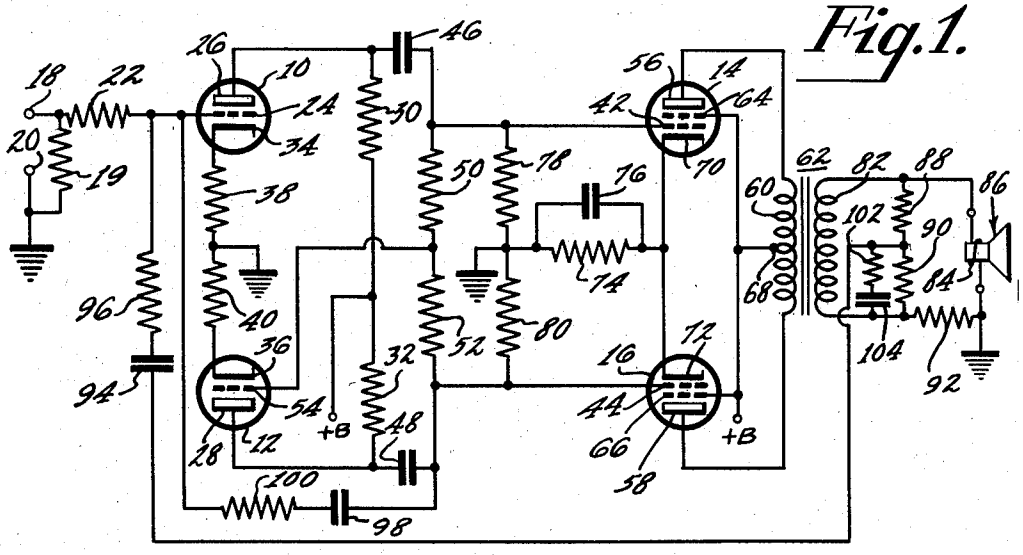
May 19, 1959 R. E. WERNER 2,887,532

AUDIO FREQUENCY AMPLIFIER

Filed Oct. 31, 1956

Fig. 1.



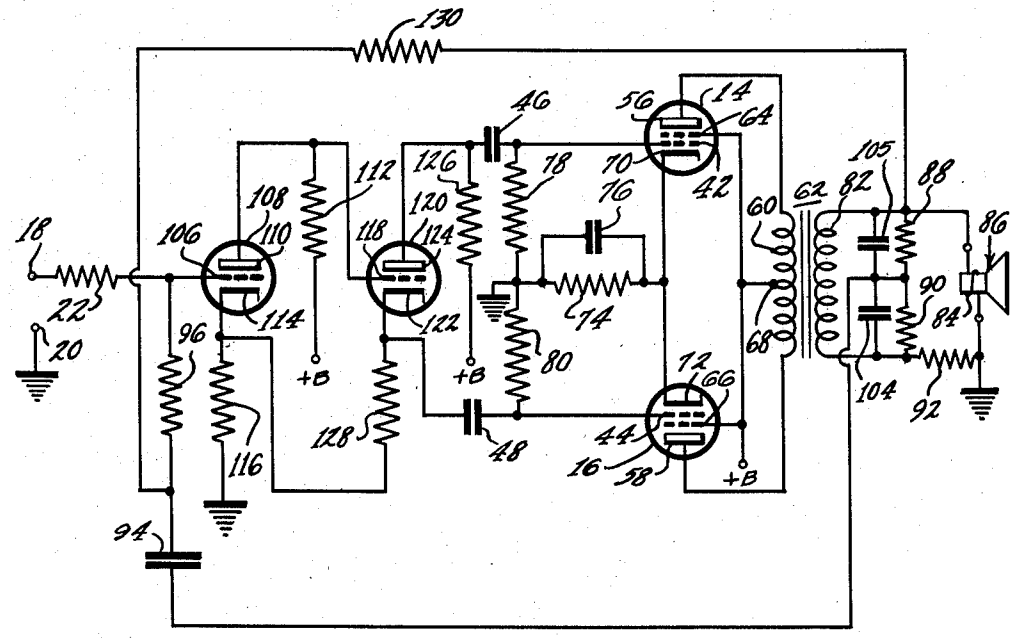


Fig. 2.

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AUDIO FREQUENCY AMPLIFIER

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8 Claims. (Cl. 179—1)

This invention relates to sound reproducing systems, and more particularly to audio frequency amplifiers having negative output impedance characteristics for driving moving coil loudspeakers.

Direct-radiator loudspeakers which are driven by an electrical signal applied to a moving voice coil of the loudspeaker have an effective electrical impedance that is determined by the electrical voice coil impedance and the equivalent electrical impedance of the mechanical impedance of the loudspeaker. The electrical impedance of the voice coil is generally called the blocked voice coil impedance, since it is measured with the voice coil blocked or prevented from moving within the magnetic field of the loudspeaker. The mechanical impedance, which is effectively in series with the blocked voice coil impedance, cannot be easily treated unless it is converted to an equivalent electrical impedance and when it is so converted it may be called the reflected mechanical impedance. In typical loudspeakers, the blocked voice coil impedance is large compared to the reflected mechanical impedance.

The acoustic output of a direct-radiator moving voice-coil loudspeaker is determined by the signal voltage that is applied across the reflected mechanical impedance, since the velocity of the voice coil is proportional to the voltage applied thereacross. The blocked voice coil impedance, however, is effectively in series with the reflected mechanical impedance. Therefore, a signal voltage from an amplifier that is applied to a loudspeaker appears across the blocked voice coil impedance and the reflected mechanical impedance in series. The fact that the blocked voice coil impedance is in series with the reflected mechanical impedance introduces several problems. The reflected mechanical impedance is effectively a tuned circuit and thus has a resonant frequency, often within the audio frequency band. This resonance introduces non-linearities in the acoustic output signal of the loudspeaker since the reflected mechanical impedance generally cannot be effectively damped because of the blocked voice coil impedance in series with it. Even with the input terminals to the voice coil shorted, the mechanical resonance is usually still troublesome.

Variation in the value of the reflected mechanical impedance with frequency also introduces certain non-linearities. At frequencies above the resonant frequency of the reflected mechanical impedance, the value of the reflected mechanical impedance is controlled largely by the mass of the moving system, whereas at frequencies below the resonant frequency it is controlled largely by the stiffness of the moving system. Since the stiffness is a non-linear function of the displacement of the cone of the loudspeaker, distortion will be introduced. The non-linearities and distortion caused by the resonances and non-linear operation of the loudspeaker system may be reduced to some extent by the proper choice of cabinets or enclosures in which the loudspeaker is mounted. Also, an especially heavy cone and voice coil for the loudspeaker will result in a low resonant frequency, but will require considerable electrical power to drive the system.

If, however, the blocked voice coil impedance could be cancelled or eliminated, the amplifier output voltage would then be applied directly across the reflected mechanical impedance rather than through the blocked voice coil impedance. The velocity of the voice coil driving the loudspeaker would then be the exact replica of the signal voltage applied to the loudspeaker. The system would be substantially free of resonances, since the reflected mechanical impedance could be effectively damped, and the system would be substantially devoid of distortion caused by non-linear compliance characteristics of the loudspeaker. The cancellation of the blocked voice impedance may be effected by making the output impedance of the amplifier driving the loudspeaker the negative of the blocked voice coil impedance of the loudspeaker.

It is therefore an object of this invention to provide an improved audio frequency amplifier for driving a moving coil loudspeaker system which substantially reduces the distortion introduced by non-linearity characteristics of the loudspeaker.

It is another object of the invention to provide an audio frequency amplifier circuit for driving a loudspeaker system having a negative output impedance to cancel or reduce the effects of the blocked voice-coil impedance of moving-coil loudspeakers.

It is another object of the present invention to provide an audio frequency amplifier having a negative reactance output impedance.

In accordance with the invention, an audio frequency signal amplifier is made to possess an output impedance that is, in effect, a negative resistance and a negative inductance in series to compensate for the positive resistance and positive inductance of the blocked voice coil impedance of a loudspeaker which is driven by the amplifier. Such output impedance is provided by a negative impedance feedback circuit which includes positive current feedback and negative voltage feedback from the output circuit to the input circuit of the signal amplifier through a bridge circuit and a common feedback path. When the bridge circuit is near balance, there will be a net negative feedback at audio frequencies, and a stable negative output impedance for the amplifier, including negative resistance and negative inductance, is provided. Positive feedback may be applied over a portion of the amplifier channel to provide increased amplifier gain to more effectively cancel the loudspeaker impedance and to reduce distortion in the amplifier by increasing the net negative feedback of the negative impedance feedback circuit.

However, the invention will be further understood when the following description is read in connection with the accompanying drawing, in which:

Figures 1 and 2 are schematic circuit diagrams of audio amplifier circuits constructed in accordance with the invention for driving moving-coil loudspeakers.

Referring now to the drawing and in particular to Figure 1, an audio frequency amplifier includes, basically, a self-balancing phase inverter utilizing first and second triode amplifier tubes **10** and **12** to supply push-pull signals to drive a pair of push-pull connected output tubes **14** and **16**, which, in turn, supply driving power to a loudspeaker **86**. Audio frequency signals to be amplified and reproduced are applied to a pair of signal input terminals **18** and **20** and appear across a grid return resistor **19**. One terminal **20** is connected to ground or a point of reference potential for the amplifier, and the other terminal **18** is connected through a series input resistor **22** to the control grid **24** of the first amplifier tube **10**. The anodes **26** and **28** of the first and second tubes **10** and **12**

are connected to a source of operating potential, +B, each through a separate load resistor 30 and 32, respectively, and the D.-C. circuit is completed by connecting the respective cathodes 34 and 36 through individual cathode bias resistors 38 and 40 to ground for the system.

The anodes 26 and 28 of the phase inverter tubes 10 and 12 are connected to the control grids 42 and 44 of the output tubes 14 and 16 through coupling capacitors 46 and 48. In order to supply an inversion signal to the second tube 12, a pair of resistors 50 and 52 of properly related values, are connected in series between the control grids 42 and 44 of the output tubes 14 and 16, and the junction of the resistors is connected to the control grid 54 of the second tube 12. The anodes 56 and 58 of the output tubes 14 and 16 are connected to the center-tapped primary winding 60 of a push-pull output transformer 62, and operating potential is supplied to the output tubes 14 and 16 by connecting the screen electrodes 64 and 66 thereof and the center tap 68 on the primary 60 to the source of operating potential, +B. To complete the D.-C. circuit for the output tubes 14 and 16 the cathodes 70 and 72 are connected through a common bias resistor 74 to ground for the system. The bias resistor 74 is by-passed by a capacitor 76 and the control grids 42 and 44 of the output tubes 14 and 16 are connected to ground through grid resistors 78 and 80, respectively.

Thus, audio frequency input signals applied to the input terminals 18 and 20 are amplified and inverted in the phase inverter tubes 10 and 12 and applied as push-pull signals to the control grids 42 and 44 of the output tubes 14 and 16. Output signals developed by the output tubes 14 and 16 are applied through the transformer secondary 82 and a resistance-capacitance network, which will be more fully described and explained hereinafter, to the moving voice coil 84 of the loudspeaker 86. The operation of such an audio frequency push-pull power amplifier as so far described is well known and further description of its operation and characteristics are not necessary other than to state that by careful design the distortion characteristics of the amplifier may be reduced to a reasonably low value.

As previously noted, the equivalent impedance presented to an amplifier by a direct radiator moving-coil loudspeaker, such as the loudspeaker 86 in Figure 1, is rather complicated and includes components of reflected mechanical impedance and the blocked electrical impedance of the voice coil. Even if the effective output impedance of the amplifier were zero, the reflected mechanical impedance of the loudspeaker, which is in effect a tuned circuit having undesired resonances, generally could not be completely damped because of the blocked electrical impedance of the voice coil 84 in series with the reflected mechanical impedance. This, of course, gives rise to distortion and various undesired transient responses. If the amplifier can be made to possess an output impedance that is the negative of the blocked voice coil impedance, the voltage across the reflected mechanical impedance of the loudspeaker can be made to be the exact replica of the signal voltage applied to the amplifier.

In accordance with the invention, a feedback circuit to provide the negative output impedance is connected between the secondary 82 of the output transformer 62 and the control grid 24 of the first amplifier tube 10. The negative impedance feedback circuit is connected to provide both positive current feedback and negative voltage feedback over the amplifier. This is accomplished by connecting first and second bridge resistors 90 and 88 in series across the secondary 82 and a third bridge resistor 92 between the secondary 82 and the voice coil 84 of the loudspeaker 80 at the system ground side thereof as shown. A resistor 102 and a capacitor 104, the function of which will be more fully explained hereinafter, are connected in series across the first bridge resistor 90. The side of the voice coil 84 connected to the third bridge resistor 92 is grounded as above noted and the junction of the pair of bridge resistors 88 and 90 is connected to the control grid 24 of the first tube 10 through a bass compensation network comprising a capacitor 94 in series with a resistor 96, the action of which will be more fully explained hereinafter.

As can be seen from an inspection of the output circuit shown in Figure 1, the resistance-capacitance network and the voice coil of the loudspeaker 86 form a bridge circuit, the first arm of which is the bridge resistor 88, the second arm is the bridge resistor 90 together with the resistor 102 and the series capacitor 104 connected thereacross, the third arm is a third bridge resistor 92, and the fourth arm is the voice coil 84 of the loudspeaker 86. The output signal of the amplifier is applied to one diagonal of the bridge circuit by connecting the secondary winding 82 of the transformer 62 to two opposite corners of the bridge circuit, that is, the junction of the bridge resistor 88 and the voice coil 84 and the junction of the bridge resistors 90 and 92. The negative impedance feedback circuit is connected across the other diagonal of the bridge by connecting the junction of the bridge resistors 88 and 90 to the control grid 24 of the first tube 10, and by connecting the junction of the third bridge resistor 92 and the voice coil 84 to ground for the system.

The output impedance characteristic of the amplifier may be best understood by the use of mathematical equations. Let Z_1 equal the impedance in the first bridge resistor 88; Z_2 the impedance of the second bridge resistor 90; Z_3 the overall impedance of the third bridge resistor 92 and the resistor 102 and series capacitor 104 connected thereacross; Z_{vc} the blocked impedance of the voice coil 84 of the loudspeaker 86; $-A$ the open circuit voltage gain of the basic amplifier; the minus sign indicating a phase reversal, Z_0 the output impedance of the basic amplifier; A' the open circuit voltage gain with the negative impedance feedback circuit connected; and Z'_0 the output impedance with the negative impedance feedback circuit connected. If $Z_1+Z_2>>Z_0$, and the resistance value of the input resistor is sufficiently high to not effectively load the negative impedance feedback circuit, which will normally be the case, it then can be shown mathematically that

$$A'=-\frac{A}{1+\frac{Z_2A}{Z_1+Z_2}} \tag{1}$$

The output impedance, then with the negative impedance feedback circuit connected can be shown to be

$$Z'_0=\frac{Z_0+Z^3-\frac{Z_1Z_3A}{Z_1+Z_2}}{1+\frac{Z_2A}{Z_1+Z_2}} \tag{2}$$

If the bridge circuit then is balanced against the blocked voice coil impedance (Z_{vc}) and A is very high

$$\frac{Z_1}{Z_2}=\frac{Z_{vc}}{Z_3} \tag{3}$$

Utilizing equations (2) and (3), it can then be shown that

$$Z'_0\approx -Z_{vc} \tag{4}$$

Thus, if the bridge circuit is balanced against the voice coil impedance and the voltage gain of the basic amplifier is very high, the output impedance of the amplifier is the complement or the negative of the voice coil impedance. The feedback voltage at the junction of the bridge resistors 88 and 90 is a summation of a negative feedback voltage developed from the voltage on the ungrounded side of the voice coil 84 and a positive current controlled feedback voltage determined by the current flowing through the third bridge resistor 92. There will be no net feedback since the bridge circuit is balanced. However, it will be noted, that the reflected mechanical impedance of the loudspeaker was not considered in these equations. The reflected mechanical impedance when the voice coil is

allowed to move will unbalance the bridge and provide a net negative feedback without altering the output impedance of the amplifier. This may be noted from Equation 2 where Z'_0, the output impedance of the amplifier with the negative impedance feedback circuit connected, is seen to be in no way dependent upon the impedance in the fourth arm of the bridge circuit in which the voice coil is connected.

The inductive component of the blocked voice coil impedance of the loudspeaker **86** is not an ideal inductance, and may be termed an impure inductance in that it has resistive components caused by hysteresis and eddy-current losses associated with the magnetic structure of the loudspeaker **86**. Accurate and complete cancellation of such an impure inductance is quite complicated and generally not economically feasible, since the inductance varies slightly. If a large percentage of the resistance of the blocked voice coil impedance in cancelled, the Q of the inductance of the blocked voice coil impedance is raised, which may result in resonance problems with the mass of the moving system in the middle range of audio frequencies unless some reduction of the voice coil inductance also is provided. Since it is not a simple matter to exactly cancel the blocked voice-coil inductance it is more practical not to attempt to cancel the blocked voice coil impedance completely. Excellent results may be obtained if a substantial portion of the blocked voice coil impedance is cancelled, preferably on the order of sixty to eighty percent, depending on the particular loudspeaker being used.

The feedback circuit of Figure 1 includes a resistor **102** and capacitor **104** connected in series across the second bridge resistor **90**. The capacitor **104** provides that the feedback will make the amplifier output impedance appear to be a negative inductance, and the resistor **104** makes the negative inductance appear impure in approximately the same ratio that the inductance of the blocked voice coil impedance of the loudspeaker **86** is impure. Since the inductance of the blocked voice coil impedance is not cancelled to the same extent as its resistance, the blocked voice coil impedance will not be as effectively cancelled at high audio frequencies as at lower audio frequencies which will result in reduced high frequency response. The capacitor **104** serves the additional function of increasing the amplifier response at high audio frequency signals to approximately compensate for this reduction in high frequency response by decreasing the net negative feedback at these high frequency signals.

At the low frequencies there is a decrease in the radiation efficiency of the loudspeaker, and the input resistor **22** to the amplifier together with the resistor **96** and the capacitor **94** in the negative impedance feedback circuit provide a bass boost circuit to compensate for this decrease in radiation efficiency. The circuit has a time constant to provide a frequency varying loading of the input circuit to the tube **10** by increasing the input at low frequencies as the impedance of the capacitor **94** rises. The values are also chosen so that there is negligible effect on the efficiency of the feedback circuit providing the negative output impedance for the lowest frequency of interest.

Below the resonant frequency of the loudspeaker the reflected mechanical impedance is essentially controlled by the stiffness of the moving system and if the blocked voice coil impedance is not completely cancelled the stiffness will reduce the low frequency response of the loudspeaker at signal frequencies below which the reflected mechanical impedance becomes small compared to the remaining blocked voice coil impedance. If uniform response is desired below that frequency an additional bass boost circuit may be added.

It will be noted that, unlike conventional high quality audio frequency amplifiers, the basic amplifier need not utilize overall negative feedback to reduce the distortion of the amplifier. Negative feedback in the amplifier shown in Figure 1 is provided only through the feedback circuit providing the negative output impedance. In order to more effectively reduce the distortion in the amplifier proper, positive feedback may be applied around the phase inverter through a capacitor **98** and a resistor **100** in series. This results in a high gain amplifier of relatively a few stages around which the feedback circuit providing the negative output impedance is connected. As will be seen from the equations hereinbefore mentioned, the high gain of the amplifier results in more effective cancellation of the loudspeaker blocked voice coil impedance, which gives rise to improved frequency and transient response. The distortion of the amplifier itself is also reduced, since the gain of the amplifier is sufficiently high that the net negative feedback of the negative impedance feedback circuit is increased to a large value. The net negative feedback need not be sufficient to cancel the positive feedback around the phase inverter stage since the distortion of the phase inverter stage can be made negligibly small by suitable design.

The amount of positive feedback around the phase inverter stage will be determined principally by the values of the resistors **96** and **100** and the capacitors **94** and **98** in the negative impedance feedback circuit and the positive feedback circuit, since the value of the input resistor **22** is very large compared to the reactance of the capacitor **94** and the resistor **96** in the negative impedance feedback circuit. Since, the impedance of the bass boost circuit in the negative impedance feedback circuit, resistor **96** and capacitor **94**, is a function of frequency, the value of the resistor **100** and the capacitor **98** in the positive feedback circuit are made to have an impedance that is a similar function of frequency so that the positive feedback is essentially uniform at all frequencies.

Referring now to Figure 2, an audio frequency amplifier embodying the invention includes many of the same components and configurations as previously described with respect to the circuit of Figure 1. However, instead of using a self-balancing phase inverter, as shown in Figure 1, a voltage amplifier and phase splitter circuit are shown. The input signal applied to the terminal **18** is applied through the input resistor **22** to the control grid **106** of a voltage amplifier tube **108**. Operating voltage is supplied to the anode by connecting it through a load resistor **112** to the source of positive operating voltage indicated at +B, and the cathode **114** is connected to ground for the system and −B through a cathode resistor **116**.

The amplified signal appearing at the anode **110** of the voltage amplifier **108** is applied directly to the control grid **118** of a phase splitter tube **120**. In order to provide substantially balanced output signals from the cathode **122** and the anode **124**, an anode load or output resistor **126** is connected between the anode **124** and the source of positive operating potential, +B, and a cathode load or output resistor **128** is connected in the cathode circuit. It will be noted that at the cathode load resistor **128** is connected back to the cathode **114** of the voltage amplifier tube **108** and thence to ground through the cathode resistor **116**. This connection supplies positive feedback from the phase splitter to the voltage amplifier across the cathode resistor **116** to provide an increase in overall gain for the amplifier for the reasons mentioned in the previous description of Figure 1.

The signals appearing at the anode and cathode **124** and **122** of the phase splitter tube **120** are applied through the coupling capacitors **46** and **48** to the control grids **42** and **44** of the output tubes. The remainder of the amplifier circuit including the negative impedance feedback circuit connections are similar to those previously described with reference to Figure 1.

Negative voltage feedback and positive current feedback is supplied through the negative impedance feedback circuit in the same manner as previously described with reference to Figure 1. The negative output imped-

ance for the amplifier thus provided by the positive and negative feedback appears inductive because of the first capacitor **104** connected across the first bridge resistor **90**. A second capacitor **105** connected across the second bridge resistor **88** provides that the negative inductance is impure in the same sense as the positive inductance of the blocked voice coil impedance of the loudspeaker **86** is impure. This second capacitor **105** performs the same function as the resistor **102** in series with the first capacitor **104** as shown in Figure 1. The resistor and capacitor **96** and **94** in the negative impedance feedback circuit provides bass compensation in the same manner as hereinbefore described, and the positive feedback provides the desirable high gain for the amplifier.

In some instances it may be desirable or necessary to change the character of the output impedance of the amplifier at extreme low frequency signals. For instance, if an inexpensive amplifier is used, low frequency transients may cause the amplifier to tend to drive the loudspeaker at a subsonic or a near subsonic signal and it is necessary to reduce the power applied to the loudspeaker at these extreme low frequency signals because the available power from an inexpensive amplifier is relatively low. This action may be accomplished by connecting a third feedback circuit including a resistor **130** between the ungrounded side of the voice coil **84** and the junction between the bass compensation resistor **96** and capacitor **94** in the negative impedance feedback circuit. At frequencies of interest, that is, those desired to be reproduced, the resistance of the resistor **130** is made sufficiently high as to have no effect on the balance of the bridge circuit for the negative impedance feedback circuit. However, at the extreme low frequencies which may cause the conditions mentioned above, a high degree of unbalance will result which produces relatively high negative feedback. The large amount of negative feedback changes the output impedance of the amplifier in a positive direction at very low frequencies and also reduces the amplifier gain at these subsonic or near subsonic signal frequencies. It should be noted that the use of the resistor **130** between the voice coil **84** and the input circuit may also be used, with exactly the same connections, in the amplifier circuit shown in Figure 1, with the same results.

An audio frequency amplifier constructed in accordance with the present invention to drive a direct-radiator, moving-coil loudspeaker is characterized by its virtually resonance and distortion free reproduction of audio frequency signals with extended low frequency response. Thus, it is adapted for wide application in sound reproducing fields requiring an accurate transducer of electrical signals representing sounds.

What is claimed is:

1. In a sound reproducing system for driving a direct radiator loudspeaker having a moving voice coil, the combination of an audio frequency signal amplifier having a signal input circuit, a signal output circuit for said amplifier including a transformer having a secondary winding, a first and a second resistor connected in series across said secondary winding, a third resistor, means connecting the voice coil of the loudspeaker and said third resistor in series across said secondary winding, means connecting the junction of said voice coil and said third resistor to a point of reference potential for said amplifier, circuit means connecting the junction of said first and second resistors to said input circuit for applying positive and negative feedback over said amplifier and providing a negative output impedance therefor, and means including a fourth resistor and a first feedback control capacitor connected across said first resistor to make said negative output impedance substantially the complement of the electrical impedance of said voice coil.

2. In a sound reproducing system, the combination in accordance with claim 1, wherein positive feedback is applied over at least a portion of said amplifier to increase the overall gain thereof to a relatively high value.

3. In a sound reproducing system for driving a direct radiator loudspeaker having a moving voice coil, the combination of an audio frequency signal amplifier having a signal input circuit, a signal output circuit for said amplifier including a transformer having a secondary winding, positive feedback means connected over at least a portion of said amplifier to increase the gain thereof to a relatively high value, a first and a second resistor connected in series across said secondary winding, a third resistor, circuit means connecting the voice coil of the loudspeaker and said third resistor in series across said secondary winding, said third resistor being connected between the voice coil and the junction of the first resistor and secondary winding, circuit means connecting the junction of said voice coil and said third resistor to a point of reference potential for said amplifier, feedback means connected between the junction of said first and second resistors and the input circuit of said amplifier providing a negative output impedance for said amplifier, means including a fourth resistor and a first capacitor in series across said first resistor to make said negative output impendance substantially the complement of the electrical impedance of said voice coil, and means including a fifth resistor and a second capacitor serially connected in said feedback means to reduce the loading of said signal input circuit at bass frequency signals and provide bass frequency boost.

4. In a sound reproducing system for driving a direct radiator loudspeaker having a moving voice coil, the combination of an audio frequency signal amplifier having a signal input circuit, a signal output circuit for said amplifier including a transformer having a secondary winding, a first and a second feedback control resistor connected in series across said secondary winding, a third feedback control resistor, circuit means connecting said voice coil and said third resistor in series across said secondary winding, said third resistor being connected between the voice coil and the junction of the first resistor and secondary winding, means connecting the junction of said voice coil and said third resistor to a point of reference potential for said amplifier, feedback circuit means connecting the junction of said first and second resistors to said input circuit for applying positive and negative feedback over said amplifier providing a negative output impedance therefor, and means including a high frequency feedback control capacitor connected across said first resistor to make said negative output impedance substantially the complement of the electrical impedance of said voice coil.

5. In a sound reproducing system, the combination in accordance with claim 4, wherein positive feedback is applied over at least a portion of said amplifier to increase the overall gain thereof to a relatively high value.

6. In a sound reproducing system, the combination in accordance with claim 4, wherein a fourth resistor and a third capacitor are connected in series in said feedback circuit means to reduce the loading of said signal input circuit at low audio frequency signals and provide bass frequency boost.

7. In a sound reproducing system for driving a direct radiator loudspeaker having a moving voice coil, the combination of an audio frequency signal amplifier having a signal input circuit, a signal output circuit for said amplifier including a transformer having a secondary winding, positive feedback means connected over at least a portion of said amplifier to increase the gain thereof to a relatively high value, a first and a second resistor connected in series across said secondary winding, a third resistor, circuit means connecting the voice coil of the loudspeaker and said third resistor in series across said secondary winding, said third resistor being connected between the voice coil and the junction of the first resistor and secondary winding, circuit means connecting the junction of said

voice coil and said third resistor to a point of reference potential for said amplifier, feedback circuit means connected between the junction of said first and second resistors and the input circuit of said amplifier providing a negative output impedance for said amplifier, means including a first capacitor connected in circuit across said first resistor and a second capacitor connected across said second resistor to control the frequency response of the amplifier and make said negative output impedance substantially the complement of the electrical impedance of the voice coil, and means including a fourth resistor and a third capacitor serially connected in said feedback means to reduce the loading of said signal input circuit at bass frequency signals providing bass frequency boost.

8. In a sound reproducing system, the combination in accordance with claim 7, wherein a fifth resistor is connected from said output circuit to the junction of said fourth resistor and said third capacitor to alter the character of said feedback means and provide a more positive output impedance for said amplifier at extreme low frequency signals.

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