United States Patent [19]

Meyers

[11] **3,798,374**

[45] **Mar. 19, 1974**

[54] **SOUND REPRODUCING SYSTEM UTILIZING MOTIONAL FEEDBACK**

[75] Inventor: **Stanley Thayer Meyers,** Red Bank, N.J.

[73] Assignee: **Rene Oliveras,** Madison, N.J. ; a part interest

[22] Filed: **Apr. 3, 1972**

[21] Appl. No.: **240,495**

[52] **U.S. Cl.** .... **179/1 F**
[51] **Int. Cl.** **H04r 3/04**
[58] **Field of Search** .... 179/1 F, 1 D; 330/109, 330/110; 333/28 T

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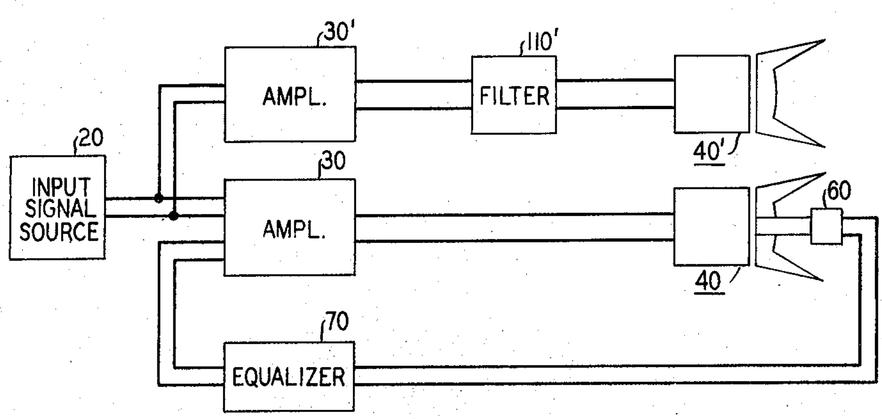
Primary Examiner—Kathleen H. Claffy
Assistant Examiner—Jon Bradford Leaheey
Attorney, Agent, or Firm—Rene Oliveras

[57] **ABSTRACT**

A sound reproducing system utilizes motional feedback to reduce loudspeaker distortion and to extend the loudspeaker's frequency response. The system substantially comprises an amplifier which is jointly responsive to the input source signal and to a feedback signal, a moving-coil loudspeaker including a main electromagnetic structure which is responsive to the amplifier's output signal for effecting axial speaker-cone motion, motional sensing means for providing a signal which is functionally related to axial cone velocity, and an equalizer exhibiting a predetermined nonlinear attenuation versus frequency characteristic and which is responsive to the motional signal for providing the feedback signal. The feedback signal is degeneratively applied to the amplifier which, in turn, forces the loudspeaker to respond linearly to the input source signal and thereby provide a uniform sound energy output. It is a feature of the present invention that the loudspeaker cone exhibits a substantially constant acceleration at low frequencies and a substantially constant velocity at higher frequencies.

16 Claims, 11 Drawing Figures



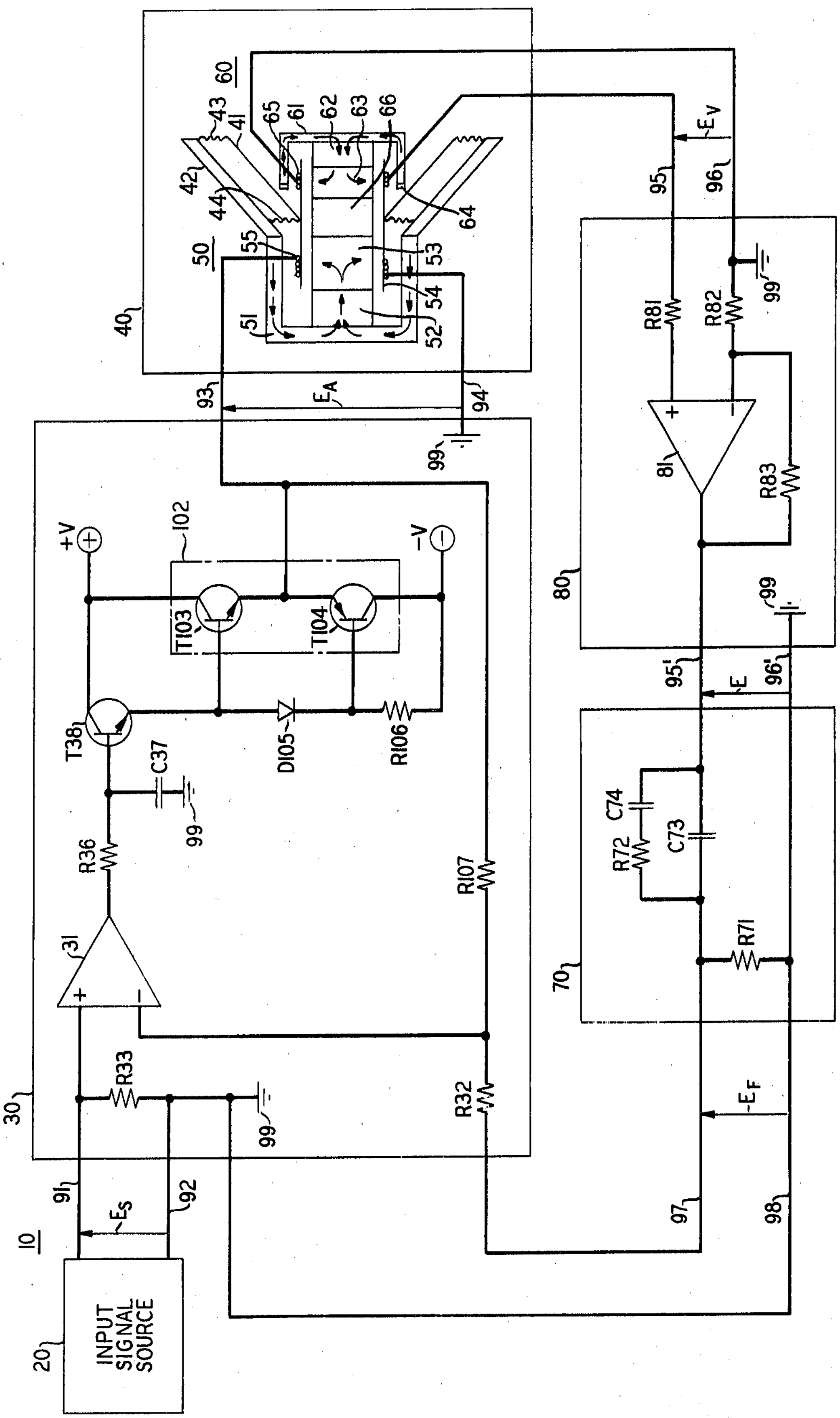


FIG. 1

FIG. 2

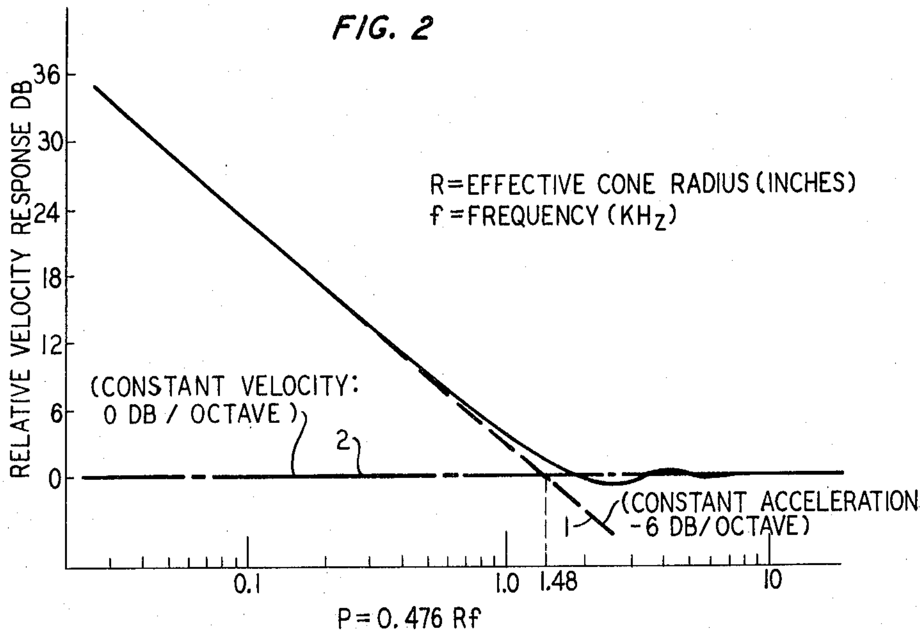

RELATIVE VELOCITY RESPONSE DB
36
30
24
18
12
6
0
R=EFFECTIVE CONE RADIUS (INCHES)
f=FREQUENCY (KHZ)
(CONSTANT VELOCITY:
0 DB / OCTAVE)
2
(CONSTANT ACCELERATION
-6 DB/OCTAVE)
1
0.1
1.0
1.48
10
P=0.476 Rf

FIG. 3

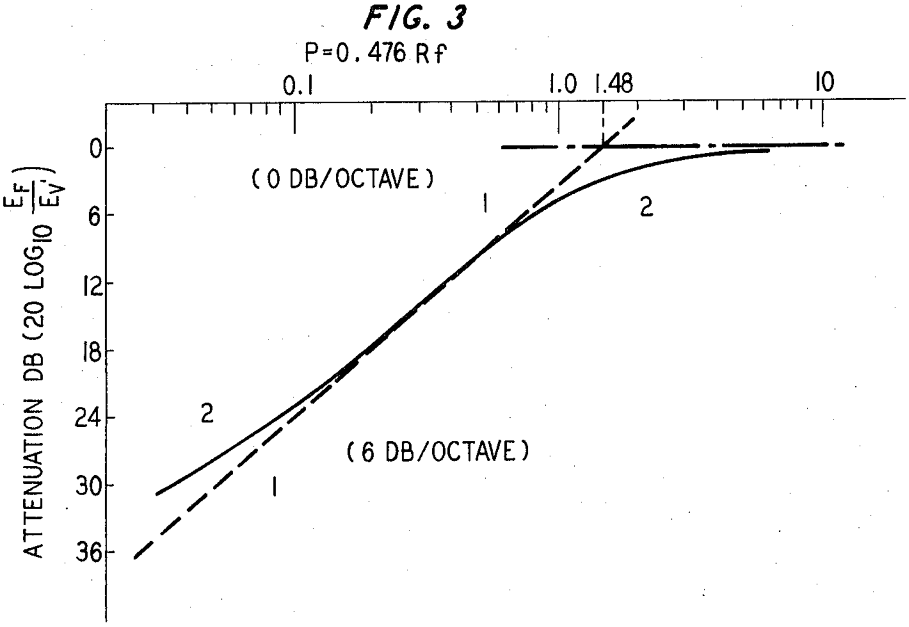

P=0.476 Rf
0.1
1.0
1.48
10
ATTENUATION DB (20 LOG10 EF/EV')
0
6
12
18
24
30
36
(0 DB/OCTAVE)
1
2
2
(6 DB/OCTAVE)
1

FIG. 4A

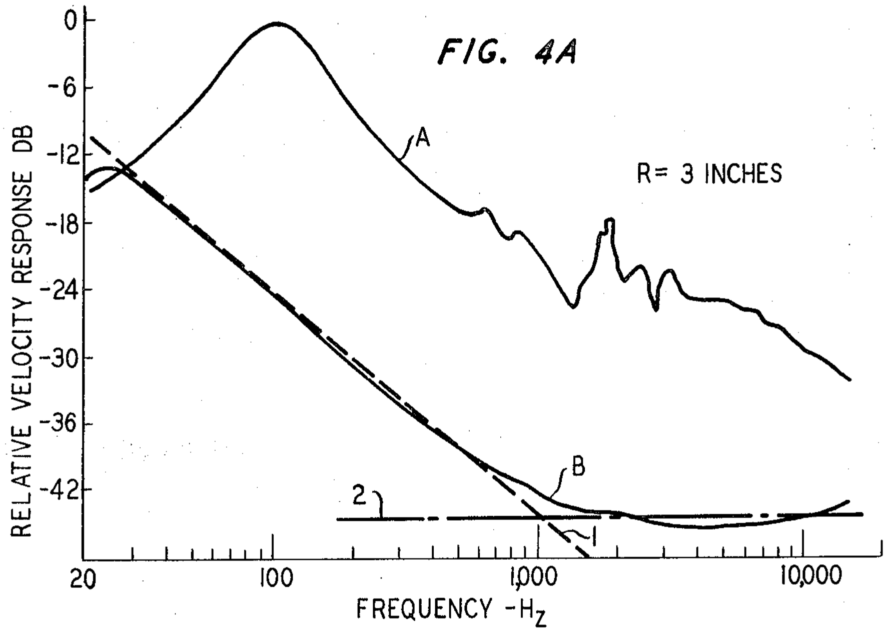

0
-6
-12
-18
-24
-30
-36
-42
RELATIVE VELOCITY RESPONSE DB
A
R= 3 INCHES
B
2
1
20
100
1,000
10,000
FREQUENCY -H_Z

FIG. 4B

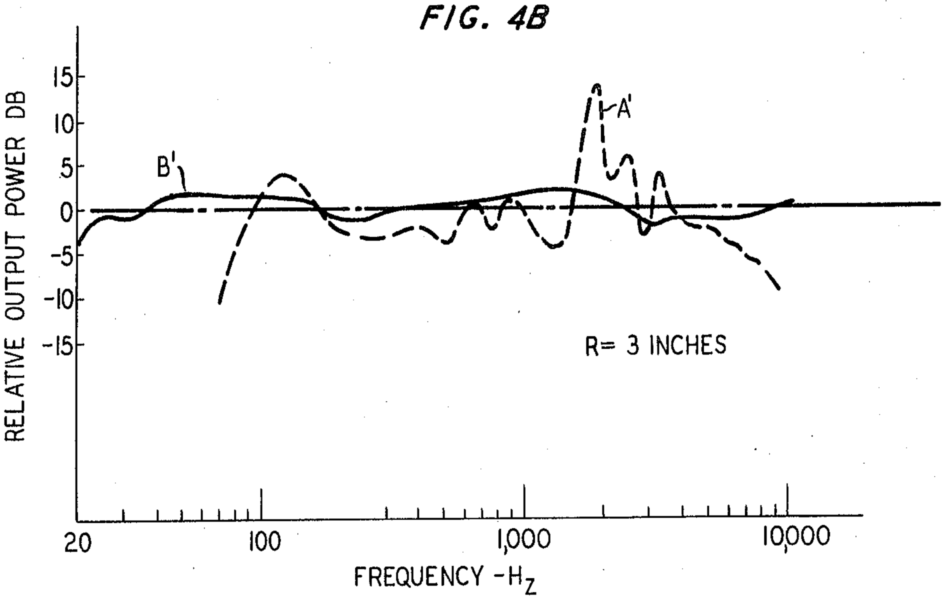

15
10
5
0
-5
-10
-15
RELATIVE OUTPUT POWER DB
B'
A'
R= 3 INCHES
20
100
1,000
10,000
FREQUENCY -H_Z

FIG. 6A

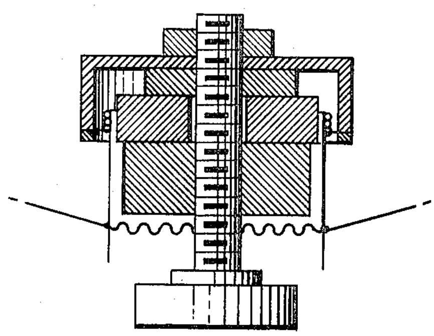


FIG. 6B

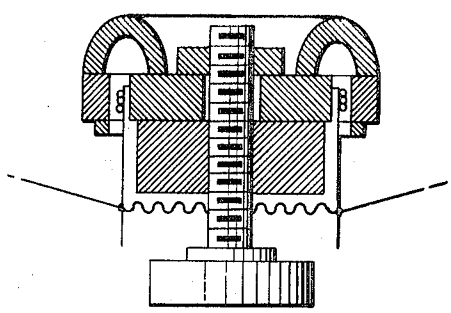


FIG. 5

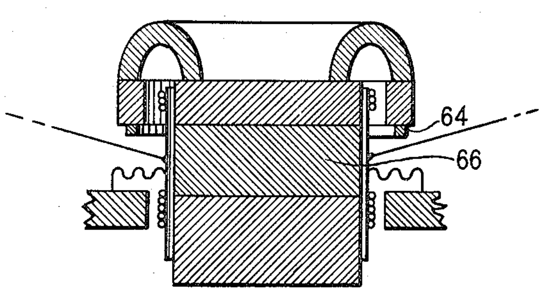


FIG. 7A

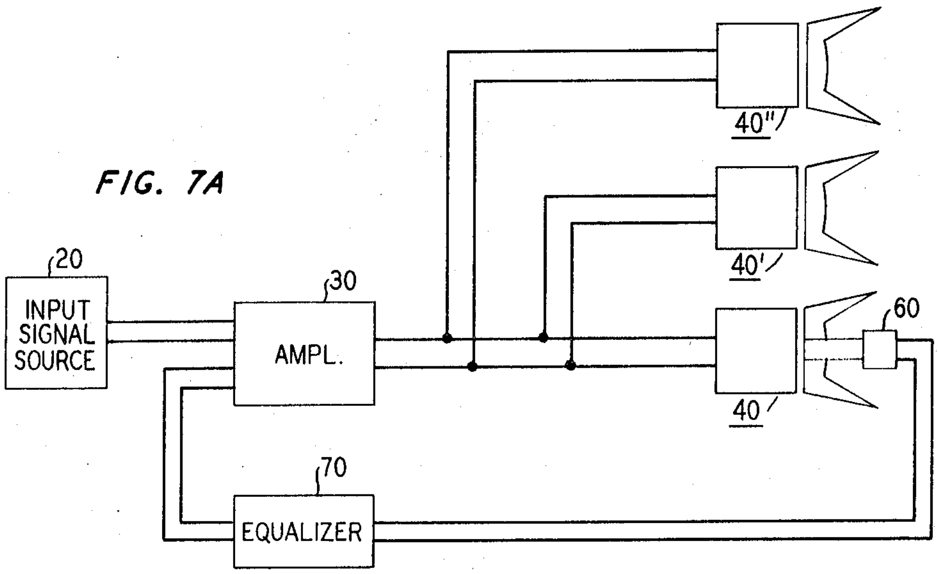


FIG. 7B

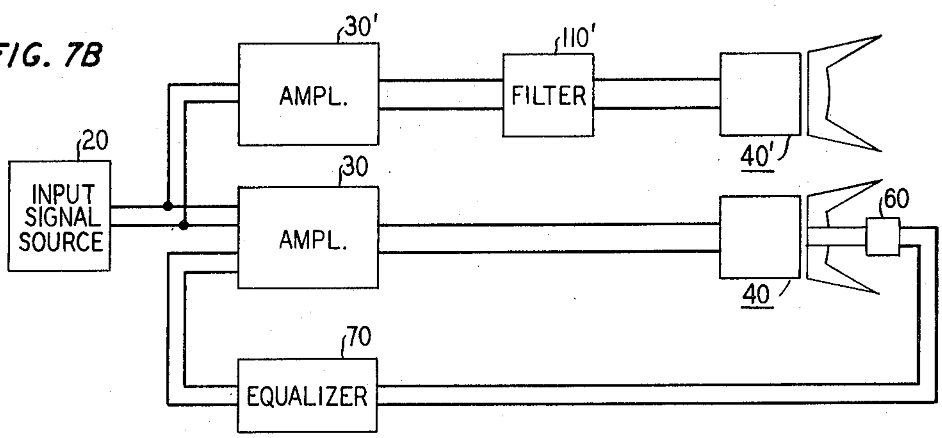
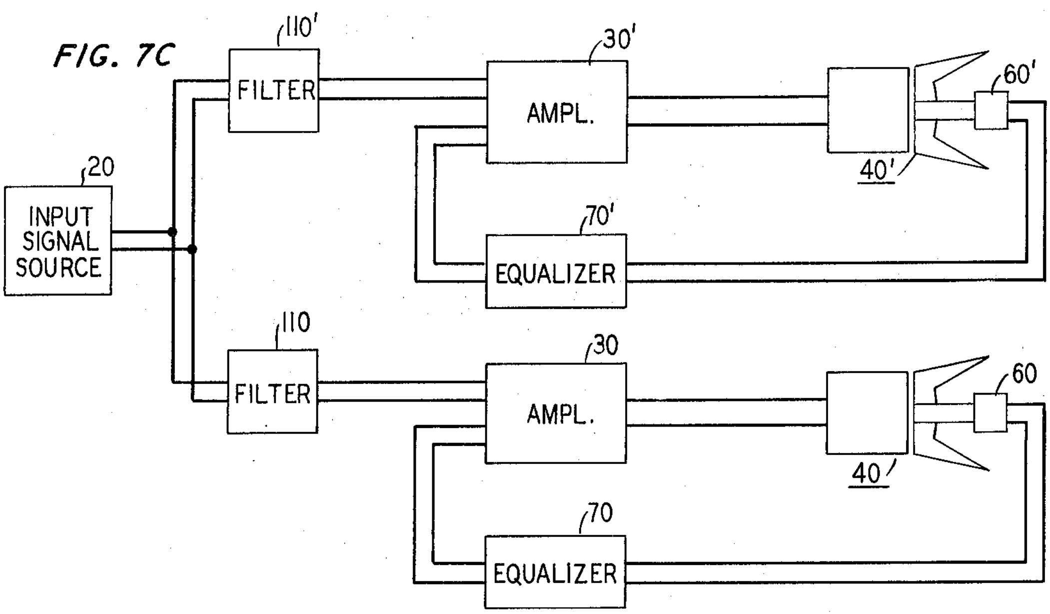


FIG. 7C



SOUND REPRODUCING SYSTEM UTILIZING MOTIONAL FEEDBACK

FIELD OF THE INVENTION

This invention relates to sound reproducing systems and, in particular, to such systems which include the loudspeaker as part of the feedback path.

BACKGROUND OF THE INVENTION

Several prior art sound reproducing systems have included the loudspeaker in a feedback path for reducing loudspeaker distortion, for extending the loudspeaker's frequency response, and for allowing the utilization of smaller acoustic enclosures. Such prior art systems, especially those which include means for magnetically sensing the axial motion of the associated speaker-cone, have considered neither the detrimental effects due to electrical interference from the loudspeaker's main electromagnetic structure nor the proper frequency shaping of the motional signal to cause the loudspeaker to respond linearly to the input source signal. Further, none of these prior art motional feedback systems have effectively compensated for inherent amplifier gain limitations.

It is therefore an object of the present invention to utilize motional feedback in a sound reproducing system for reducing loudspeaker distortion.

It is another object of this invention to utilize motional feedback in a sound reproducing system for linearly extending the associated loudspeaker's frequency response.

It is a further object of this invention to utilize motional feedback in a sound reproducing system having relatively small loudspeaker enclosures.

It is still a further object of this invention to reduce electrical interference applied to the motional sensing means by the loudspeaker's main electromagnetic structure.

It is a still further object of this invention to utilize a motional sensing means which is substantially free of electrical interference from the associated loudspeaker's main electromagnetic structure.

It is a still further object of this invention to properly shape the motional signal so that the loudspeaker responds linearly to the input source signal.

It is a still further object of this invention to compensate for inherent amplifier gain limitations in a sound reproducing system which utilizes motional feedback.

SUMMARY OF THE INVENTION

According to the present invention, a sound reproducing system utilizing motional feedback to reduce loudspeaker distortion substantially comprises an amplifier which is jointly responsive to the input source signal and to a feedback signal, a moving-coil loudspeaker including a main electromagnetic structure which is responsive to the amplifier's output signal for effecting axial speaker-cone motion, motional sensing means for providing a signal which is functionally related to axial cone velocity, and an equalizer exhibiting a predetermined nonlinear attenuation versus frequency characteristic and which is responsive to the motional signal for providing the feedback signal. The feedback signal is degeneratively applied to the amplifier which, in turn, forces the loudspeaker to respond linearly to the input source signal and thereby exhibit a uniform sound energy output.

According to the present invention, the loudspeaker cone exhibits a velocity versus frequency characteristic which is substantially approximated by a first straight line having a −6 db/octave slope and by a second straight line having a 0 db/octave slope, these lines intersecting where $0.476\ Rf \approx 1.5$; R being the effective speaker-cone radius in inches and f being the operating frequency in KHz.

According to specific embodiments of this invention, the motional sensing means is either of the type which is integral with the loudspeaker structure or of the type which is attached as an applique to a pre-existing conventional loudspeaker structure.

It is an advantage of the present invention that relatively small loudspeaker enclosures can be utilized.

It is another advantage of this invention that loudspeaker diaphragm performance is substantially independent of enclosure characteristics.

It is a further advantage of this invention that the motional sensing means can be used in conjunction with conventional loudspeakers as an applique and in specially built speakers which include the motional sensing means built integrally therewith.

It is a feature of the present invention that the loudspeaker produces a substantially uniform sound energy output.

It is another feature of this invention that the motional signal is properly shaped and thereafter degeneratively applied to the amplifier to force the loudspeaker to respond linearly to the input source signal.

It is a further feature of this invention that the loudspeaker cone exhibits a unique axial-velocity characteristic.

It is a still further feature of this invention that the equalizer characteristic modifies the loudspeaker's response throughout the frequency domain.

DESCRIPTION OF THE DRAWING

The above and other objects, advantages, and features of the present invention will be better appreciated by a consideration of the following detailed description and the drawing in which:

FIG. 1 illustrates a sound reproducing system according to the present invention;

FIG. 2 shows an ideal velocity characteristic according to the present invention whereby the loud-speaker produces a substantially uniform sound-energy output;

FIG. 3 shows an equalizer attenuation characteristic according to the present invention used to shape the motional signal to provide the feedback signal;

FIG. 4A shows actual loudspeaker velocity characteristics for the cases wherein no feedback is used and wherein feedback is used according to the present invention, while FIG. 4B shows the corresponding sound energy output versus frequency curves;

FIG. 5 illustrates an embodiment of a motional sensing means similar to the one shown in FIG. 1;

FIGS. 6A and 6B illustrate two further embodiments of motional sensing means which are particularly adaptable to applique techniques; and

FIGS. 7A, 7B, and 7C illustrate various configurations which include the present invention.

DETAILED DESCRIPTION

In FIG. 1, there is shown sound reproducing system

10 according to the present invention generally comprising power amplifier circuit **30**, loudspeaker **40**, and equalizer circuit **70**. Loudspeaker **40**, which in this case is advantageously of the moving-coil type, further comprises cone or diaphragm **41**, main electromagnetic structure **50**, and cone motion sensing means **60**. It should be noted, however, that the teaching of the present invention can be applied to any type of loudspeaker which includes relative moving parts to produce an acoustic output; for instance, a loudspeaker of the electrostatic type can be utilized. In system **10**, input signal Es from source **20** is applied via lines **91** and **92** to amplifier **30** while output signal Ea of amplifier **30** is applied via lines **93** and **94** to loudspeaker **40**. In conventional manner, main electromagnetic structure **50** responds to amplifier signal Ea to cause axial motion of cone **41**.

According to the present invention, sensing means **60** responds to the motion of cone **41** near its apex to provide motional signal Ev; this signal is functionally related to the axial velocity of the cone and therefore simultaneously indicates the distortion components radiated thereby. In this case, cone **41** is advantageously chosen to move substantially as a rigid piston so that motional signal Ev reflects the true sound energy output thereof. Motional signal Ev is then applied via lines **95** and **96** to linear gain amplifier **80** to produce amplified motional signal E which, in turn, is applied via lines **95'** and **96'** to equalizer circuit **70** to produce feedback signal Ef. Equalizer circuit **70** exhibits a predetermined nonlinear attenuation versus frequency characteristic which will be discussed in detail hereinafter. Finally, feedback signal Ef is degeneratively applied via lines **97** and **98** to amplifier **30** whereby loudspeaker **40** is forced to respond linearly to input source signal Es.

In light of the above, the application of feedback signal Ef to the amplifier **30** causes the cone's motion to be under the exclusive control of input source signal Es. Therefore, by choosing an appropriate equalizer characteristic, the speaker's sound energy output, i.e., its frequency response, can easily be controlled. Generally, the equalizer characteristic is chosen so that cone **41** exhibits a predetermined axial velocity versus frequency characteristic, to be further discussed hereinafter, which, in effect, causes loudspeaker **40** to radiate a substantially uniform sound energy output. This, of course, reduces the harmful effects caused by loudspeaker distortion.

In FIG. **2**, there is shown according to the present invention the ideal velocity versus frequency characteristic which cone **41** must exhibit in order to provide a substantially uniform sound energy output over the frequency band of interest. In the FIG., relative axial cone velocity in decibels (dB) is plotted as a function of parameter p, which is defined by 0.476Rf, where R is the effective cone radius in inches and f is the operating frequency in KHz. In conventional manner, effective cone radius is defined as the maximum distance from the axis of the cone to that part of the rim that moves essentially as a rigid continuation of the cone. This ideal velocity characteristic is shown by the solid curve and can be theoretically defined by a characteristic which is the inverse of the radiation resistance as expressed theoretically by well-known relationships involving Bessel functions. This, in part, explains the oscillatory portions of the curve above $p = 1.5$. As is apparent from this FIG., the ideal velocity characteristic can be approximated by a first straight line having a slope of −6 db/octave and by a second straight line having a slope of 0 db/octave, these two lines intersecting at $p \approx 1.5$. In light thereof, it is apparent that at low frequencies the cone must exhibit a substantially constant acceleration; whereas at higher frequencies the cone must exhibit a substantially constant velocity. As noted above, the nominal breakpoint between the low and high frequency regions occurs at $p = 1.5$. This point occurs where the operating frequency is equal to about three times the reciprocal of the effective cone radius. From the control viewpoint, therefore, the cone is forced to exhibit a substantially constant acceleration at relatively low frequencies and a substantially constant velocity at relatively high frequencies, the nominal breakpoint dividing these two frequency regions being located at $p = 1.5$.

In FIG. **3**, there are shown ideal and actual equalizer characteristics which force speaker **40**, when respectively driven by ideal and practicable amplifiers, to substantially exhibit the ideal velocity characteristic of FIG. **2**. In FIG. **3**, attenuation in dB is plotted as a function of $p = 0.476$ Rf, as defined before. In the region where p is less than 1.5, the ideal characteristic is shown by the dashed line while the actual characteristic is shown by the solid curve. Above $p = 1.5$, the actual and ideal characteristics are substantially coincident; therefore, only the actual characteristic is shown. It is apparent that the ideal characteristic is approximated by a first straight line having a +6 dB/octave slope and by a second straight line having a 0 dB/octave slope, the two lines intersecting where $p = 1.5$. According to the present invention, the actual attenuation characteristic deviates from the ideal characteristic, especially at low frequencies, to provide a relatively lower attenuation effect. In other words, the actual characteristic comprises a concave upward portion over the low frequency region at its left end and a nearly +6 dB/octave slope at its center; the actual characteristic further comprises a concave downward portion over the higher frequencies which asymptotically approaches a 0 dB/octave slope at its right end. The actual characteristic is necessary in order to compensate for amplifier feedback-gain limitations at low frequencies and for air loading of the diaphragm at high frequencies. Otherwise, if equalizer **70** provided the ideal characteristic at low frequencies, instead of the actual characteristic, then amplifier **30** would have to provide exceedingly high gain at these low frequencies. It appears that the ideal equalizer characteristic is a reflected image of the ideal velocity characteristic while the actual equalizer characteristic is a distorted reflected image of the ideal velocity characteristic.

As is shown in FIG. **1**, equalizer circuit **70** includes resistors **R71** and **R72** and capacitors **C73** and **C74**. Elements **R71** and **C73** in combination substantially provide the ideal characteristic of FIG. **3** at low and high frequencies; however, elements **R72** and **C74** in combination are added to modify the otherwise ideal characteristic at the low frequency end thereby yielding the actual characteristic (solid curve) of FIG. **3**. In this particular embodiment, the values of **R71, R72, C73** and **C74** are 470 ohms, 33 Kohms, 0.25 uf and 0.1 uf, respectively.

In FIG. **4A**, there are shown actual cone velocity curves A and B for system **10** of FIG. **1**, wherein speaker **40** has an effective cone radius of 3 inches and the associated enclosure has a volume of 1.2 cubic feet. Curve A corresponds to the case without motional feedback, while curve B corresponds to the case including motional feedback according to the present invention, the above-described equalizer circuit being utilized. Again, the intersecting straight line approximation to the ideal velocity curve is shown. It is apparent that above $p = 1.5$ (corresponding to $f = 1.1$ KHz) there occurs a substantially constant velocity region; whereas below $p = 1.5$ there occurs a substantially constant acceleration region, as explained before. It is apparent that the natural speaker-cone resonance has been reduced from its initial value of 100 Hz for the case without feedback to a value of approximately 25 Hz for the case with feedback. If necessary, more elaborate equalizer circuitry than that used herein could be utilized to yield a closer approximation to the ideal velocity curve, as will be apparent to those skilled in the art.

In FIG. 4B, conventional sound amplitude or energy versus frequency curves corresponding to the velocity curves of FIG. 4A are shown, curves A′ and B′, respectively, corresponding to curves A and B of FIG. 4A. The present curves are derived from the previous curves by using well known acousto-mechanical relationships, such as discussed in standard texts on direct radiator loudspeakers. From FIG. 4B, it is apparent that the overall speaker frequency response has been substantially improved, especially at the lower and upper ends of the applicable frequency spectrum. It is therefore apparent that a small diameter speaker with feedback can replace a large diameter speaker without feedback and yet provide similar acoustic performance. Similar reasoning applies to replacing a large number of required identical speakers not utilizing feedback with a smaller number of identical speakers which utilize feedback and still provide comparable performance.

Reference again to FIG. 1 shows power amplifier circuit **30** further includes high-gain operational amplifier **31** having its non-inverting and inverting input terminals, respectively, connected to line **91** and, via resistor **R32**, to line **97**. The non-inverting input terminal receives input source signal Es and is connected via resistor **R33** to ground **99**. The output terminal of amplifier **31** is connected via resistor **R36** to the base of transistor **T38**. Capacitor **C37** is connected between the base of **T38** and ground **99** to improve stability with feedback. Push-pull output stage **102**, including transistors **T103** and **T104**, is driven by the emitter of transistor **T38**. The emitters of this output stage are jointly connected to output line **93**. Diode **D105** couples the bases of transistors **T103** and **T104** in order to compensate for any inherent joint base-emitter offset voltage. This minimizes breaks in signal continuity in amplifier output signal Ea when both these transistors are off during periods of input signal transitions. Resistor **R106**, which connects the base of transistor **T104** to negative voltage supply −V, provides for maximum base current and thus for peak signal drive in the negative direction.

In FIG. **1**, net internal feedback is provided via resistors **R107** and **R32**. The latter is in series with the output impedance of equalizer circuit **70**, which is relatively small. Feedback via resistor **R107** provides dc feedback which minimizes dc offset in the output of amplifier **30** so that the rest position of voice coil **55** is displaced as little as possible. The ac part of the feedback via **R107** is combined with the equalized motional feedback component Ef from equalizer **70** via **R32** to yield a net ac negative feedback component to the inverting input of operational amplifier **31**. In this case, for ac control of speaker **40**, the ac motional feedback component should predominate. Distortion normally inherent to amplifier circuit **30** is substantially reduced, since the amplifier, in response to feedback signal Ef on line **97**, is forced to exhibit a gain versus frequency characteristic which causes loudspeaker **40** to respond linearly to input source signal Es. Regardless of the particular design of amplifier circuit **30**, the fact that main voice-coil **55** is a current sensitive device should always be taken into account.

As mentioned before, loudspeaker **40** includes cone **41**, main electromagnetic structure **50**, and motional sensing means **60**, which, in this embodiment, is built integrally with the speaker. In FIG. **1**, the horizontal direction corresponds to the speaker's axial direction. Main electromagnetic structure **50**, which is rigidly secured to speaker frame or housing or chassis **42**, further includes cup-shaped iron outer pole piece **51**, solid cylindrical permanent magnet **52**, solid cylindrical iron inner pole piece **53**, and main voice coil **55** would on the rearward end of substantially rigid, thin cylindrical bobbin **54**. Bobbin **54**, in turn, is mechanically connected to the rearward end or apex portion of cone **41**. In this particular embodiment, the axial length of main voice coil **55** is advantageously made substantially longer than the axial length of its associated magnetic air gap in order to assure substantially uniform coil reaction in the gap field over large excursions. This field's path is shown by the arrows. In conventional manner, structure **50** responds to amplifier output signal Ea to cause axial motion of main voice coil **55**, the opposite ends of the coil being connected to lines **93** and **94**. This, in turn, causes axial motion of cone **41** via bobbin **54**. Axial motion of the cone is stabilized and radial motion thereof is suppressed by flexible centering suspensions or webs **43** and **44** (compliant annulli). The rearward and forward portions of cone **41** are rigidly attached to the inner peripheries of webs **44** and **43**, respectively, while the outer periphery of each web is secured to frame **42**. In this embodiment, line **94** is grounded, thereby making amplifier circuit **30** direct current coupled to loudspeaker **40**.

Reference again to FIG. **1** shows motional sensing means **60** further includes cup-shaped iron outer pole piece **61**, ring **64**, solid cylindrical permanent magnet **62**, solid cylindrical iron inner pole piece **63**, solid cylindrical member **66**, and feedback coil **65** wound on the forward end of bobbin **54**. Ring **64** and member **66** are advantageously made of a nonmagnetic metal of good electrical conductivity such as copper, aluminum, etc., to minimize leakage interference elements **64** and **66** are shown in detail in FIG. **5**. The electrical conductivity of member **66** causes the production of eddy currents which tend to counteract and substantially compensate for the interfering electrical fields produced by main electromagnetic structure **50**. Further electrical interference compensation is effected by short circuiting ring **64**. (It is apparent that member **66** mechanically interconnects inner pole piece **53** of main electromagnetic structure **50** and inner pole piece **63** of motional sensing means **60**.) The inner diameter of ring **64** is advantageously made as small as possible without interfering with the motion of feedback coil **65**. In other words, ring **64** and member **66** assure electrical isolation between structure **50** and sensing means **60.** As before, the axial length of feedback coil **65** is advantageously made substantially longer than the axial length of its associated gap in order to assure that the coil always moves within a substantially uniform magnetic flux. It is apparent, however, that while main voice coil **55** and feedback coil **65** are mechanically coupled via common bobbin **54**, they are electrically independent of each other. This is due in part to the presence of ring **64** and member **66.** Therefore, the axial motion imparted to cone **41** by structure **50** is also imparted to feedback coil **65.** In turn, feedback coil **65** interacts with the magnetic field produced by associated magnet **62** to produce motional signal Ev. This signal is produced across the opposite ends of feedback coil **65** which connect to lines **95** and **96**, line **96** being grounded in this embodiment. In a manner similar to that discussed above, the flux within the gap is produced by pole pieces **61** and **63.** Again, the path of the associated magnetic flux is shown by the dashed line. According to the present invention, elements **61, 62, 63, 64, 66, 53, 52,** and **51** can advantageously be secured by adhesive means.

Motional signal Ev, which is functionally related to the axial velocity of cone **41** and which indicates the sound energy output of loudspeaker **40**, is applied via input resistor **R81** to the non-inverting input of operational amplifier **81.** Amplifier circuit **80** is inserted into the feedback path in order to linearly compensate for the low level of Ev and the attenuating effect occuring thereafter at equalizer circuit **70.** This, of course, guarantees the application of reasonable feedback signal levels to amplifier **30.** In addition, this allows the use of finer wire and fewer turns in the construction of feedback coil **65** and minimizes the magnitude of the required magnetic flux to be provided by magnet **62.** The inverting input of operational amplifier **81** is grounded via resistor **R82** while negative feedback is applied to the amplifier via resistor **R83.** The operation of amplifier circuit **80** is well understood by those skilled in the art.

Amplified signal E, which is linearly proportional to motional signal Ev, is now applied via lines **95'** and **96'** to equalizer circuit **70**, line **96'** being connected to ground **99.** Thereafter, output signal Ef of equalizer circuit **70** is degeneratively applied to amplifier circuit **30**; in this embodiment, the feedback signal is applied to the inverting input of operational amplifier **31** via resistor **R32.** Thus, amplified motional signal E is shaped by equalizer **70** to yield feedback signal Ef, which, in turn, forces loudspeaker **40** to exhibit the ideal velocity characteristic of FIG. **2.**

In reference now to FIG. **5**, there is shown another embodiment of a motional sensing means which is built integrally with its associated speaker. In this case, the permanent magnet is one-half of a hollow toroid rather than a solid cylinder while the outer pole piece is a hollow cylinder rather than cup-shaped. Again, ring **64** and member **66** are included to electrically isolate the feedback coil from the speaker's main electromagnetic structure. Herein, the magnet's inner and outer poles are circular annulli of approximately equal cross-sectional area.

In FIGS. **6B** and **6A**, there are respectively shown motional sensing means which are similar to those already discussed with reference to FIGS. **1** and **5** but which are adapted to be attached to a pre-existing conventional speaker as an applique. In these structures, the connecting members are advantageously made of two portions; one portion being initially secured to the pre-existing inner pole piece of the speaker's main electromagnetic structure by adhesive means while the second portion and the remaining elements of the motional sensing means are thereafter attached to the first portion via an associated threaded member. The whole structure is ultimately secured via a locknut. In addition to having a connecting member which includes two connecting sections, the present structures include a separate bobbin piece which is centered via its own associated web. The connection of the new bobbin piece to the pre-existing cone and the mechanical connection of the elements required in the applique device will not be further discussed herein.

With reference to multiple enclosure sound reproducing systems, it is apparent that the main electromagnetic loudspeaker structure's varying characteristics may result in non-uniform response of their associated cones. The utilization of motional feedback according to the present invention reduces these differences in resulting cone motion. Therefore, by carefully controlling the manufacture of the motional sensing means and the associated equalizer circuit within reasonable bounds, performance differences from enclosure to enclosure, which would otherwise occur, are substantially eliminated.

The broad advantages and features of a sound reproducing system according to the present invention have already been discussed. As may be seen in FIG. 7A, one specific application of the invention is shown wherein common power amplifier circuit **30** responds to source **20** to drive a plurality of identical loudspeakers **40, 40'**, and **40''** having identical frequency amplitude and distortion characteristics. However, only speaker **40** contains a motional sensing means **60** which provides a motional signal to its associated equalizer **70.** The equalizer, of course, provides the feedback signal to amplifier **30.** This configuration is inherently economical since only one feedback loop, providing the necessary compensation, is required to drive more than one speaker. Another specific application is shown in FIG. 7B wherein amplifier **30** responds to source **20** to drive speaker **40.** Associated with speaker **40** are motional sensing means **60** and equalizer **70** which in combination provide a feedback signal to the amplifier. Also included is separate and independent amplifier **30'** which responds to source **20** to drive speaker **40'** via filter **110'**. In this case, motional feedback is utilized to drive speaker **40** over a first frequency range while speaker **40'** is driven over a complementary frequency range which is determined by filter **110'**. Speakers **40** and **40'** are not necessarily identical. Finally, in FIG. 7C, two independent motional feedback circuits are shown. In the first circuit, amplifier **30** responds to source **20** via filter **110** to drive speaker **40.** Speaker **40** further includes motional sensing means **60.** As before, equalizer **70** provides a feedback signal to amplifier **30.** In the second circuit, amplifier **30'** responds to source **20** via filter **110'** to drive speaker **40'**. Associated with speaker **40'** are motional sensing means **60'** and equalizer **70'** which, in combination, provide a feedback signal to the amplifier. In this case, filters **110** and **110'** are chosen so that speakers **40** and **40'** operate in complementary or nonoverlapping frequency regions. In the above and other examples which utilize motional feedback according to the present invention, speakers capable of large cone excursions, such as that described by R. T. Bozak in his U.S. Pat. No. 3,436,494 are recommended.

In a sound reproducing system according to the present invention, as in any conventional sound reproducing system of the prior art, the required loudspeakers are chosen to fit the particular application. In other words, the loudspeaker should be substantially capable of performing at low or high frequencies, as the case may be. For instance, the loudspeaker should initially be chosen of the appropriate cone size so that rigid cone motion results in the frequency range of interest. This, of course, results in improved loudspeaker performance, especially at the low frequencies. The loudspeaker is also chosen so that high frequency beaming and low frequency Doppler distortion are minimal. Further, well known enclosure design and multispeaker system design techniques should be considered. These considerations, of course, will be apparent to those skilled in the art inasmuch as such considerations need be taken into account in the design of almost any sound reproducing system and not just in the design of a sound reproducing system according to the present invention.

While the arrangement according to the present invention utilizing motional feedback in a sound reproducing system has been described in terms of specific embodiments, it will be apparent to those skilled in the art that many modifications are possible within the spirit and scope of the disclosed principle.

What is claimed is:

1. A sound reproducing system comprising:
- first amplifying means jointly responsive to a source signal and to a first feedback signal;
- first sound energy producing means responsive to said first amplifying means;
- first means for sensing the sound energy output of said first producing means; and
- first equalizing means exhibiting a predetermined nonlinear attenuation versus frequency times a constant characteristic and being responsive to said first sensing means for providing said first feedback signal, said characteristic having a positive slope over the lower portion of a first frequency range and a zero slope over the rest of said first frequency range;
- whereby said first sound energy producing means radiates a substantially uniform sound energy output over said first frequency range.

2. The sound reproducing system of claim **1** wherein said first sound energy producing means is a loudspeaker of the moving-coil type including a cone and a voice coil, said voice coil responding to said first amplifying means for axially driving said cone; and said first sensing means responds to the motion imparted to said cone by said voice coil.

3. The sound reproducing system of claim **2** wherein said first sensing means responds to the axial velocity imparted to said cone by said voice coil.

4. The sound reproducing system of claim **3** wherein said first sensing means includes a coil which is mechanically coupled to said cone and which interacts with an associated magnetic field to produce an electrical signal which is functionally related to the axial velocity imparted to said cone by said voice coil.

5. The sound reproducing system of claim **2** wherein said cone exhibits a velocity versus frequency characteristic which is substantially approximated by a first straight line having a slope of −6 db/octave and by a second straight line having a slope of 0 db/octave, said lines intersecting where 0.476 Rf is approximately equal to 1.5, R being the effective radius of said loudspeaker cone and *f* the operating frequency thereof.

6. The sound reproducing system of claim **4** further including:
- in association with said voice coil, a first permanent magnet, a first inner pole piece, and a first outer pole piece, which in combination form the main electromagnetic structure of said loudspeaker;
- in association with said sensing coil, a second permanent magnet, a second inner pole piece, and a second outer pole piece, which in combination form said motional sensing means; and
- an appropriately shaped non-magnetic electrically conductive metallic member which is rigidly attached to said second outer pole piece and which is located between said second outer pole piece and said main electromagnetic structure.

7. The sound reproducing system of claim **4** further including:
- in association with said voice coil, a first permanent magnet, a first inner pole piece, and a first outer pole piece, which in combination form the main electromagnetic structure of said loudspeaker;
- in association with said sensing coil, a second permanent magnet, a second inner pole piece, and a second outer pole piece, which in combination form said motional sensing means; and
- an appropriately shaped non-magnetic, electrically conductive metallic member mechanically securing said second inner pole piece to said first inner pole piece.

8. The sound reproducing system of claim **2** wherein said cone exhibits a substantially constant acceleration over a low frequency region and a substantially constant velocity over a high frequency region, said regions meeting where 0.476 Rf is approximately equal to 1.5, R being the effective radius of said loudspeaker cone and *f* the operating frequency thereof.

9. The sound reproducing system of claim **1** wherein said first sound energy producing means is a loudspeaker of the electrostatic type.

10. The sound reproducing system of claim **1** also comprising linear amplifying means serially interposed between said first sensing means and said first equalizing means.

11. The sound reproducing system of claim **2** wherein said first equalizing means exhibits an attenuation versus frequency characteristic which is substantially approximated by a first straight line having a slope of +6 db/octave and by a second straight line having a slope of 0 db/octave, said lines intersecting where 0.476 Rf is approximately equal to 1.5, R being the effective radius of said loudspeaker cone and *f* the operating frequency thereof.

12. The sound reproducing system of claim **2** wherein said first equalizing means exhibits an attenuation versus frequency characteristic which is substantially approximated by a curve which is concave upward at its lower end and is concave downward at its upper end with an intervening slope approaching 6 db/octave and an ultimate slope at the upper end approaching 0 db/octave.

13. The sound reproducing system of claim **1** further comprising: second amplifying means responsive to said source signal; filtering means responsive to said second amplifying means; and second sound energy producing means responsive to said filtering means.

14. The sound reproducing system of claim **1** further comprising a plurality of identical sound energy producing means which are responsive to said first amplifying means and which are identical to said first sound energy producing means.

15. The sound reproducing system of claim **1** further comprising:

second amplifying means jointly responsive to said source signal and to a second feedback signal;

second sound energy producing means responsive to said second amplifying means;

second means for sensing the sound energy output of said second sound energy producing means; and

second equalizing means exhibiting a predetermined nonlinear attenuation versus frequency characteristic and being responsive to said second sensing means for providing said second feedback signal,

whereby said second sound energy producing means radiates a substantially uniform sound energy output over a frequency range which does not overlap with said first frequency range.

16. A sound reproducing system comprising:

an amplifier jointly responsive to an input source signal and to a feedback signal;

a loudspeaker of the moving-coil type including a cone and a voice coil, said voice coil responding to said amplifier for axially driving said cone;

means for sensing the axial velocity of said cone; and

an equalizer exhibiting a predetermined nonlinear attenuation versus frequency characteristic and being responsive to said sensing means for providing said feedback signal,

whereby said cone exhibits a velocity versus frequency times a constant characteristic which is substantially approximated by a first straight line having a slope of −6 db/octave and by a second straight line having a slope of 0 db/octave, said lines intersecting where 0.476 Rf is approximately equal to 1.5, R being the effective radius of said loudspeaker cone and *f* the operating frequency thereof.

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