicates. Although it might appear that a deviation in either direction from optimum would result in a drop in sound output, the radiated sound output power is proportional to the square of volume current produced by the speaker cone movement rather than the amount of sound power delivered to the interior of the enclosure. Hence, an increase in enclosure volume results in a lower acoustic impedance, thus increasing the volume current and, hence, the radiated sound power output. Deviation on the up-side is, therefore, not as critical as deviation on the down-side, as it increases bass efficiency.

While the volume tolerance of −40 percent and +80 percent may appear broad, when related to the mean linear dimensional variation of the actual physical structure, they are quite restrictive. The mean linear dimension is substantially proportional to the cube root of volume, and in the case of a cube, it is exactly so. Referencing then to the cube root of volume, the tolerances may be stated as $\sqrt[3]{V}$ −18 percent to +21.5 percent.

The basic two-cavity systems described have been shown as having cavities *Ca*–**1** and *Ca*–**2** of equal volume. While this relationship gives good performance, fairly good performance may also be obtained with unequal volumes. It is important, however, to have the overall internal volume in correspondence with the relationships I have given in my formula for enclosure volume.

Using the same loudspeaker and internal volume as before, I have set up and evaluated samples of differing cavity volumes, for example, dividing the enclosure so that the second cavity volume was twice that of the first. The second cavity was tuned to the correct frequency for the speaker cone area and enclosure internal volume, and then modified into a band-pass filter as described herein. Flow-resistance damping of the second sub-cavity coupling aperture was employed as an acoustic resistance termination for the band-pass filter sub-system. A diagram of the modified configuration is shown in FIG. **8A**. The reflected electrical impedance characteristic before modifying the second cavity with the partition **131** is shown by the solid curve in FIG. **8B**. The dotted curve in FIG. **8B** shows the reflected impedance with the second cavity converted into the band-pass filter sub-system, as shown in FIG. **8A**. The radiated sound pressure response characteristic of FIG. **8A** is shown by the dash curve in FIG. **8B**.

As can be seen from the curves in FIG. **8B**, the response of the system is still fairly good. The reflected impedance curves point up one of the characteristics of this type of system, which is, as the ratio of second cavity volume to first-cavity volume increases, the spread between the impedance peaks increases and the middle impedance peak become more dominant. As can also be seen, the variation in impedance peak spread is not sufficient to significantly interfere with the application of my second-cavity modification technique. My investigations indicate that useful performance can be obtained over a range of 0.4 to 1.8 in the ratio of first-cavity volume to second-cavity volume.

I have found that my second-cavity modification technique is also applicable to the type of basic two-cavity system wherein the external port aperture is located in the second cavity. Also, my formula for scaling enclosure volume is applicable. The basic acoustic configuration is illustrated by the diagram in FIG. **9A**. The relationships of the acoustic element values are such that the capacitance of the first cavity will resonate with the inertance of the port aperture at the frequency F_r, and the capacitance of the second cavity will resonate with the inertance of the coupling aperture, likewise at F_r. The reflected electrical impedance characteristic is shown by the dotted curve in FIG. **9B**, and the radiated sound pressure characteristic is shown by dotted curve in FIG. **9C**.

The modification technique is the same as before, with the exception that the port aperture is located in the first sub-cavity.

A diagram of this modified system is shown in FIG. **9D**.

Although the functioning of this type of system is different from that of FIGS. **4A** and **5A**, the basic relationships of the reactive acoustic elements are again such that, where the acoustic termination resistance is equal to zero in the modified system of FIG. **9D**, its acoustic functioning is essentially the same as that of the unmodified system of FIG. **9A**. In applying my formula for enclosure volume to this type of system, $F_{r\text{-}C2}$ is determined by the conditions that exist when the port aperture is sealed off.

The reflected impedance characteristic with the modifications, including the acoustic terminating resistance, is shown by the solid curve in FIG. **9B**. These curves were based on data taken with the use of the same Altec loudspeaker and the same 1.2 cubic feet internal enclosure volume, and the same low-frequency amplifier compensation was employed. It can be seen that the bass range of this type of system is inferior to that where the port is in the first cavity, although the response is otherwise very uniform.

I have also found an additional technique for improving the bass response range and acoustic cone loading where the port aperture is in the first cavity. I have found that the relative phase relationship of the motion of the speaker cone and the motion of air at the port aperture is such that increased cone loading or effective radiation resistance can be achieved by directing this air motion toward the area immediately in front of the speaker cone. As shown in FIG. **10A**, the port aperture can be split into two slots **141** and **142**, one on either side of the speaker **143**, and louvres or deflectors **146** and **147**, respectively, used to direct the air motion equally and oppositely toward the speaker, thus maximizing the advantage. Also, the improvement can generally be effected by tuning the port aperture (or apertures) so that its resonance with the first cavity is at a somewhat lower frequency than F_r.

The advantages realized from the use of port aperture deflection comprise an improvement on the order of 1.5 db in both power handling ability and sound power output in the low end of the bass range.

Orthogonal views of a model employing the port aperture deflection and inertance adjustment as

described are shown in FIGS. 10A, 10B, 10C and 10D. The same 8-inch speaker and 1.2 cubic foot enclosure volume are employed. The dotted curve in FIG. 10E shows the reflected electrical impedance characteristic of this system. The dash curve in FIG. 10E shows 6 db/octave amplifier equalization used for making the measurements of sound pressure output vs. frequency from which the solid curve in FIG. 10E was made. As can be seen from the FIG. 10E, the output of this system is down only 1.5 db from the average response level at 37 Hz. The frequencies F_r and $F_{r\text{-}C2}$ are again both 74 Hz. Thus, a full octave of useful response below the system basic resonance frequency is achieved. Also, my measurements show that the maximum output capability of this system at 40 Hz is 16 times (12 db) greater than that of the system shown in FIG. 3C.

In the specific example shown in FIGS. 10A through 10D, the complete enclosure had a height of 23 ¼inches, a width of 15 inches, and a depth of 8 inches. The bottom chamber 142' had an internal height of 4 inches, and the chamber immediately above, an internal height of 5 ¾inches. The external ports 141 and 142 were 5 inches tall and five-sixteenths inches wide. The width of the louvres 146 and 147 covering the ports 141 and 142 was 1 ⅛ inches. The coupling apertures 151 and 152 had cross arms 3 ½ inches and 4 inches long, respectively, the width of each being one-half inch. The aperture areas of 151 and 152 were each 2⅝ square inches.

The solid curve in FIG. 11 shows the radiated sound pressure characteristic of a system employing a 5-inch speaker in an enclosure constructed in accordance with the formula for enclosure volume. This system incorporates the same features as the system illustrated in FIGS. 10A, 10B, 10C and 10D. The effective cone area is 11.6 square inches. $F_{r\text{-}C2}$ is 135 Hz. According to the formula given heretofore, the internal volume of the enclosure should therefore be approximately:

$$V = 2.9 \times 11.6/135 = 0.249$$

In point of fact the internal volume was actually made equal to 0.247 cubic feet with the results shown in FIG. 11.

The dash curve in FIG. 11 shows the amplifier equalization employed for the sound pressure response measurements. The damping factor, referring to the ratio of voice-coil resistance to amplifier internal output impedance was 1:1. Using the same damping factor and no equalization, the well-known 8 inch acoustic suspension system with the 0.65 cubic foot internal enclosure volume previously referred to herein gave the response shown by the dotted curve in FIG. 11. Although the efficiency and power handling capability in the lower bass region was substantially better for the acoustic suspension system, the efficiency of the 5 - inch model was 7 db greater in the region above 300 Hz. This system handles all the power (sound power output) that an average person can comfortably listen to in an average-size living room, while reproducing music program material with bass notes in the 70 cycle (Hz) region.

The speaker used employed an alnico V magnet of 2.15 oz., which is only a small fraction of that of the acoustic suspension speaker, and the linear excursion is only one-sixteenth inch peak to peak. The outside dimension of the enclosure, exclusive of the port aperture deflectors, are 4.31 × 9.5 × 16.0 inches.

Whereas the present invention has been shown and described herein in what is conceived to be the best mode contemplated, it is recognized that departures may be made therefrom within the scope of the invention which is, therefore, not to be limited to the details disclosed herein, but is to be afforded the full scope of the invention as hereinafter claimed.

What is claimed is:

1. A loudspeaker system comprising:
- first cavity means constituted by an enclosing wall means and confined air space and functionally operable as an acoustic capacitance;
- loudspeaker means mounted to and forming a portion of said wall means of said first cavity means;
- second cavity means constituted by an enclosing wall means and confined air space and functionally operable as an acoustic capacitance;
- coupling aperture means functionally operable as an acoustic inertance linking the acoustic capacitance of said first cavity to the acoustic capacitance of said second cavity;
- the inertance of said coupling aperture means producing a value of acoustic reactance that is equal to and of opposite sign to the acoustic reactance produced by the effective acoustic capacitance of said second cavity means at some specific frequency, F;
- port aperture means in a side wall means functionally operable as an acoustic inertance linking the acoustic capacitance of one of said cavities to the radiation impedance of the exterior system atmosphere;
- said loudspeaker system producing a radiated sound pressure vs. frequency curve characterized by a band of response below F, wherein radiation from said port aperture means supports the front-wave radiation from said loudspeaker; and
- wherein the sum of the effective internal air space of said first cavity means plus the effective internal air space of said second cavity means, the effective cone area of said loudspeaker means, and F are related substantially in accordance with the following formula:

$$V = 2.9\,A/F + 80\% - 40\%$$

Where:
- V = total effective internal air space of cavity means, in cubic feet
- A = effective piston area of loudspeaker cone, in square inches
- F = frequency at which the reactance of said coupling aperture means is equal to and of opposite sign to that of said second cavity means.

2. System as in claim 1, wherein the ratio of said internal air space of said first cavity means to that of said second cavity means falls within the range of 0.4 to 1.7.

3. System as in claim 1, wherein said coupling aperture means is an acoustic inertance of relatively good efficiency substantially free of acoustic resistance.

4. System as in claim 1, wherein said port aperture means is in the enclosing wall means of said first cavity means.

5. System as in claim 1, wherein said port aperture means is in the enclosing wall means of said second cavity means.

6. System as in claim 2, wherein said coupling aperture means is an element of acoustic inertance of relatively good efficiency substantially free of acoustic resistance.

7. System as in claim 1, wherein said port aperture means is located in said first cavity means; and including also deflection means cooperatively operable with said port aperture means whereby sound energy emanating from said port aperture means is directed toward the area immediately in front of said loudspeaker means.

8. A loudspeaker system comprising:

first cavity means constituted by an enclosing wall means and confined air space and functionally operable as an element of acoustic capacitance;

loudspeaker means mounted to and forming a portion of said wall means of said first cavity means;

second cavity means constituted by an enclosing wall means and confined air space adjoined to said first cavity means and functionally operable as an element of acoustic capacitance;

coupling aperture means functionally operable as an acoustic inertance linking the acoustic capacitance of said first cavity to the acoustic capacitance of said second cavity;

the inertance of said coupling aperture means producing a value of acoustic reactance that is equal to and of opposite sign to the acoustic reactance produced by the acoustic capacitance of said second cavity means at a specific frequency F;

port aperture means functionally operable as an element of acoustic inertance linking the acoustic capacitance of one of said cavities to the radiation impedance of the exterior system atmosphere;

said loudspeaker system, when unmodified, producing a radiated sound pressure vs. frequency curve characterized by a response band below F wherein port aperture radiation is additive to said loudspeaker front-wave radiation, followed by a valley in response in the region above F;

second cavity modification means for modifying said second cavity means and said coupling aperture means to cooperatively function as band-pass filter means and comprising;

division means separating said second cavity means into first sub-cavity means and second sub-cavity means, said first sub-cavity means and said second sub-cavity means each functionally operable as elements of acoustic capacitance;

the sum of the acoustic capacitance of said first sub-cavity means and the acoustic capacitance of said second sub-cavity means being equal to the unmodified said second cavity means;

said division means incorporating sub-cavity coupling aperture means functionally operable as an element of acoustic inertance and linking the acoustic capacitance of said first sub-cavity means to the acoustic capacitance of said second sub-cavity means;

the acoustic reactance produced by the inertance of said sub-cavity coupling aperture means being equal to and of opposite sign to the acoustic reactance produced by the acoustic capacitance of said second sub-cavity means at a frequency in the region of said response valley;

the acoustic inertance of said sub-cavity coupling aperture means and the acoustic capacitance of said second sub-cavity means cooperatively functioning as termination arm in said band-pass filter means;

the acoustic inertance of said coupling aperture means and the acoustic capacitance of said first sub-cavity coupling aperture means cooperatively functioning as transmission arm means in said band-pass filter means;

the acoustic reactance produced by the acoustic inertance of said coupling aperture means being equal to and of opposite sign to the acoustic reactance produced by the acoustic capacitance of said first sub-cavity means at a frequency in the region of said response valley; wherein, at said frequency F, reactance produced by the inertance of said sub-cavity coupling aperture means and the capacitance of said second sub-cavity means as combined with the reactance produced by the capacitance of said first sub-cavity means results in a value of acoustic reactance that is substantially equal to and of opposite sign to the value of reactance produced by the inertance of said coupling aperture means as modified;

said termination arm means incorporating substantial damping means;

whereby said band-pass filter means selectively absorbs and dissipates sound energy in the frequency region of said response valley; and

whereby said band-pass filter means functions essentially in the same manner as the unmodified said second cavity means and the unmodified said coupling aperture means in the frequency region below said frequency F, said modification means having substantially no effect on said response band below F, while raising substantially said valley.

9. System as in claim 8, wherein the ratio of the acoustic capacitance of said first cavity means to the acoustic capacitance of said second cavity means falls within the range of 0.4 to 1.7.

10. System as in claim 8, wherein said coupling aperture means is an acoustic inertance of relatively good efficiency substantially free of acoustic resistance.

11. System as in claim 8, wherein the sum of effective air space of said first cavity means plus the effective air space of said second cavity means, the effective cone area of said loudspeaker means, and the frequency F are related substantially in accordance with the following formula:

$$V = 2.9\,A/F + 80\% - 40\%$$

Where:

V = total effective internal air space of cavity means in cubic feet

A = effective piston area of loudspeaker cone in square inches

F = frequency at which the reactance of said coupling aperture means is equal to and of opposite sign to that of said second cavity means.

12. System as in claim 8, wherein said port aperture means is located in said enclosing wall means of said first cavity means.

13. System as in claim 8, wherein said port aperture means is located in said enclosing wall means of said first sub-cavity means; and

wherein said port aperture means is functionally operable as an element of acoustic inertance linking the acoustic capacitance of said first sub-cavity means to the radiation impedance of the external system atmosphere.

14. System as in claim 8, wherein said port aperture means is located in said first cavity means; and including also deflection means cooperatively operable with said port aperture means, whereby sound energy emanating from said port aperture means is directed toward the area immediately in front of said loudspeaker means.

15. A loudspeaker system comprising:

first cavity means constituted by an enclosing wall means and confined air space and functionally operable as an element of acoustic capacitance;

loudspeaker means mounted to and forming a portion of said wall means of said first cavity means;

second cavity means constituted by an enclosing wall means and confined air space adjoined to said first cavity means and functionally operable as an element of acoustic capacitance;

coupling aperture means functionally operable as an acoustic inertance linking the acoustic capacitance of said first cavity to the acoustic capacitance of said second cavity;

the inertance of said coupling aperture means producing a value of acoustic reactance that is equal to and of opposite sign to the acoustic reactance produced by the effective acoustic capacitance of said second cavity means at a specific frequency *F;*

port aperture means functionally operable as an element of acoustic inertance linking the acoustic capacitance of one of said cavity means to the radiation impedance of the exterior system atmosphere;

said loudspeaker system, when unmodified, producing a radiated sound pressure vs. frequency curve characterized by a response band below *F*, wherein port aperture radiation is additive to said loudspeaker front wave radiation, followed by a valley in response in the region above *F;*

second cavity modification means for modifying said second cavity means and said coupling aperture means so that their cooperative function is essentially that of a single cavity means and single aperture means in the frequency region below *F*, while also functioning as a frequency selective sound energy absorption means in the frequency region of said response valley, said modification means having substantially no effect on said response band below *F*, while raising substantially said valley.

16. System as in claim 15, wherein said second cavity means is functionally operable as a band-pass filter means, and includes:

division means separating said second cavity means into first sub-cavity means and second sub-cavity means, said first sub-cavity means and said second sub-cavity means each functionally operable as elements of acoustic capacitance.

17. System as in claim 15, wherein the ratio of the acoustic capacitance of said first cavity means to the acoustic capacitance of said second cavity means falls within the range of 0.4 to 1.7.

18. System as in claim 15, wherein said coupling aperture means functions as an acoustic inertance of relatively good efficiency.

19. System as in claim 15, wherein the sum of the effective air space of said first cavity means plus the effective air space of said second cavity means, the effective cone area of said loudspeaker means, and the frequency $F_{r\text{-}c2}$ are related substantially in accordance with the following formula:

$$V = 2.9\,A/F + 80\% - 40\%$$

Where:

V = total effective internal air space of cavity means in cubic feet

A = effective piston area of loudspeaker cone in square inches

F = frequency at which the reactance of said coupling aperture means is equal to and of opposite sign to that of said second cavity means.

20. System as in claim 15, wherein said port aperture means is located in said enclosing wall means of said first cavity means.

21. System as in claim 15, wherein said port aperture means is located in said enclosing wall means of said second cavity means; and

wherein said port aperture means is functionally operable as an element of acoustic inertance linking the acoustic capacitance of said first sub-cavity means to the radiation impedance of the external system atmosphere.

22. System as in claim 15, and the incorporation of deflection means cooperatively operable with said port aperture means, whereby sound energy emanating from said port aperture means is directed toward the area immediately in front of said loudspeaker means.

* * * * *

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CERTIFICATE OF CORRECTION

Patent No. 3,690,405 Dated September 12, 1972

Inventor(s) Edwin A. Hance

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the drawings, Fig. 10B should be canceled and the following substituted therefor:

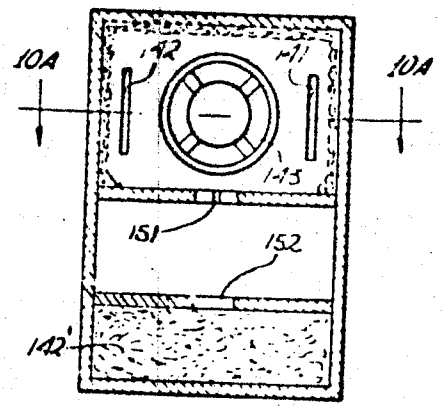


Fig 10B

Signed and sealed this 1st day of May 1973.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents

FORM PO-1050 (10-69)

USCOMM-DC 60376-P69
* U.S. GOVERNMENT PRINTING OFFICE : 1969 O—366-334.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

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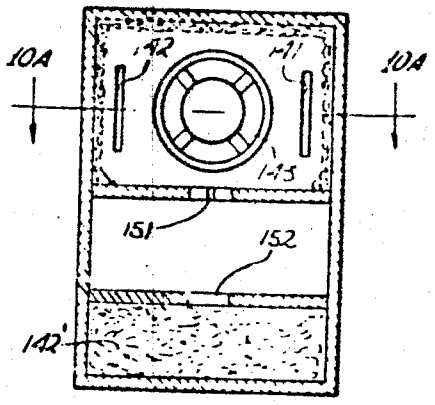


Fig.10B

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