SOUND REPRODUCTION COMPENSATION SYSTEM

Filed Sept. 15, 1965



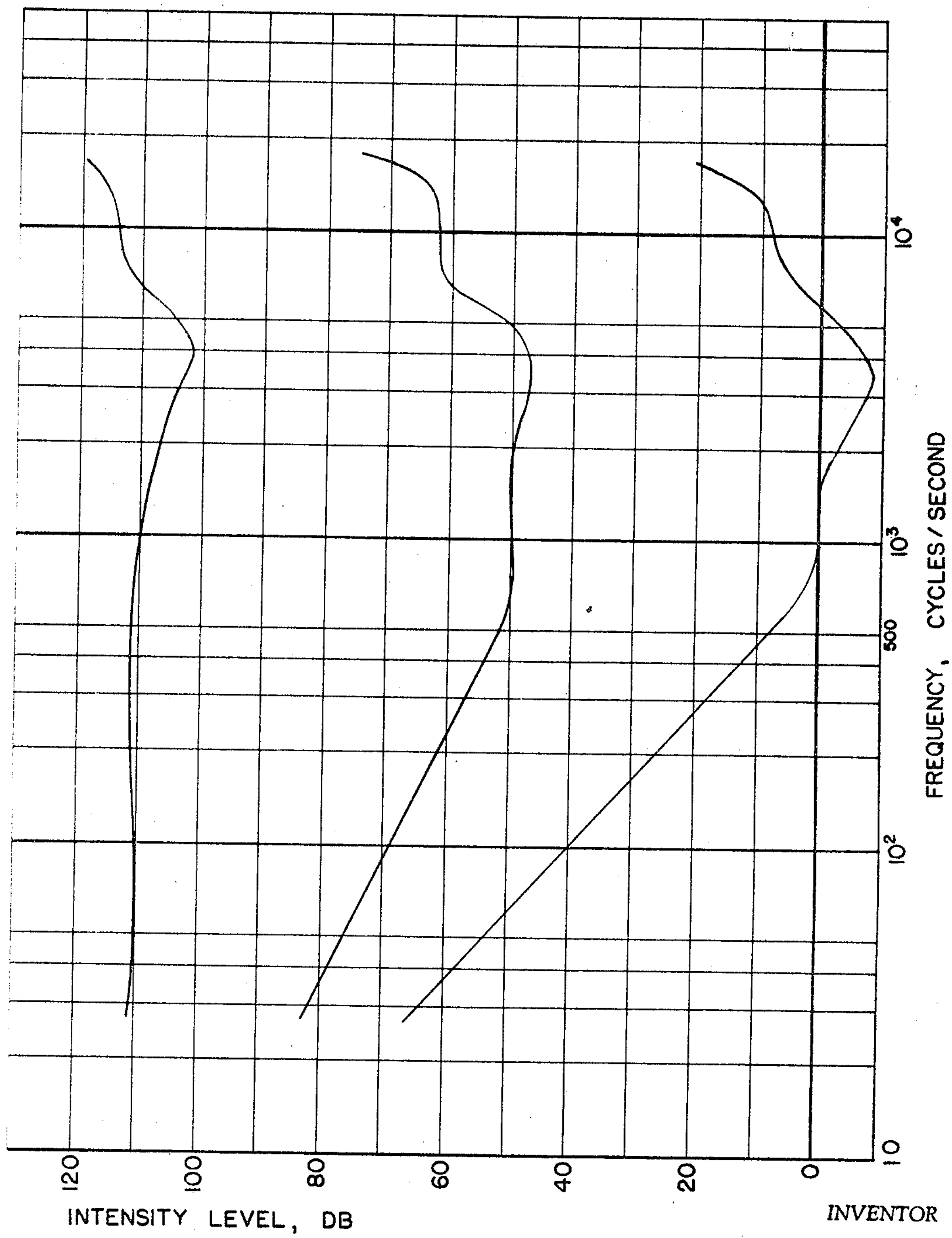


Fig. 1

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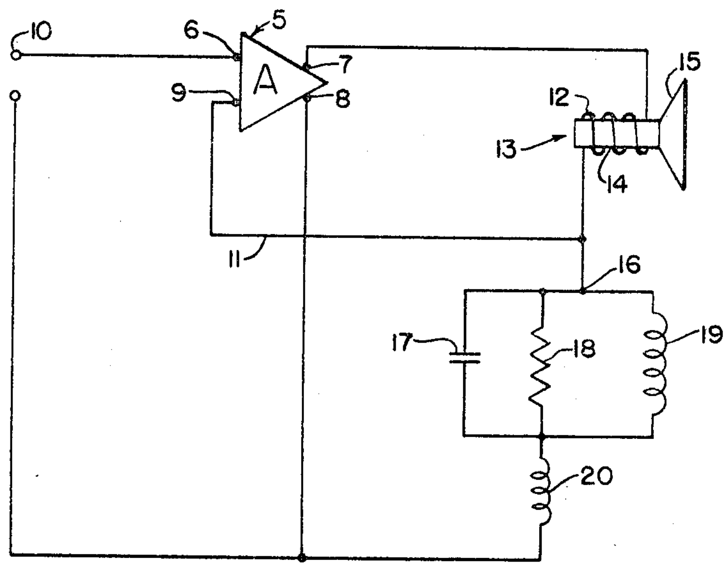


Fig. 2

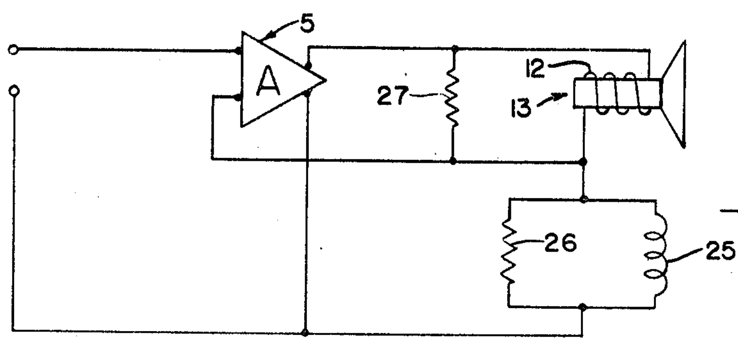


Fig. 3

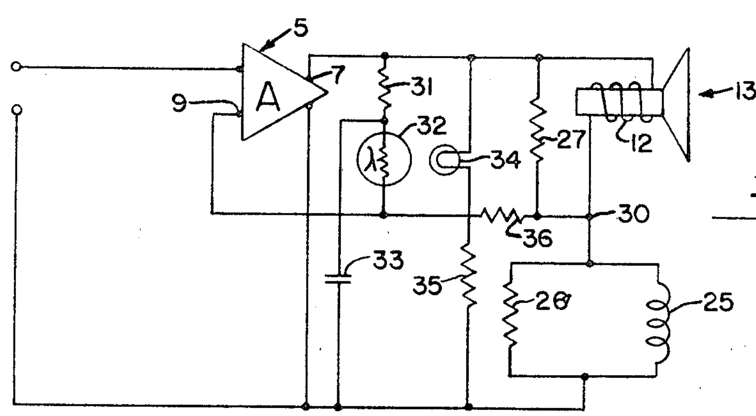


Fig. 4

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# United States Patent Office

3,449,518
Patented June 10, 1969

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3,449,518
SOUND REPRODUCTION COMPENSATION SYSTEM

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Filed Sept. 15, 1965, Ser. No. 487,461
Int. Cl. H04m 1/02
U.S. Cl. 179—1 16 Claims

## ABSTRACT OF THE DISCLOSURE

A sound reproduction system which compensates for the nonlinear characteristics of a conventional loudspeaker such that the speaker sound output is constant over the audible frequency range and prevents damage to the speaker at high signal levels by employing frequency-sensitive and level-sensitive feedback networks in conjunction with a feedback amplifier and a loudspeaker. At low volumes, the frequency-sensitive network operates with the amplifier to increase the output level of low-frequency signals, while at high volumes, a level-sensitive network tends to cancel the effect of frequency-sensitive network, thus protecting the speaker from damage.

This invention relates to sound reproduction apparatus, and more particularly to apparatus for reproducing sound with compensation for the nonlinear characteristics of a signal-to-sound transducer and for protecting the signal-to-sound transducer from damage.

It is well known that at low frequencies the sound output of a conventional loudspeaker is reduced due to the mechanical and electrical characteristics of the speaker. This is due to the current limiting effects of the series resistance of the speaker voice coil at low frequencies. By compensating for undesirable speaker characteristics, such as reducing this resistance, constant sound output from the speaker can be achieved.

It is also well known that the response of the human auditory system to sound waves varies with the frequency and intensity of the sound waves. The work of Fletcher and Munson, described in their paper in the Journal of the Acoustical Society of America, volume 5, number 2 (1933), pp. 82–108, established that sound at a very high loudness level, near the level of feeling, is heard almost equally well at any frequency over the range of normal hearing, but that at lower loudness levels, low-frequency sounds must be more intense to be heard as well as higher frequency sounds. These relationships are shown at p. 91 of the above mentioned paper, especially at FIG. 4.

The relationships of hearing response to sound intensity are of considerable importance in designing an audio system which is to reproduce sound so that it seems more realistic to the listener. Efforts have been made in the past to merely emphasize the low frequencies in recognition of the poorer response of human hearing to those low frequencies. However, as will be evident from the Fletcher-Munson curves, mere emphasis of low frequencies is not sufficient to allow the listener to hear all frequencies equally well at all intensity levels.

It is therefore an object of the present invention to provide an improved sound reproduction apparatus wherein constant sound output from the speaker is provided.

Another object of the present invention is to provide an improved sound reproduction apparatus which compensates for variation in human hearing response with sound frequency and level.

Still another object of the present invention is to provide an improved sound reproduction system which compensates for the nonlinear characteristics of a loudspeaker.

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Another object of the present invention is to provide an improved sound reproduction system wherein the voice coil is protected from being overloaded.

Yet another object of the present invention is to provide an improved sound reproduction system wherein low frequency sound is emphasized at low levels of loudness but not at higher levels of loudness.

Another object is to provide an improved sound signal amplification apparatus wherein the amplification of signals in the lower portion of the audible frequency spectrum is greater at low loudness levels than at high loudness levels.

Briefly described, a preferred embodiment of the present invention includes a conventional broad-band audio amplifier, the output of which is connected to the drive coil of a conventional electrical signal-to-sound transducer, such as a permanent magnet loudspeaker. A negative feedback system is provided to properly compensate the system as described above, the feedback system including an impedance network in series with the loudspeaker coil to provide negative, or degenerative, current feedback. As used in this context, the term "current feedback" refers to a feedback signal which is developed across an impedance network in series with the load impedance. The feedback voltage developed across the network depends on the current delivered to it by the load which is a function of the impedance of the network and the load. The magnitude of this feedback changes with frequency so that at higher frequencies the signal produced by the feedback circuit is greater than at lower frequencies. The signal is connected to the amplifier degeneratively so that the effective amplification of the signal is greater at lower frequencies than at higher frequencies.

To provide for compensation as a function of loudness level, a signal level-sensitive circuit is incorporated. This circuit includes a source of light connected to the amplifier output, the intensity of the light emanating from this source being directly proportional to the level of the signal at the amplifier output. A photosensitive transducer, preferably a photoresistor, is connected between the amplifier output and the degenerative feedback input to the amplifier to provide a negative voltage feedback signal component the magnitude of which is proportional to the resistance of the photoresistor, and, therefore to the intensity of the light. The term "voltage feedback" refers to a signal developed by an impedance in parallel with the load. The signals developed in both cases of current and voltage feedback will, of course, be voltages, and each is a component of the total feedback signal delivered to the amplifying apparatus. A capacitor is also connected to the photoresistor to give the voltage feedback circuit a particular frequency sensitive characteristic so that the voltage feedback circuit is more effective at low levels and at low frequencies than any level of high frequencies.

Feedback signals can, in the general case, be delivered to the amplifying apparatus in phase or out of phase with the primary signal, i.e., as either positive (regenerative) or negative (degenerative) feedback. The phase and therefore the effect is governed by the connection within the amplifier, as will be recognized by one skilled in the art, and need not be discussed in detail herein.

In order that the manner in which the foregoing and other objects are attained in accordance with the invention can be understood in detail, particularly advantageous embodiments thereof will be described with reference to the accompanying drawings, which form a part of this specification and wherein:

FIG. 1 is a graphical representation of the statistical normal response of the human auditory system at representative sound loudness levels;

FIG. 2 is a schematic diagram of one embodiment of the invention including circuitry for providing low-frequency compensation;

FIG. 3 is a schematic diagram of a second embodiment showing a simplified apparatus for providing low-frequency compensation; and

FIG. 4 is a schematic diagram of a third embodiment of the invention showing an apparatus for providing compensation for frequency and intensity level.

Referring now to FIG. 1, it will be seen that the response of the human auditory system at varying loudness levels is not a linear function, but instead depends upon both level and frequency. In FIG. 1, three representative curves, derived from the Fletcher and Munson paper cited above, show that at a loudness level corresponding to 110 decibels (db) human auditory system response is relatively flat up to 1,000 cycles per second, and that deviation above that frequency is relatively small, on the order of ±10%. For practical purposes, the response can be considered flat throughout the hearing range of frequencies at this loudness level. It should be observed that this is a rather high level, approaching the level of feeling, as pointed out by Fletcher and Munson, referring to the data published by R. R. Riesz, in The Relationship Between Loudness and the Minimum Perceptible Increment of Intensity, published in the Journal of the Acoustical Society of America, vol. 4, page 211 (1933).

At lower levels, the response is quite different. At the curve which crosses 50 db at 1,000 cycles, curve **2** in FIG. 1, it will be seen that below 500 cycles the human hearing response degenerates with decrease in frequency at the rate of approximately 25 db per decade. As seen in curve **3**, at a still lower loudness level, the hearing response below 500 cycles degenerates at the rate of approximately 45 db per decade. From these curves, it is clear that a 100 cycle sound must be somewhat more intense than a 1,000 cycle sound to be heard as well as the 1,000 cycle sound at a low level. However, sounds at 100 and 1,000 cycles at the same high loudness level will be heard approximately equally well. For a more detailed discussion of this phenomenon, and of the testing methods used to obtain this data, reference is again made to the Fletcher and Munson paper.

FIG. 2 shows a first embodiment of the subject invention for compensating for signal-to-sound transducer characteristics. Here, a conventional broad-band amplifier indicated generally at **5** is provided with a signal input terminal **6**, a signal output terminal **7**, a common terminal **8** which is connected to a point of reference potential, and a feedback input terminal **9**. Input terminal **6** is connected to a terminal **10** which can be connected to a source of electrical signals to be amplified and reproduced by the system in the form of sound. Feedback terminal **9** is connected within the amplifier to provide negative or degenerative feedback to the amplifier. As will be recognized by one skilled in the art, the manner in which terminal **9** can be connected within the amplifier depends upon the particular type of amplifier employed, for example, a cathode resistor connection in a vacuum tube amplifier, or an emitter connection in an appropriate common emitter stage in a transistor amplifier. Terminal **9** is connected via conductor **11** to the frequency compensation portion of the circuit.

Output terminal **7** is connected to one terminal of the drive coil **12** of a conventional loudspeaker indicated schematically at **13**. Speaker **13** includes, in addition to coil **12**, a permanent magnet **14** which responds to current passed through coil **12** to drive a cone **15** which produces the compression waves referred to herein as sound. The other terminal of coil **12** is connected to conductor **11**, and also to a junction **16** at one end of a compensating network. The network includes a parallel circuit including a capacitor **17**, a resistance **18**, and an inductor **19**, the parallel circuit being connected in series circuit relationship with a coil **20**. The other terminal of coil **20** is connected to the reference potential point.



In operation, signals amplified by amplifier **5** are passed from terminal **7** to the coil of loudspeaker **13** and through the frequency compensating network. It will be seen that the current passing through coil **12** will also pass through the frequency compensating network, and that the series circuit of the drive coil and the compensating circuit form a voltage divider.

It should be pointed out at this stage that one possible function of the circuit described herein is to cause the loud-speaker cone to move at constant velocity over the frequency range of interest. It will be recognized that, if the compensation network shown in FIG. 2 were the precise electrical equivalent of the impedance of the speaker assembly, the ratio of the voltage across the coil to the voltage across the compensating network would remain constant with variations in frequency, and that there would be no improvement in speaker response. Assuming that the values of inductor **19** and capacitor **17** are selected to be equivalent to the fundamental resonance of the speaker cone, that resistor **18** represents the lumped mechanical resistance in the speaker, and that inductor **20** is equivalent to the leakage inductance of the speaker coil **12**, then the network shown is equivalent to the speaker impedance but without that resistance equivalent to the series resistance of coil **12**. Elimination from the compensating network of the equivalent of the coil series resistance and elimination of the inductor **20** (the equivalent of speaker coil leakage inductance) would force the speaker cone to move at approximately constant velocity because these elements, which tended to limit the current in the speaker, have been removed. With the degenerative effect of these elements removed, the current is only limited by that part of the network which is equivalent to the motional impedance. Such a speaker would then act like a theoretically perfect speaker, one having constant cone velocity regardless of frequency changes over a wide range.

However, the ultimate object is to obtain constant level of sound output from the speaker. As a practical matter, at frequencies toward the low end of the audio range where the diameter of the speaker cone is small relative to the wavelength of the sound being produced, a constant cone velocity will produce constant sound output. However, at higher frequencies, where the wavelength becomes small relative to cone diameter, a constant velocity would create rising sound output because of the relatively higher mechanical efficiency of the transducer at these frequencies. It is therefore necessary to leave inductor **20** in the circuit to restore the degenerative effect in the higher frequency range, thereby producing constant sound output.

Thus, the circuit of FIG. 2 shows a compensation circuit in series with the load, i.e., the speaker coil, with a feedback signal taken from the junction between these two circuit portions and delivered to the amplifier input degeneratively. This will be recognized as a current feedback system which, with appropriate circuit values selected in accordance with the particular speaker to be employed, will produce an output properly compensated for loudspeaker response at all audible frequencies.

The circuit of FIG. 3 is a simplified and less expensive embodiment of the system of FIG. 2, wherein broad band amplifier **5** is connected to one terminal of a drive coil **12** of a conventional loudspeaker **13**, as in the circuit of FIG. 2. The compensation circuit includes an inductor **25** connected in parallel circuit relationship with a resistor **26** between the other terminal of coil **12** and a point of reference potential. Coil **20** shown in FIG. 2 is omitted in the circuit of FIG. 3. This is possible since with an increase in frequency above the midrange, the reactances of coil **12** and inductor **25** become very large so that most of the current passes through resistor **27** and resistor **26**. Therefore, at high frequencies the ratio of the voltages approaches a constant, that being the ratio of resistor 27 and resistor 26. Resistor values of 27 and 26 are chosen to compensate for the effect of the increased sound output due to the higher mechanical efficiency of the speaker at high frequencies, as discussed above. Capacitor 17 shown in FIG. 2 may be omitted in the circuit of FIG. 3 since the effect of the high speaker impedance occurring at resonance is limited by resistor 27. Therefore, matching the resonant frequency of the speaker is not critical. A resistance 27 is connected in parallel with coil 12.

The value of inductor 25 is selected to have an inductive reactance which is low compared with the speaker impedance so that the voltage across the compensating circuit will rise with increasing frequency until the reactance of col 25 equals the resistance of resistor 26. This point is advantageously selected to be at a frequency of 500 cycles.

A more sophisticated circuit capable of completely compensating for the characteristics discussed with reference to FIG. 1, is shown in FIG. 4, wherein a broad band amplifier 5 is connected to one terminal of a speaker coil 12 of a conventional loudspeaker indicated generally at 13, the other terminal of coil 12 being connected to a junction point 30. As discussed with reference to FIG. 3, a parallel circuit including a resistor 26 and an inductor 25 is connected between junction point 30 and a point of reference potential, and a resistance 27 is connected in parallel circuit relationship with speaker coil 12, these elements being included to compensate for degeneration of speaker response with frequency.

In addition, the circuit of FIG. 4 includes the series circuit of a fixed resistance 31 and a photoresistive transducer 32 connected between the output terminal 7 and the feedback input signal terminal 9 of amplifier 5. A capacitor 33 is connected between the junction of elements 31 and 32, and a point of reference potential. A light source, shown as a conventional incandescent lamp 34, is connected in series circuit relationship with a resistance 35 between the output of amplifier 5 and a point of reference potential. A resistance 36 is connected between junction point 30 and the feedback signal input terminal 9 of amplifier 5.

The circuit elements 25, 26 and 27 operate in substantially the manner described with reference to FIG. 3, and need not be further described. Transducer 32 is a conventional photoresistive cell having a light sensitive portion and characterized by a resistance value which changes when the sensitive portion is exposed to radiant energy. Cell 32 is of the type which is characterized by a decrease in resistance with an increase of the intensity of the radiant energy impinging upon the photosensitive portion thereof. Transducer 32 and lamp 34 are advantageously located so that the sensitive portion of the transducer is exposed to the light emitted from the lamp and to no other light.

In operation, as the amplitude of the signals appearing at output terminal 7 of amplifier 5 increases, the current flowing through the series circuit including lamp 34 and resistance 35 increases. At low signal levels, the current flowing through the series circuit is insufficient to cause the lamp 34 to glow. The resistance of transducer 32 is very high, and the series circuit including the transducer has no effect on the amplifier gain. As the signal level increases, lamp 34 begins to glow and the radiation impinging on transducer 32 causes the resistance thereof to decrease and allows a current to flow through resistor 31, transducer 32 and resistor 36, the voltage across these three elements being equal to the voltage across the speaker coil 12. With current now flowing in resistor 36, the voltage feedback signal component provided to terminal 9 of amplifier 5 is increased by that amount of voltage developed across resistor 36, thus reducing the effect of the frequency compensating circuit at low frequencies. At very high levels, the effect of the circuit including transducer 32 becomes dominant, allowing the amplifier to maintain a substantially flat response. Capacitor 33 is connected in series with resistance 31 between amplifier terminal 7 and ground to avoid a gain change in the higher frequency ranges.

As will be recognized by one familiar with acoustical phenomena, the circuit values employed in the above embodiments can be adjusted to provide compensation slopes differing in some degree from pure compensation, and that such differences may be desirable to allow for the sound absorption characteristics of objects in the listening environment. The phenomenon of "room gain," caused by selective absorbtion of midrange and high frequencies by chairs, rugs, draperies and other soft objects, can be considered if desired to refine the compensation characteristics of the apparatus disclosed herein.

While certain advantageous embodiments have been chosen to illustrate the invention, it will be understood by those skilled in the art that various changes and modifications can be made therein without departing from the scope of the invention as defined in the appended claims.

What is claimed is:

1. Sound reproduction apparatus comprising, in combination

electrical signal amplifier means for normally amplifying by a substantially constant factor all electrical signals at frequencies within the range of normal human hearing, said amplifier means including
  an input terminal,
  an output terminal, and
  a feedback input terminal connected in said amplifier means to provide signals thereto degeneratively;

transducer means having drive coil means and signal-to-sound compression wave generating means for converting electrical signals supplied to said drive coil means into sound waves;

first circuit means interconnecting said drive coil means and said output terminal of said amplifier means;

signal generating circuit means connected in series circuit relationship with said drive coil means for developing an electrical signal which varies in magnitude in proportion to the frequency of the signal provided by said amplifier means to the series circuit including said drive coil means and said signal generating circuit means,
  said signal generating circuit means having an output terminal; and

second circuit means interconnecting said output terminal of said signal generating circuit means and said feedback signal input terminal of said amplifier means for providing said electrical signal to said amplifier.

2. Apparatus according to claim 1, wherein

said signal generating circuit means comprises
  a parallel circuit including a first inductance, a resistance, and a capacitance, and a second inductance in series circuit relationship with said parallel circuit.

3. Apparatus according to claim 1, wherein

said signal generating circuit means comprises a parallel circuit including a resistance and an inductance, and

the apparatus further comprises
  a resistance in parallel circuit relationship with said drive coil.

4. Sound reproduction apparatus comprising, in combination

electrical signal amplifier means having
  an input terminal,
  an output terminal, and
  a feedback input terminal connected to provide degenerative feedback to said amplifier means,
  said amplifier means being normally operative to amplify substantially equally all signals pro-

vided at the signal input terminal thereof within the frequency range of normal human hearing;

transducer means for converting electrical signals into corresponding sound waves and including signal-to-sound compression wave generating means and a drive coil for operating the same;

first circuit means interconnecting said drive coil and said output terminal of said amplifier means;

feedback circuit means comprising

a first primarily inductive impedance element,

a primarily capacitive impedance element connected in parallel circuit relationship with said first inductive element,

a resistance connected in parallel circuit relationship with said capacitive and first inductive elements, and

a second primarily inductive impedance element, said second primarily inductive impedance element, the parallel combination of said first primarily inductive impedance element, said primarily capacitive impedance element and said resistance, and said drive coil being connected in series circuit relationship across the output of said amplifier means; and

second circuit means interconnecting the junction of said drive coil and said feedback circuit means with said feedback signal input terminal of said amplifier means for providing electrical signals developed by said feedback circuit means degeneratively to said amplifier means.

**5.** Sound reproduction apparatus comprising the combination of

electrical signal amplifier means having

an input terminal,

an output terminal, and

a feedback input terminal connected to provide degenerative feedback to said amplifier means,

said amplifier means being normally operative to amplify substantially equally all signals provided at said input terminal within the frequency range of normal human hearing;

transducer means for converting electrical signals into corresponding sound waves and including a drive coil and signal-to-sound compression wave generating means;

first circuit means interconnecting said drive coil and said output terminal of said amplifier means;

first feedback signal component generating circuit means for producing a first feedback signal component which varies in magnitude with changes in frequency of signals provided at the output terminal of said amplifier means;

second feedback signal component generating circuit means for producing a second feedback signal component which increases in amplitude with changes in the amplitude of signals provided at the output terminal of said amplifier means, and which decreases in amplitude with increases in the frequency of signals provided at the output terminal of said amplifier means; and

second circuit means interconnecting said first feedback signal component generating circuit means, and second feedback signal component generating circuit means and said feedback input terminal of said amplifier means.

**6.** Apparatus in accordance with claim **5** wherein said transducer means comprises a permanent magnet loudspeaker having a voice coil and a vibratory cone.

**7.** Apparatus in accordance with claim **5** wherein said second feedback signal component generating circuit means comprises

radiant energy source means connected to said output terminal of said amplifier means for emitting radiant energy the intensity of which increases as the signal level at the output terminal of said amplifier means increases; and

second transducer means connected between said output terminal of said amplifier means and said second circuit means,

said second transducer means having a radiant energy sensitive portion and being characterized by a resistance value which varies with changes in the intensity of radiant energy impinging on said sensitive portion,

said second transducer means being located with said sensitive portion exposed to radiant energy from said source means.



**8.** Apparatus in accordance with claim **5** wherein said second feedback signal component generating circuit means comprises

a lamp having a filament which emits light when supplied with electric current;

a resistance connected in series circuit relationship with said lamp,

said series circuit being connected to said output terminal of said amplifier means;

a photoresistive transducer having a light-sensitive exposed portion and an internal resistance which decreases as the intensity of light impinging on said sensitive portion increases,

said photoresistive transducer being located to receive, at said sensitive portion, light emitted from said lamp; and

a third resistance connected in series circuit relationship with said photosensitive transducer between said output terminal of said amplifier means and said second circuit means.

**9.** Apparatus in accordance with claim **8** wherein said second feedback signal component generating circuit means further comprises

capacitor means connected between the junction of said third resistance and said photoresistive transducer and a point of reference potentials for rendering said second feedback signal component generating circuit means increasingly less effective as the frequency of the signal at said output terminal of said amplifier means increases.

**10.** Apparatus in accordance with claim **5** wherein said first feedback signal component generating circuit means comprises

a parallel circuit including a first resistance and an inductance, said parallel circuit being connected in series circuit relationship with said drive coil; and

a second resistance connected in parallel circuit relationship with said drive coil.

**11.** Apparatus in accordance with claim **10** wherein

the value of said inductance is chosen so that its reactance is equal in absolute magnitude to the value of said resistance at a frequency of approximately 500 cycles per second.

**12.** Apparatus in accordance with claim **10** wherein said second feedback signal component generating circuit means comprises

radiant energy source means connected to said output terminal of said amplifier means for emitting radiant energy the intensity of which increases as the signal level at the output terminal of said amplifier means increases; and

second transducer means connected between said output terminal of said amplifier means and said second circuit means,

said second transducer means having a radiant energy sensitive portion and being characterized by a resistance value which varies with changes in the intensity of radiant energy impinging on said sensitive portion,

said second transducer means being located with said sensitive portion exposed to radiant energy from said source means.

13. In combination with a sound reproduction apparatus including a broad-band amplifier and a signal-to-sound compression wave generating means driven by a drive means connected to receive the signal from the amplifier, a sound compensation circuit for operating the sound reproduction apparatus to compensate for the nonlinear characteristics of the signal-to-sound compression means and the drive means and for protecting the signal-to-sound compression means and the drive means from damage, comprising

- first feedback signal component generating circuit means degeneratively connected in series with the drive means of the signal-to-sound compression wave generating means and the broad-band amplifier,
  - said first feedback signal component generating circuit means being frequency sensitive such that the higher the operating frequency the greater the first feedback signal component and the lower the resulting signal from the amplifier, and
- second feedback signal component generating circuit means degeneratively connected in parallel with the drive means of the signal-to-sound compression wave generating means,
  - said second feedback signal component generating circuit means being amplitude sensitive such that the larger the signal from the amplifier the greater the second feedback signal component and the lower the resulting signal from the amplifier.

14. A sound compensation circuit in accordance with claim 13, wherein the broad-band amplifier has a feedback input terminal and the drive means includes a drive coil, and wherein said first feedback signal component generating circuit means comprises

- a parallel network including a resistor, a capacitor and a first inductor connected in series with said drive means, thereby forming a junction point, said junction point connected to said feedback input terminal of said broad-band amplifier; and
- a second inductor connected in series with said parallel network, said capacitor and first inductor combination substantially resonant at the fundamental frequency of the signal-to-sound compression wave generating means, the resistor substantially equal to the lumped mechanical resistance of the signal-to-sound compression wave generating means, and the second inductor substantially equal to the leakage inductance of the drive coil.

15. A sound compensation circuit in accordance with claim 13, wherein the broad-band amplifier has a feedback input terminal and the drive means includes a drive coil and wherein said first feedback signal component generating circuit means comprises



- a parallel network including a first resistor and an inductor connected in series to said drive means, thereby forming a junction point, said junction point connected to said feedback input terminal of said broad-band amplifier; and
- a second resistor connected from the output of the broad-band amplifier to said junction point,
  - the reactance of said inductor and said first resistor being equal at a frequency of approximately 500 cycles per second,
  - said second resistor passing increasing amounts of signal from the broad-band amplifier as the reactance of the drive coil increases with the frequency thereof to compensate for the nonlinear response of the signal-to-sound compression wave generating means and the drive means above approximately 500 cycles per second.

16. A sound compensation circuit in accordance with claim 13, wherein said broad-band amplifier has a feedback terminal and wherein said second feedback signal component generating circuit means comprises

- a photosensitive transducer connected from the output of the broad-band amplifier to said feedback terminal, the resistance of said photosensitive transducer decreasing with increasing illumination directed thereto,
- a light source directed to focus its illumination on said photosensitive transducer connected to the output of said broad-band amplifier so that increasing signals therefrom cause increasing illumination from said light source, and
- a capacitor bypassingly connected to said photoresistive transducer for effectively operationally removing said photosensitive transducer above approximately 500 cycles per second.

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