June 12, 1962 A. G. BOSE 3,038,964

LOUDSPEAKER SYSTEM

Filed Dec. 18, 1956 2 Sheets-Sheet 1

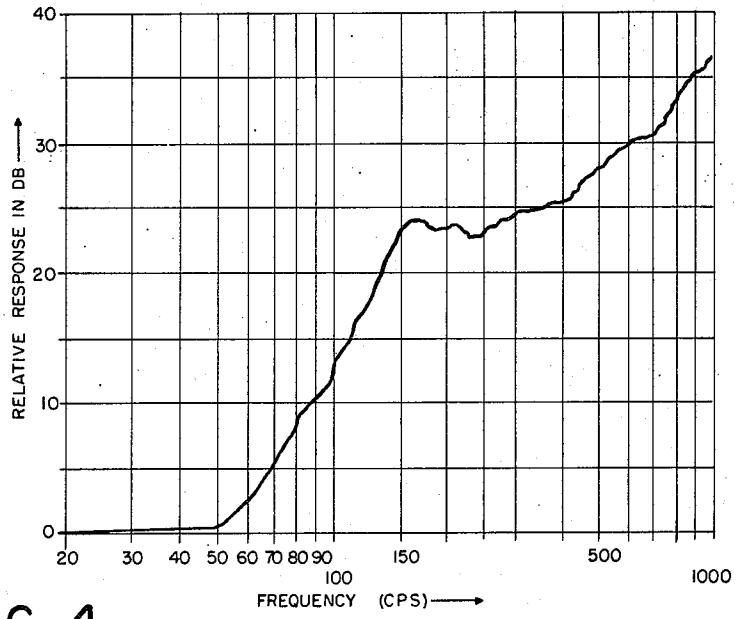


FIG. 4

FIG. 1

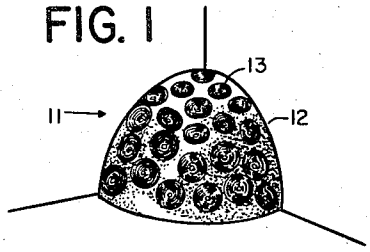


FIG. 6

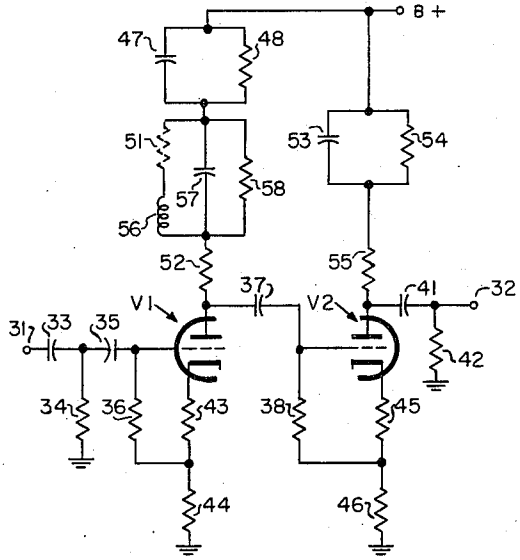
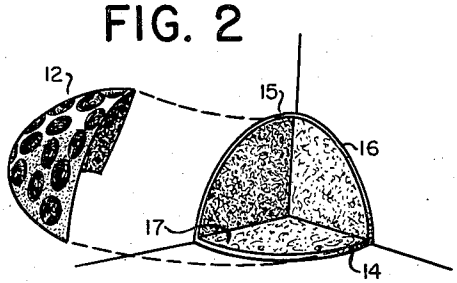


FIG. 2



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LOUDSPEAKER SYSTEM

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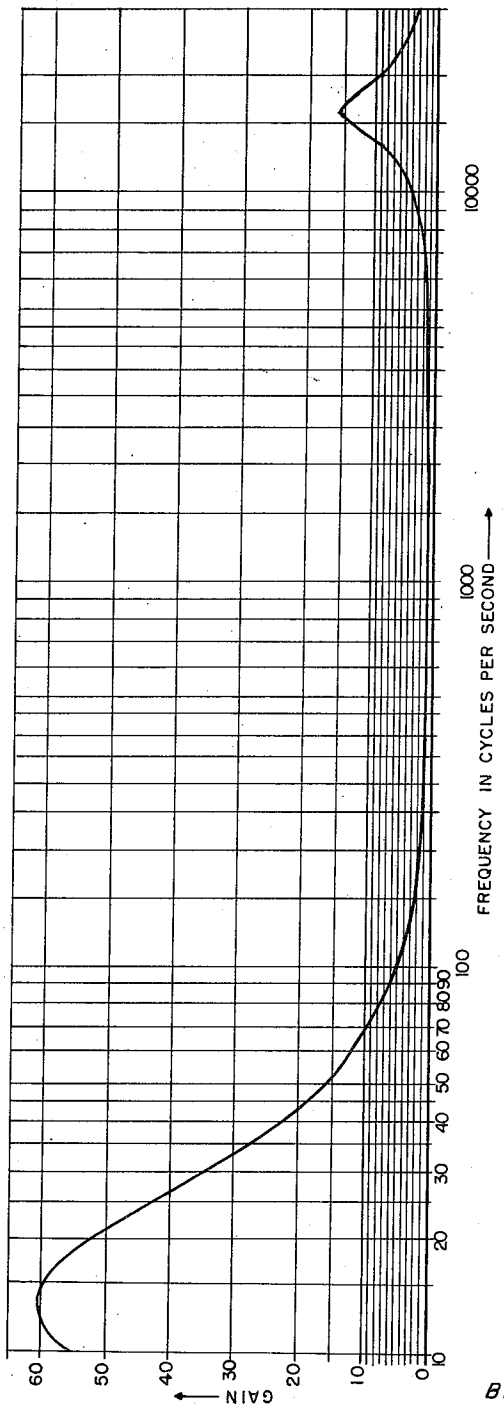
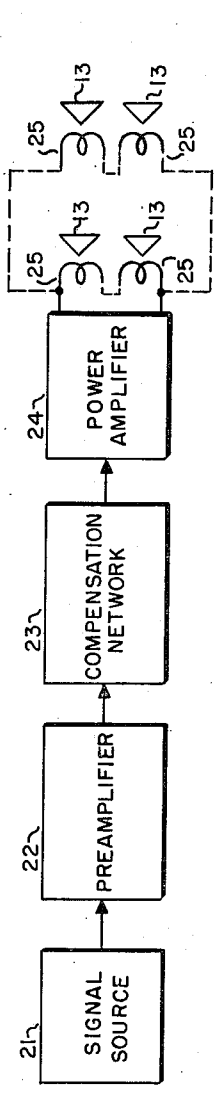


FIG. 5

FIG. 3



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LOUDSPEAKER SYSTEM

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Filed Dec. 18, 1956, Ser. No. 629,084
12 Claims. (Cl. 179—1)

The present invention relates in general to transducers and in particular to loudspeaker systems. A loudspeaker system arranged according to the invention reproduces sound with remarkable fidelity despite its low cost and compact arrangement. This application is a continuation-in-part of the copending application of Amar G. Bose entitled Pressure Wave Generation, Serial No. 602,195, filed August 6, 1956 (now Patent Number 2,915,588).

In the prior art, it has been the practice to design high fidelity systems wherein the loudspeaker system is energized by a source having a frequency response characteristic which is substantially flat over the audio spectrum. In order to respond to electrical signals from such a source, efforts have been directed toward the development of loudspeaker systems which will satisfactorily reproduce signals having frequency components in the entire audio spectrum.

At the same time, other desirable characteristics sought to be attained include, the ability to reproduce sound without harmonic or intermodulation distortion, efficient conversion of electrical to acoustical power, omnidirectional radiation characteristics, and integration of the program source; that is to say, all frequency components of the sound should appear to come from the same source.

While prior art systems have attained some of these characteristics, the better systems have utilized a plurality of speakers, each speaker being energized with a signal having a selected portion of the audio spectrum. The signals may be coupled to the respective speakers from a single power amplifier through a passive electrical or mechanical crossover network, by separate power amplifiers which are in turn energized by an electronic crossover network, or by combinations of the aforementioned.

Although the amplitude response, as a function of frequency, of two speakers, energized by respective crossover network bandpass filters designed to pass adjacent segments of the audio spectrum, appear to add graphically so that the overall response is substantially flat, the actual overall response is not flat because of the different phase characteristics of the two filter-energized speakers. For example, consider a crossover frequency f_c where in the amplitude response is ½ the response at the middle range of both speakers thus energized. If signals of frequency f_c emerged from both speakers in phase, the resultant response would seem to be the same as at mid-band. However, such is not practically the case. To illustrate an extreme case, consider a lower range filter-energized speaker which imparts a phase lead of 90° to signals of frequency f_c in association with a higher range filter-energized speaker which imparts a phase lag of 90° to signals of frequency f_c. The respective acoustic signals of frequency f_c which emerge from the lower and higher range speakers from the respective filters are of equal amplitude but differ in phase by 180°. The net effect of the acoustic signals from the two speakers being out of phase, is that they effectively cancel.

To lessen the difference in phase characteristics introduced electrically and reduce these effects, the fall and rise of the amplitude response of the crossover network filters is made gradual. This introduces another difficulty, for then some high frequencies may energize the low frequency speaker and some low frequencies may energize the high speaker, thereby increasing the degree of intermodulation distortion.

Although satisfactory reproduction of the high frequency signals has been obtained with electrostatic speakers and compression tweeters, the solid angle uniformly energized with acoustic energy by such speakers is limited. Electrostatic speakers require a high voltage source to supply a biasing potential. Furthermore, they are relatively inefficient and when used with an associated speaker to reproduce the lower frequencies, care must be taken to properly balance the acoustic output from both speakers. This usually dictates a requirement that the low frequency speaker also be relatively inefficient. If high acoustic output levels are desired, a costly high powered amplifier must be used to drive such a system.

Still greater difficulties have been experienced in reproducing the low frequencies. To improve the low frequency response, efforts have been directed toward the design of special enclosures in which the low frequency loudspeaker is housed. One such type of enclosure is known as a folded horn and is designed with a view toward providing an improved impedance match between the loudspeaker and air, the design procedure being based largely on the concept of radiation resistance. Radiation resistance is a measure of the ability of a pulsating diaphragm, such as a vibrating loudspeaker, to couple acoustic energy into air, the greater the radiation resistance, the higher the degree of coupling. Accordingly, a folded horn is designed to present a large radiation resistance to the speaker diaphragm. Although improvements in low frequency response result from the use of such structures, the better units are of complex design, bulky and expensive. Furthermore, the frequency range over which the impedance match obtains is limited.

Another common approach utilizes a bass reflex cabinet having one or more ports and housing an enclosed loudspeaker supported upon a baffle. The volume of the cabinet is designed so that at a selected frequency, the back wave from the loudspeaker emerges from the port substantially in phase with the frontal wave. Design of such enclosures involves a compromise, since waves of other frequencies emerge from the port in phase opposition to the frontal wave.

As a result of these and other difficulties, the loudspeaker system has been the weakest link in high fidelity sound reproduction systems. Some of the difficulties encountered in attempting to generate low frequency sound waves will be better understood by considering the nature of a pressure wave in an acoustical medium.

An acoustical medium is a compressible medium capable of responding to pressure changes with corresponding changes in density. Thus, a pressure wave may be activated in the medium by imparting forces thereon in a cyclical manner. For example, the action of a single loudspeaker set in the wall of a room whereby it imparts forces upon the air therein in response to a low frequency electrical signal is much like a piston moving in and out. If a hollow hard-surfaced cylinder having the same diameter as the piston and concentric about its axis were placed against the wall, substantially equal axial forces would be imparted upon the air column within the cylinder, and movement of the pressure wave therein would be substantially axial; that is, the particle velocity at any point within the cylinder is substantially axial, there being negligible velocity components orthogonal to the cylinder axis. Now if the cylinder is removed and the piston moved in and out, the air particles which are compressed at points of high density seek regions of lesser density, and since the cylinder no longer confines them to axial motion along the piston axis, velocity components orthogonal to the cylinder axis are imparted to the particles. Many of the particles then impart forces to particles along the sides instead of on other particles farther out from the piston along an axial direction. Stated in terms of a propagating wave, removal of the cylinder results in the direction of propagation formerly entirely axial

having components orthogonal to the axis. The pressure intensity of the wave along the axis is accordingly reduced. To compensate for this effect the excursion of the piston must increase appreciably. In the case of a single loudspeaker the excursions are often so great that operation of the latter is over its nonlinear region thereby introducing unwanted harmonic and intermodulation distortion. This effect is most noticeable at low frequencies.

Thus at low frequencies the loudspeaker must be capable of moving a relatively large volume of air adjacent its vibrating diaphragm. This may be accomplished by utilizing a relatively large diaphragm and/or arranging the amplitude of its vibrations to be relatively large. In order to lessen the severity of nonlinear distortions which result when the voice coil secured to the vibrating diaphragm moves within a non-uniform magnetic field, the better low frequency speakers, commonly called "woofers," require heavy permanent magnets arranged in a magnetic circuit which must be carefully aligned with respect to the voice coil. To lessen the extent of diaphragm excursions, the diaphragm is chosen to be of relatively large diameter, twelve to fifteen inches in the more costly "woofers." The large mechanical mass of such speakers markedly reduces their effectiveness at high frequencies. As a result, they are normally arranged whereby a mechanical or electrical crossover network limits their response to low frequency components of the signal from an electrical energizing source, the higher frequency components being directed to one or more high frequency speakers.

If the spacing between speakers energized in this manner is appreciable, the sound emanating therefrom does not emerge from an integrated program source. To lessen this effect, coaxial speakers have been designed wherein the axes of all the speakers in the system coincide. However, each speaker in the system still has its own directivity pattern, which normally differs from that of the others and encompasses a smaller solid angle as the frequency of the excitation signal increases.

Accordingly, the solid angle over which best balance of low, middle and high frequency sound intensities may be obtained is limited. This is usually confined to a relatively small angle about the axis of the speakers. Even though proper balance is obtained along the speaker axis, much of the sense of presence is still missing, presence being the effect upon a listener that the original source of the sound is present in the room.

It is a primary object of the present invention to provide a loudspeaker system for providing sound reproduction in a manner which conveys to the listener the effect that the original source of sounds is present in the room. Ancillary to this object is the provision of means for generating with negligible intermodulation or harmonic distortion sound waves in response to an electric signal which may include spectral components encompassing substantially the entire audio spectrum.

It is an object of the invention to provide a compact loudspeaker system of pleasing appearance according to the preceding object which utilizes inexpensive individual loudspeakers, a supporting structure therefor relatively easy to fabricate, and an electrical network formed of a relatively small number of inexpensive standard components which requires no adjustment, retains a selected desired electrical characteristic over extended periods, and is capable of responding to a wide range of input signal amplitudes without introducing undesired nonlinear distortion.

Another object of the invention is the provision of a loudspeaker system which may be arranged to have substantially any desired frequency response characteristic.

A further object of the invention is the provision of a loudspeaker system which utilizes a plurality of individual loudspeakers in cooperation with an electrical network in a manner which precludes two or more loudspeakers from emitting acoustic signals phased to provide undesired cancellation effects in response to any electrical signal applied to the system.

Still another object of the invention is the provision of a loudspeaker compensation circuit which may be energized by a preamplifier and having sufficient gain at the middle range of frequencies to drive an associated power amplifier to maximum power output, a markedly increased gain at the low range of frequencies and a higher gain at the higher frequencies, yet introduces negligible harmonic or intermodulation distortion.

Broadly speaking, the invention contemplates utilizing at least one transducer which sets up pressure waves in air in response to an input electrical signal and has relatively poor low frequency characteristics. An electrical compensation network, having a frequency response characteristic which compensates for deficiencies in the transducer response, is coupled to the transducer.

In one form of the invention, there is provided at least one loudspeaker having a fall off in response below a lower middle frequency and coupled to an electrical compensation network. The compensation network has a frequency response characteristic which is substantially uniform from a frequency just above the lower middle frequency to a selected upper middle frequency and rises with decreasing frequency from a frequency just below said lower middle frequency to a selected low frequency.

A single conventional loudspeaker exhibits a frequency response characteristic which is substantially zero from zero frequency to a first low frequency, and rises rapidly from the first low frequency to the lower middle frequency. Above the lower middle frequency, there may be a dip in the response. Above this frequency, the response may continue substantially flat, or exhibit a rise or fall. However, the rate of rise or fall as a function of frequency is much less than the rate of rise from said first low frequency to the lower middle frequency. For such a conventional loudspeaker, the lower middle frequency is normally the lowest frequency at which a resonant peak response is exhibited. For electrostatic transducing elements, the lower middle frequency is normally higher than for conventional loudspeakers.

In a more specific form, the apparatus comprises a plurality of loudspeakers connected in phase and coupled to a compensation network having a frequency response characteristic which is substantially uniform from a frequency just above the lower middle frequency of a single one of the loudspeakers to a selected upper middle frequency. From a frequency just below the lower middle frequency to a selected low frequency, the response rises with decreasing frequency. Below the selected low frequency, the response falls with decreasing frequency. From the selected upper middle frequency to a selected high frequency, it rises with increasing frequency. Above the selected high frequency, the response falls with increasing frequency. The overall network response is such that compensation is obtained for the low frequency and high frequency fall off in the response of the in-phase-connected speakers within the audible range. At the same time, the middle range of frequencies, to which the speakers respond satisfactorily, is uniformly passed, while signals of frequency below and above the audible range, which might tend to overload the power amplifier, appear at the output of the compensation network with a relatively small amplitude.

In a preferred embodiment, the loudspeakers are closely-spaced upon a spherical surface which bounds an enclosed volume, any other bounding surfaces of the volume being planes formed of radii perpendicular to the spherical surface. When the enclosed volume is a small portion of a larger volume having one or more planar bounding surfaces, any planar surfaces which bound the enclosed volume are preferably substantially coplanar with planar bounding surfaces of the larger volume. Loudspeakers arranged in this manner co-act to exhibit a substantially omnidirectional radiation characteristic

substantially independent of frequency, and optimum compensation is obtained through substantially the entire solid angle subtended by the spherical surface.

A preferred form of the compensation network comprises a single dual triode with associated circuit components. In the plate circuit of each triode is a low frequency compensation network which comprises a first resistor serially-connected to a second resistor shunted by a capacitor, the ratio of the second resistance to the first resistance being related to the ratio of the network gain at the selected low frequency relative to the midband gain, and the value of the capacitor being related to the low frequency where the magnitude of the slope of the frequency response characteristic is a maximum. In the plate circuit of the first triode, the low frequency compensation network is serially-connected to the high frequency compensation network which comprises an inductor tuned to the selected high frequency. The tuned circuit is damped to provide the desired rate of rise in frequency response near the selected high frequency and the value of the inductor is related to the desired rate of rise in the frequency response just above the middle range of frequencies. The inductor resistance forms a portion of the low frequency network first resistance.

Other features, objects and advantages of the invention will become apparent from the following specification when read in connection with the accompanying drawing in which:

FIG. 1 illustrates a preferred form of the loudspeaker arrangement;

FIG. 2 shows the arrangement of FIG. 1 with the front spherical surface removed to illustrate means for enclosing the volume along the sides of a room corner;

FIG. 3 is a block diagram of an arrangement for coupling the compensation network to the loudspeakers;

FIG. 4 illustrates a portion of a conventional small-speaker frequency response characteristic;

FIG. 5 is the preferred frequency response characteristic of a compensation network for coupling to the speaker arrangement of FIG. 1; and

FIG. 6 is a schematic circuit diagram of a compensation network which exhibits the frequency response characteristic of FIG. 5.

With reference now to the drawing, and more particularly FIG. 1 thereof, a preferred loudspeaker arrangement **11**, especially suitable for location in the corner of a room, is illustrated. A one-eighth spherical surface **12** is covered with a plurality of loudspeakers like loudspeaker **13**.

In FIG. 2, the surface **12** is removed and the sides **14**, **15** and **16**, which enclose the volume adjacent the walls and floor are seen to be planar surfaces which are substantially 90° sectors of circles. Each of the latter surfaces is preferably lined with a sound absorbent material such as fiberglass insulation and are joined together at preferably tight-fitting joints. They may be formed of wood which is glued, nailed or screwed together. Surface **12**, which may be plastic, fiberglass, moulded plywood, or other suitable material, is secured to the structure thus formed by the same or other suitable means. The closely-spaced loudspeakers, like loudspeaker **13**, are symmetrically positioned about holes in the surface **12**, preferably in a manner which effects a substantially air-tight seal. Thus, the speaker-covered surface **12**, together with sides **14**, **15** and **16** enclose a relatively small substantially air-tight volume. As a practical matter, it has been discovered that the volume need not be air-tight to achieve desired results. In fact, those skilled in the art may deliberately place openings in the volume in order to achieve different acoustical characteristics without departing from the inventive concepts.

By exciting all the speakers on surface **12** in phase with a low-frequency electrical signal, substantially equal radial forces are imparted upon the air adjacent the surface to launch a spherical wave in the air, substantially free of the low frequency propagational effects described above. Moreover, at higher frequencies, the relatively small loudspeakers act like many tweeters, each oriented in a different direction, to produce a substantially omni-directional radiation pattern over the listening areas in the room. Furthermore, since each speaker diaphragm need only move a fraction of its normal displacement when used alone to produce a given volume level in the room, each speaker may be driven harder at the low frequencies, yet still operate over its linear range, thereby extending system frequency response, while reducing speaker harmonic and intermodulation distortion to a remarkably low level, even at the low frequencies.

By combining the speakers in the manner described, the loudspeakers employed may be inexpensive and have relatively poor low frequency characteristics when singly excited by an electrical signal, yet yield substantially any desired response when co-acting and compensated according to the invention. In fact, there are additional advantages to employing relatively small individual loudspeakers. A small loudspeaker is characterized by a relatively good high frequency response by virtue of the small mass of its coil and diaphragm and normally has a relatively high lower middle frequency. Below this frequency, the response smoothly decreases. The smoothness of the decrease facilitates electrical compensation therefor, while the relatively small rate of decrease minimizes the number of components required to effect compensation. If a speaker is utilized which has a lower middle frequency of lesser value, the decrease in response occurs at a lower frequency and normally at a greater rate. Thus, a network to compensate for such a speaker would most likely require more and larger components.

With reference to FIG. 3, there is illustrated a block diagram of an electrical system utilizing the compensated loudspeaker system. A signal source **21**, such as a phonograph, microphone, tuner or the like energizes preamplifier **22**. The output signal from the latter energizes compensation network **23** which boosts spectral components of the input signal at the high and low frequency ends of the audio spectrum to compensate for the fall off in response of the loudspeakers. The compensated signal from the latter network is applied to power amplifier **24** which in turn drives the speaker voice coils **25** of the loudspeakers **13**. The loudspeakers may be connected in parallel, series or series-parallel as long as they are connected so that electrical signals of like polarity actuate each speaker diaphragm in the same direction along the respective voice coil axes; that is to say, the speakers are driven in phase. Normally, the speakers are connected in a manner which presents the proper load impedance to the driving power amplifier. Where each transducing element is not a conventional loudspeaker, they are connected so that electrical signals of like polarity effect an initial pressure change upon the air adjacent the respective elements in the same direction relative to a surface which includes the elements.

Certain additional advantages result when the speakers are connected in series to present a relatively high impedance to the power amplifier. The latter may then be of the transformerless type, capable of exceptionally high linearity and virtually free from oscillation.

Referring to FIG. 4, there is graphically represented a portion of the frequency response characteristic of a single small loudspeaker as measured in an anechoic chamber. It is seen that the response is substantially zero from 20 cycles to 50 cycles, rises at a substantially linear rate in decibels per octave from 50 cycles to the lower middle frequency at substantially 160 cycles, dips slightly thereafter and rises at a more gradual rate to 1000 cycles.

Referring to FIG. 5, the preferred frequency response characteristic of a network for compensating the speaker arrangement of FIG. 1 is illustrated. Voltage gain relative to the midband gain at 1000 cycles is plotted as a function of the logarithmically-scaled frequency. From

about 150 cycles to substantially 14 cycles the response is seen to rise with decreasing frequency while below the latter frequency the response falls as the frequency decreases. From 200 cycles to 5000 cycles, the response is seen to be substantially flat, thereafter rising with increasing frequency to a peak at substantially 16,000 cycles and then decreasing as the frequency increases beyond the latter frequency.

The response is substantially uniform at the middle range of frequencies where the individual speakers respond satisfactorily and no compensation is desired. At the low and high ends of the audio frequency band, the fall off in speaker response is compensated for by the indicated frequency response of the compensation network. The rise in response with decreasing frequency at the low end is preferably terminated at a selected low frequency which is low enough so that adequate compensation is obtained in the range of low audible frequencies while being high enough so that lower inaudible frequencies emerge from the compensation network with relatively small amplitude. Signals of such frequencies may be derived from poorer quality program sources, such as lower grade phonograph turntables. If signals having substantial amplitudes at such frequencies are present in the output signal of the compensation network, the power amplifier becomes overloaded with lesser amplitudes of desired signal and the system dynamic range is accordingly reduced. A typical value for this selected low frequency is 14 cycles, corresponding to the low frequency maximum of the response curve of FIG. 5.

For similar reasons, at the high frequency end it is desired to have a rise in response with increasing frequency to a selected high frequency followed by a tapering off in response at higher frequencies. The selected high frequency is preferably high enough so that adequate compensation is obtained in the range of high audible frequencies while being low enough so that higher inaudible frequencies emerge from the compensation network with relatively small amplitude. A typical value for this selected high frequency is 16,000 cycles, corresponding to the high frequency maximum of the response curve of FIG. 5.

Referring to FIG. 6, there is illustrated a schematic circuit diagram of a preferred embodiment of compensation network 23 of FIG. 3 which has the frequency response characteristic of FIG. 5. The circuit is seen to comprise a pair of triodes, V1 and V2, together with associated components. Input terminal 31 is energized by preamplifier 22 and the output signal, which includes the desired compensation, is coupled from terminal 32 to power amplifier 24. The interstage coupling networks formed of capacitor 33 and resistor 34, capacitor 35 and resistor 36, capacitor 37 and resistor 38, and capacitor 41 and resistor 42 are preferably arranged to have the same effective time constant, the latter time constant being related to the selected low frequency described above in connection with the frequency response characteristic of FIG. 5.

Tubes V1 and V2 are biased at a desired potential by coupling the respective grids through associated grid resistors 36 and 38 to the junction of cathode resistors 43 and 44, and 45 and 46 respectively. The desired potential is chosen so that the circuit provides maximum gain with minimum distortion.

The low frequency compensation circuits include the shunt combination of capacitor 47 and resistor 48 serially connected with coil resistance 51 and resistor 52 in the plate circuit of tube V1, and the shunt combination of capacitor 53 and resistor 54 serially-connected to resistor 55 in the plate circuit of tube V2. The zero and pole distribution in the complex frequency plane of the low frequency compensation circuit serially-connected to each plate is preferably the same. Thus, the values of capacitors 47 and 53, and resistors 48 and 54 are substantially the same, while the value of resistor 55 is substantially equal to the sum of coil resistance 51 and resistor 52. The ratio of resistance 48 to the latter sum is related to the low frequency gain, the higher the ratio, the higher the low frequency gain. The value of capacitor 47 is related to the slope of the low frequency response curve; the higher the value, the lower the frequency at which the magnitude of the slope of the low frequency response curve is a maximum. In other words, increasing capacitor 47 moves the low frequency portion of the response curve of FIG. 5 to the left. It is to be understood that in the preferred circuit, corresponding changes are made in the parameters in the plate circuit of tube V2 to maintain the desired zero and pole pattern.

The high frequency compensation circuit includes coil 56 shunted by capacitor 57 and damping resistor 58. The inductance of coil 56 is chosen to provide the desired compensation at a relatively low high frequency while capacitor 57 tunes the coil to the selected high frequency described in connection with the response curve of FIG. 5. Damping resistor 58 together with coil resistance 51 is related to the gain at the selected high frequency. If coil resistance 51 is sufficiently high damping resistor 58 may be eliminated. An advantage of placing all the high frequency compensation in the plate circuit of tube V1 is that the high frequency output impedance at terminal 32 is substantially the relatively low value of resistor 55; hence, there is no need for a cathode follower output stage, even though the physical location of the power amplifier stage may be relatively far from the compensation circuit.

Having described the circuit arrangement, its mode of operation will be discussed by considering in order low, middle range and high frequency input signals. A low frequency input signal applied at terminal 31 is coupled to the grid of tube V1 by the intervening resistor-capacitor network. At the low and middle range frequencies the impedance of coil 56 is small compared to the sum of coil resistance 51 and resistance 52 may be neglected. Coil 56 also effectively bypasses resistance 58, which may be neglected. The impedance of capacitors 47 and 53 are relatively large at the lower frequencies. Consequently, the plate load impedances are relatively large and the gain of each stage correspondingly high. As the frequency increases, the impedance of the capacitors decreases and the gain is accordingly reduced until at the middle range of frequencies the capacitive impedance is small compared to the resistance of the serial combination of resistor 52 with coil resistance 51 and the resistance of resistor 55. The gain is then determined by the latter resistors.

At higher frequencies, when the impedance of coil 56 becomes comparable to that of coil resistance 51 with resistor 52, the gain increases until the resonant frequency of the tuned circuit is reached. The gain at this frequency is related to the ratio of resistor 58 to resistor 52. Above the resonant frequency, the response falls off.

The time constant of the interstage coupling networks is sufficiently high to pass the lower audible frequencies with negligible attenuation, yet sufficiently low to attenuate the very low frequencies, the time constant largely determining the selected low frequency discussed in connection with the response curve of FIG. 5. By choosing the time constants of the four interstage coupling networks to be the same, there results a fourth order zero on the real axis to provide a relatively high decrease in response as a function of frequency below the selected low frequency.

The actual time constant of the coupling networks formed of capacitors 35 and 37 with resistors 36 and 38 is different from the remaining interstage coupling networks because the latter resistors are connected to a tapped cathode resistance instead of to ground. This will be better understood from the following example. If a change of one volt on the grid of tube V1 causes a change of one-half volt at the junction of resistors 43 and

44, the actual voltage change across resistor 36 is only one-half volt, whereas if it were connected directly to ground, the change would be one volt. Thus, the current flowing through resistor 36 is the same as that which would flow through a resistor of twice its value directly connected to ground. Accordingly, the actual time constant of capacitor 35 and resistor 36 under such circumstances would be selected to be one-half that of capacitor 31 and resistor 34.

Typical values of circuit parameters are tabulated below.

Resistor 34	ohms	18,000
Resistors 36 and 38	do	200,000
Resistors 43 and 45	do	390
Resistors 44 and 46	do	620
Resistor 52	do	1,300
Resistor 55	do	1,500
Resistor 58	do	51,000
Resistor 42	do	180,000
Resistors 48 and 54	do	68,000
Coil resistance 51	do	200
Capacitor 33	microfarads	1.0
Capacitors 35 and 37	do	.05
Capacitor 57	micromicrofarads	1,600
Capacitors 47 and 53	microfarads	0.5
Capacitor 41	do	0.1
Tubes V1 and V2		½ 12AX7
B+ potential	volts	390

The exemplary circuit described above provides an R.M.S. output signal of greater than 2.0 volts at all frefrencies within the audible range without visible distortion to a sine wave observed upon an oscilloscope. This has been found to be sufficient to drive a typical 25 watt high fidelity power amplifier to its limit without introducing aurally or visually discernible distortion. When utilized between a Heathkit WA–P1 preamplifier and W5M amplifier to compensate the speaker system of FIG. 1 in which twenty-two Carbonneau four-inch speakers connected in phase with a 58-ohm resistor shunting two parallel chains of eleven speakers in series were connected to the 16-ohm output of the power amplifier, reproduction of sounds encompassing substantially the entire audio spectrum was obtained with unusual realism and virtually free of distortion. The sound of the solo tympani was reproduced with remarkable fidelity as well as the full range of solo and orchestral violins. The sound of solo instruments nearest the microphone when recording stood out, with the rest of the orchestral sound appearing to emanate from the background. At any frequency, the sound intensity was substantially the same at any point within the room a given distance from the spherical surface. An improvement in the quality of sound emanating from the well-known Baruch-Lang speaker, which utilizes four Carbonneau speakers, was also observed when energized with the above-described electrical system, including the compensation network.

The specific apparatus described herein is by way of example only. A single loudspeaker may be compensated according to the principles of the invention. Electrostatically actuated diaphragms, corona transducers and other transducers which respond to an electrical signal by setting up sonic waves may be substituted for the specific loudspeakers described. Utilizing the inventive concepts, those skilled in the art may construct different compensation networks and may determine different desired frequency response characteristics to compensate for a specific arrangement of a transducing system.

A desired frequency response may be determined in the following manner. The transducing system is positioned preferably in an anechoic chamber and a calibrated microphone placed at a point facing the speaker system where it is desired compensation be most correct. A power amplifier energizes the transducing system with a signal originating from an audio oscillator, the amplifier output being adjusted so that the calibrated microphone responds to a pressure wave of constant intensity over the audio spectrum. The output voltage from the power amplifier is measured and plotted as a function of frequency to yield substantially the desired frequency response characteristic of the compensation network. If the transducing system is the preferred system wherein a plurality of transducers are arranged on a spherical surface, proper compensation may be obtained for substantially the entire solid angle subtended by the spherical surface.

It is apparent that those skilled in the art may make numerous departures from and modifications of the specific apparatus described herein without departing from the inventive concepts. Consequently, the invention is to be construed as limited only by the spirit and scope of the appended claims.

What is claimed is:

1. A loudspeaker system comprising, a plurality of small loudspeakers connected in phase, each having a poor response below a first frequency at the lower end of the middle range of audio frequencies and a satisfactory response in at least said middle range, and an electrical compensation network coupled to said loudspeakers for delivering the full range of audio frequency signal spectral components to all said loudspeakers and having means for uniformly attenuating spectral components of a signal in a band within said middle range extending from a frequency just above said first frequency to a second frequency at the upper end of the middle range of audio frequencies, said attenuating means imparting progressively less attenuation as the frequency decreases in the band from a third frequency just below said first frequency to a fourth frequency at the low end of the low range of audio frequencies so that the frequency response characteristic of said loudspeaker system is substantially uniform between said first and fourth frequencies.

2. A transducing system comprising a plurality of closely-spaced small transducing elements connected in phase, the in-phase-connected transducing elements exhibiting a marked fall off in response below a first frequency at the lower end of the middle range of audio frequencies, and an electrical circuit coupled to said in-phase-connected transducing elements for coupling signal spectral components within the full audio frequency range to all said elements, said circuit comprising a plurality of intercoupled networks having like zero and pole patterns in the complex frequency plane each including a resistively shunted capacitor serially-connected to a resistor of value small compared to the shunting resistance across said capacitor, the values of said resistors and capacitors selected to provide a frequency response of said circuit which is substantially uniform above a frequency slightly higher than said first frequency, and rises with decreasing frequency below said first frequency to substantially compensate for the fall off in response of said in-phase-connected transducing elements below said first frequency while uniformly passing the middle range of audio frequencies to which said in-phase-connected transducing elements respond satisfactorily.

3. A transducing system comprising at least one transducing element which exhibits a marked fall off in response below a lower middle frequency, and a lesser fall off in response above a high frequency, and an electrical compensation network coupled to said element and comprising the series combination of a resistively shunted capacitor, a resistance of value small compared to the shunting resistance across said capacitor and a tuned circuit whose resonant frequency is at the high end of the audio spectrum, the values of said resistors and capacitors selected to provide a network response which is substantially uniform above a frequency slightly higher than said lower middle frequency, and rises with decreasing frequency below a frequency slightly lower than

said lower middle frequency, the parameter values of said tuned circuit selected to provide a network response which rises with increasing frequency above said high frequency whereby compensation for fall off in high frequency response of said transducing element is obtained.

4. A transducing system comprising a plurality of closely-spaced transducing elements connected in phase, the in-phase-connected transducing elements exhibiting a marked fall off in response below a first frequency at the lower end of the middle range of audio frequencies and a lesser fall off in response above a high audio frequency, and an electrical circuit coupled to said in-phase-connected transducing elements and comprising a plurality of cascaded networks each including a resistively-shunted capacitor serially-connected to a resistor of value small compared to the shunting resistance across said capacitor, and a tuned circuit in series with one of said cascaded networks and having a resonant frequency at the high end of the audio spectrum, the values of said resistors and capacitors selected to provide a circuit response which is substantially uniform above a frequency slightly higher than said lower middle frequency, and rises with decreasing frequency below said lower middle frequency to substantially compensate for the fall off in response of said in-phase-connected transducing elements below said lower middle frequency, the parameter values of said tuned circuit selected to provide a circuit response which rises with increasing frequency above said high frequency whereby compensation for fall off in high frequency response of said transducing elements is obtained.

5. A transducing system comprising, a plurality of closely-spaced transducing elements connected in phase, the in-phase-connected transducing elements exhibiting a marked fall off in response below a lower middle frequency and a lesser fall off in response above a high frequency, and an electrical circuit coupled to said in-phase-connected transducing elements and comprising input and output terminals, a plurality of networks each including a resistively-shunted capacitor serially-connected to a resistor of value small compared to the shunting resistance across said capacitor, at least one tuned circuit, whose resonant frequency is at the high end of the audio spectrum, in series with one of the resistively shunted capacitors and its associated resistor of relatively small value, coupling means interposed between said input terminal and the first of said networks, between the last of said networks and said output terminal, and between said first and last networks, the values of said resistors and capacitors selected to provide a circuit response which is substantially uniform above a frequency slightly higher than said lower middle frequency, and rises with decreasing frequency below said lower middle frequency to substantially compensate for the fall off in response of said in-phase-connected transducing elements below said lower middle frequency, the parameter values of said tuned circuit selected to provide a circuit response which rises with increasing frequency above said high frequency whereby compensation for fall off in high frequency response of said in-phase-connected transducing elements is obtained, each of said coupling means having a time constant sufficiently high to pass the lower audible frequencies with negligible attenuation and sufficiently low whereby the very low inaudible frequencies are attenuated.

6. A transducing system comprising, a plurality of closely-spaced transducing elements connected in phase, the in-phase-connected transducing elements exhibiting a marked fall off in response below a lower middle frequency and a lesser fall off in response above a high frequency, and an electrical compensation circuit coupled to said in-phase-connected transducing elements and having a frequency response characteristic which is substantially uniform from a frequency just above said lower middle frequency to substantially said high frequency, rises with decreasing frequency from a frequency just below said lower middle frequency to a selected low frequency, falls with decreasing frequency below said selected low frequency, rises with increasing frequency from said high frequency to a selected higher frequency, and falls with increasing frequency above said selected higher frequency, said electrical compensation circuit comprising first and second tubes, first and second low frequency compensation networks in the plate circuits of said first and second tubes respectively, each low frequency compensation network comprising a first resistance serially connected to a second resistance shunted by a capacitor, the ratio of the second to first resistances being related to the ratio of the circuit gain at said selected low frequency relative to the gain in the mid-band region of substantially uniform response, the value of said capacitor being related to the low frequency where the magnitude of the slope of the frequency response characteristic is a maximum, serially connected to said first low frequency compensation network, a high frequency compensation network comprising an inductor tuned to said selected higher frequency and damped to provide a rate of rise in frequency response near the selected high frequency substantially compensating for the fall off in response of said in-phase-connected transducing elements in that region, the value of said inductor being related to the desired rate of rise in frequency response which substantially compensates for the fall off in response of said in-phase-connected transducing elements in the frequency range just above said high frequency, said inductor also having distributed resistance which forms a portion of said first low frequency network first resistance.

7. A loudspeaker system comprising, a plurality of small loudspeakers connected in phase and exhibiting a marked fall off in response below a first frequency at the lower end of the middle range of audio frequencies and a relatively uniform response in said middle range above said first frequency, and means for coupling signal spectral components within the full range of audio frequencies to all said in-phase-connected loudspeakers, said coupling means including means for uniformly attenuating signal spectral components above said first frequency and imparting progressively less attenuation with decreasing frequency to signal spectral components in the band below said first frequency, said band extending at least to a second frequency at the low end of the lower range of audio frequencies to substantially compensate for said marked fall off in response.

8. A loudspeaker system comprising, a plurality of small loudspeakers connected in phase and exhibiting a marked fall off in response below a first frequency at the lower end of the middle range of audio frequencies, a relatively uniform response in said middle range above said first frequency, and a lesser fall off in response above a second frequency at the lower end of the high range of audio frequencies, and means for coupling signal spectral components within the full range of audio frequencies to said in-phase-connected loudspeakers, said coupling means including first means for uniformly attenuating all audio signal spectral components above said first frequency and imparting progressively less attenuation with decreasing frequency to signal spectral components in the band below said first frequency, said band extending to a third frequency at the low end of the lower range of audio frequencies, and second means cascaded with said first means for uniformly attenuating all audio signal spectral components below said second frequency and imparting progressively less attenuation with increasing frequency to signal spectral components in the band extending from said second frequency to a fourth frequency at the high end of the high range of audio frequencies.

9. Apparatus in accordance with claim 8 wherein said coupling means includes third means for imparting progressively greater attenuation with decreasing frequency to all signal spectral components in the band below said third frequency, and said second means imparts progres-

sively greater attenuation with increasing frequency to all signal spectral components in the band above said fourth frequency.

10. Apparatus in accordance with claim 7 and further comprising, means for enclosing a substantially fluid-tight first volume adapted to be situated within a relatively large second volume, that portion of said enclosing means exposed to said second volume being a substantially spherical surface, any other portions of said enclosing means being surfaces generally parallel to bounding surfaces of said second volume, and a vibratable diaphragm for each of said small loudspeakers, said spherical surface being formed with a plurality of closely-spaced openings covered by respective ones of said diaphragms.

11. A loudspeaker system comprising, a plurality of closely-spaced small loudspeakers connected in phase, there being at least four of said loudspeakers, said in-phase-connected loudspeakers exhibiting a marked fall off in response below a first frequency at the lower end of the middle range of audio frequencies relative to the response at the center of said middle range of frequencies, and means for coupling signal spectral components within the full range of audio frequencies to all said in-phase-connected loudspeakers, said coupling means including means for imparting progressively less attenuation with decreasing frequency in a band below said first frequency, said band extending at least to a second frequency at the low end of the lower range of audio frequencies, said coupling means co-operating with said in-phase-connected loudspeakers to cause the frequency response characteristic of said system to be substantially uniform in the band between said first and second frequencies.

12. A loudspeaker system in accordance with claim 11 wherein said coupling means further comprises second means for imparting progressively more attenuation with decreasing frequency in the band below said second frequency, said second means comprising a plurality of cascaded networks, each of said networks consisting of a coupling capacitor in series with a resistance, the effective time constant of each of said networks being substantially the same, said time constant being shorter than the period of a sinusoidal cycle at said second frequency.

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