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W. W. CLEMENTS
SOUND REPRODUCING MEANS

2,948,778

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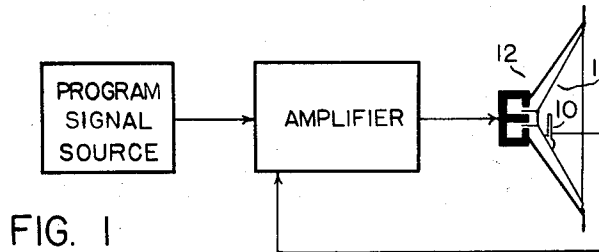


FIG. 1

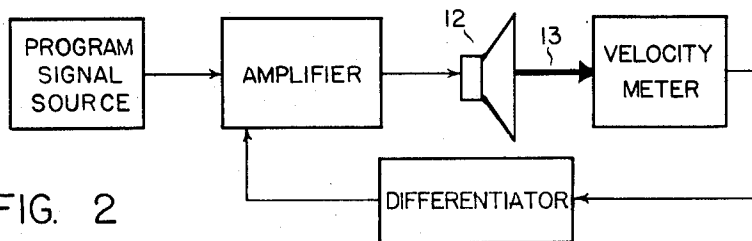


FIG. 2

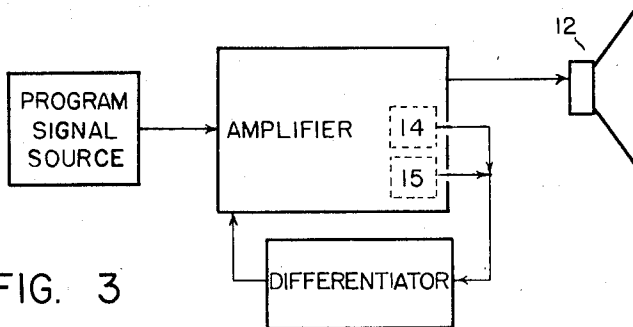


FIG. 3

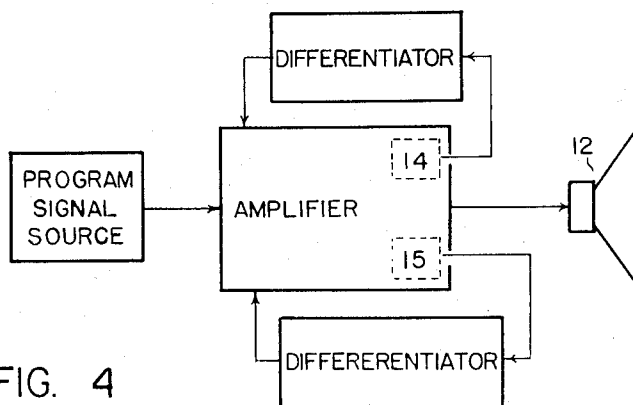


FIG. 4

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My invention relates to systems for sound reproduction which incorporate moving-coil type loudspeakers.

It is possible for a loudspeaker, by itself, to impose serious limitations upon the quality of sound obtainable from an otherwise excellent reproduction system. Associated with one such limitation is the resonance which can be defined in the low frequency range of nearly any moving-coil type loudspeaker. This is the principal resonance affecting the operation of such loudspeakers and its frequency is called simply "the resonant frequency." The term is used loosely to apply to either mounted or unmounted units. It is, of course, when a speaker is mounted or enclosed that its reproduction characteristics become important and it is this latter condition that I imply hereinafter. I will also speak in particular of "direct-radiator" systems, which type is in most general use at this time. My remarks apply with lesser force to "horn-loaded" systems. However many of these become virtual direct-radiator systems at low frequencies.

In actual practice the following effects can be noted in connection with the principal resonance: In the frequency region extending for some distance above the resonant frequency the sound output is relatively unaffected by loudspeaker characteristics. At and near the resonant frequency the sound output tends to be accentuated. Below the resonant frequency the sound output is rapidly attenuated with falling frequency. At any more than one octave below the resonant frequency the output is usually so reduced by comparison with that at other frequencies as to be virtually useless. If speaker and enclosure be designed to effect a higher resonant frequency, these effects accordingly take place at higher frequencies and the band of transmitted frequencies is thereby narrowed. Conversely, if a lower resonant frequency can be achieved, then lower sound frequencies are reproduced. The reproduction of the lowest notes is held to be a desirable objective in high quality sound systems. Also the lower the frequency of the peak in response the less objectionable it becomes from a standpoint of sound quality and the easier it becomes to deal with it by restricting amplifier input at the lowest frequencies. Unfortunately, in the present state of the art, resonant frequencies found in practice are much higher than these considerations would dictate.

The resonance in question is a mechanical phenomenon. Like other simple mechanical resonances it is associated with a weight and a springiness or, more correctly, a mass and a compliance. Both qualities are involved with the operation of the loudspeaker diaphragm, which must vibrate in order to induce sound waves in the air with which it is in contact. The diaphragm is built to be very light, but it still has appreciable mass. Moreover the diaphragm is only a part of the moving system. There is also a "voice-coil" which is necessary to drive the diaphragm and which is built integrally with it in conventional equipment. In addition some mass effect is contributed by certain auxiliary structure and by the air that moves back-and-forth with the diaphragm.

As the diaphragm moves in either direction from its neutral position it encounters a restoring force which would tend to return it to neutral. This restoring force

is partly contributed by the diaphragm suspension system, which is designed to make the vibratory action center about a neutral position. If the loudspeaker is mounted in a cabinet that is totally enclosed, or nearly so, the enclosure, too, contributes a restoring force, due to the compression or rarefaction of the air within it as the diaphragm moves. The total restoring force is substantially proportional to the extent of excursion from neutral position. The ratio of restoring force to excursion is the measure of the stiffness, which is defined as the reciprocal of the compliance.

The resonant frequency can be defined as that frequency at which the mechanical reactance due to total effective moving mass is numerically equal to the mechanical reactance due to total effective stiffness. Qualitatively speaking, the respective parameters have the same effect on frequency as in the case of a weight bouncing on the end of a rubber band. Increasing the stiffness of the rubber band will cause the frequency of bounce to increase and vice versa. Increasing the mass of the weight will cause said frequency to decrease and vice versa.

It can be seen that in order to re-design a loudspeaker for a lower resonant frequency, it is necessary either to decrease the stiffness or to increase the moving mass. But there are considerations that oppose the employment of either measure. To decrease the suspension stiffness of the loudspeaker proper and yet maintain strength and stability in the suspension is a mechanically difficult proposition. As for stiffness due to the enclosure, it is the enclosure types otherwise most suited for low-frequency reproduction that manifest such stiffness. The smaller (and hence the more convenient and economical) an enclosure of one of these types, the more stiffness it contributes. An average-size enclosure would supply enough stiffness to hold the resonant frequency of a typical matching loudspeaker well up in the audio band, even if suspension stiffness in the loudspeaker proper could be completely abolished. To permit resonant frequencies to be brought down considerably, say to the region from 15 to 25 cycles (per second), by the method of reducing stiffness, would require enclosures to be impractically large and expensive.

On the other hand, to increase the moving mass is to cut loudspeaker efficiency sharply. Loudspeakers that achieve improved low-frequency reproduction by means of added mass in the moving system require the expenditure of greatly increased amounts of amplifier output power at all frequencies as payment for said improvement which occurs only at the lowest frequencies. By way of example, to decrease the resonant frequency one octave by this method would require that total mass be increased by a factor of four. This would result, according to efficiency formulas given by Olson and by Beranek, in loudspeaker efficiency being decreased approximately sixteen times. Such a loss in efficiency is reflected in increased voice-coil heating, which can become a problem in its own right. Besides these drawbacks the method of mass loading has the additional disadvantage of placing extra gravitational strain on the suspension system and tending to make mounting position critical.

On the credit side it can be pointed out that additional mass loading produces a definite decrease in the amplitude distortion in the sound output due to any non-linearity in the suspension system. This decrease in distortion is brought about by the increased influence of the mass in controlling the motion of the moving system. In other words, the increased effect of the mass "snows under" the effect of the stiffness and hence minimizes the effect of any variation in the latter with excursion. (This generalization fails to hold, however, at the very lowest frequencies where the mass loses its

dominance and where the increased excursion associated with an improved output may stretch the mechanical suspension system into regions of greater non-linearity.)

An object of my invention is to provide improved low-frequency response characteristics in sound reproducing systems utilizing moving-coil type loudspeakers.

Another object of my invention is to permit the use of smaller loudspeaker enclosures in such systems, while still maintaining a given quality of low-frequency performance.

Another object of my invention is to provide reduced amplitude distortion in the sound output of such systems.

Mass in the moving system makes its influence on loudspeaker performance felt by means of the forces it exerts in the process of being accelerated and decelerated. The strategy of my invention is to introduce extra forces which act on the moving system. These forces are so timed and apportioned as to simulate the forces that would be exerted by extra mass attached to the voice-coil. Said extra forces are developed in the voice-coil by means of extra currents that are induced to flow therein. The overall effect can be described as the apparent synthesis of mass by electrical means. The moving system is induced to act substantially as if it had greater mass than it actually has. Meanwhile the synthetic mass, or more correctly the pseudo mass, has no weight, so gravitational effects are avoided.

In applying my invention, the extra currents that are caused to flow in the voice-coil in order to produce forces simulating inertial forces share the same voice-coil winding with currents representing the program material to be reproduced. The two current components thus defined can be respectively supplied by two amplifiers but I find it somewhat preferable to use only one amplifier to supply both. An amplifier may be adapted for such service by comparatively minor changes in circuitry. Two types of electrically-embodied intelligence can be defined as being amplified simultaneously in an amplifier so used. One of these, embodied as a program signal, controls the current component in the output representing the program material to be reproduced. It may be derived from any conventional source for such a signal such as radio or phonograph apparatus, wire transmission means, etc. (Such sources are well known to those skilled in the art. The presence of one or more of them is necessary to the operation of my invention but is not directly concerned with the structure or principle thereof.) The other type of intelligence referred to is embodied as one or more auxiliary signals and controls the current component in the output that achieves the apparent synthesis of mass already described. The auxiliary signal or signals may be developed from the actual motion of the moving system through various simple and inexpensive means.

To produce a given value of acoustic power output at a given frequency from a given loudspeaker installation requires that a given net value of A.C. current be maintained in the voice-coil. This in turn necessitates that a given amount of waste power be dissipated in the voice-coil. These considerations are not affected by the manner in which voice-coil current, via its components, is determined. Also the demands for power output at frequencies where response is already satisfactory will presumably not be affected by measures taken to change the resonant frequency. In other words the method of my invention cannot cost extra power except in the small portion of the band of reproduced frequencies where power output is actually increased thereby. By contrast, the equivalent mechanical method costs extra power at every frequency above that of its lowered resonance. Moreover the penalty is a considerable one, as indicated above by sample figures on efficiency.

An effect achieved by my invention not accountable for by analogy with true mass loading is the reduction

that occurs in the amplitude distortion originating in the amplifier. This effect is predicted by a more complex analysis, however, and it is confirmed in practice. The more the pseudo-mass that is developed, the greater the reduction in distortion that occurs.

To sum up; applying actual extra mass loading to the moving system of a conventional loudspeaker would achieve the advantages of extending the sound output response to lower bass regions with a given enclosure and reducing amplitude distortion at all but the lowest frequencies. By means of my invention these advantages may be gained at a fraction of the cost in power for and without the gravitational consequences of said mass loading. As a bonus, distortion originating in the amplifier is reduced. These effects are achieved with a relatively small increase in the complexity and cost of the system.

Other objects and advantages will be made apparent to one skilled in the art by the following description and claims, taken in conjunction with the accompanying drawings in which:

Figs. 1, 2, 3, and 4 are block-type diagrammatic representations of four illustrative embodiments of my invention, one general type of embodiment being represented in each figure. The arrowed fine lines in these figures represent electrical connections, with arrowheads pointing in the direction of the flow of influence. The arrowed heavy line in Fig. 2 represents a mechanical connection.

The amount of force, f_x , required to simulate the presence of a given mass, M_x , in a moving system is given by,

$$f_x = M_x a \quad (A)$$

where a is the acceleration of the system. In my invention the specified force is developed by means of an extra current, i_x , that is caused to flow in the voice-coil. From loudspeaker theory,

$$f_x = BL i_x \quad (B)$$

where B and L are loudspeaker design constants. Combining Eqs. A and B:

$$i_x = \frac{M_x}{BL} a \quad (C)$$

Eq. C defines quantitatively the departure from conventional design for sound reproduction systems that is involved in my invention. The acceleration of the moving system is made to govern an auxiliary current substantially proportional to it that is caused to flow in the voice-coil. This task must be accomplished without imposing appreciable mechanical load on the moving system, for one of the purposes of the invention is to avoid such loading. But it takes power to force the specified current through the voice-coil. Therefore amplification is required. Also measurements in two different systems, mechanical and electrical, must be dealt with. Therefore transduction is required to translate mechanical intelligence into electrical. In preferred embodiments of my invention equipment normally present in sound reproduction apparatus is enlisted to help out with one or both of these processes, amplification and transduction, while simultaneously continuing to fulfill its normal role.

For instance any sound reproducing apparatus employing a loudspeaker must include or be served by an amplifier. In preferred embodiments of my invention this same amplifier is employed to develop the said auxiliary current. For the purpose one or more auxiliary signals are supplied to amplifier inputs, collectively depicting the acceleration of the moving system. The amplifier, then, must be responsive to both the program signal and the auxiliary intelligence in order to produce current components representing each in the output. The net output current will be the vector sum of the components just mentioned. (This is true whether summation is

regarded as taking place between output currents or between signals in pre-output circuitry.) However, in accordance with the principle of superposition, the effect of the net output current will be the sum of the effects of its components.

The auxiliary intelligence may not require as much amplification as the program signal. Hence the representation for the amplifier used in Figs. 1, 2, 3 and 4 is intended to convey the sense that the auxiliary signal or signals do not necessarily traverse as many stages in the process of amplification as does the program signal. In other words the auxiliary intelligence may be injected subsequent to the point at which the program signal begins its amplification. For introducing an auxiliary signal into the amplifier circuitry any conventional means of signal mixing or injection will serve, as long as it doesn't present an improper load to the source of said signal. In some cases the auxiliary signal source means will have to be lightly loaded and so will require a vacuum tube or transistor control element for its sole use. At the same time, an amplifier will often require a "phase inverter" for its normal operation. It happens that some phase inverter circuits make a spare control element available. (An example is the "cathode-coupled" circuit.) These circumstances may be taken advantage of to avoid the necessity of using an extra tube or transistor as in a conventional "mixer" circuit.

The portion of the amplifier involved in amplifying the auxiliary signal or signals should be designed to keep low-frequency phase shift small to down below the lowest frequency to which it might be desired to move the resonance. In order to accomplish this a specially designed output transformer may be necessary. Alternatively, an output-transformerless amplifier may be utilized.

An amplifier characteristic which may easily be controlled in the design process by one skilled in the art is the value (real or apparent) of the output impedance. The choice of a suitable value for use in the present invention is governed by the following considerations: The effects of mass synthesis and reduction of amplifier distortion can be obtained at almost any value of said output impedance. However, if a value be chosen that is low enough to permit output current to be appreciably influenced by normal changes (with frequency) in the value of the motional impedance of the loudspeaker, there will also take place an increase in the apparent resistive damping in the vibratory system. The lower the output impedance, the more noticeable will be this damping effect.

Mass and damping effects in a vibratory system, being in quadrature, do not interfere with each other but are superimposed one upon the other. Nevertheless, excessive damping will harm the low frequency response of a loudspeaker system and will thus sacrifice one of the advantages that could otherwise be achieved by the invention. The amount of damping that can be tolerated in a given instance will depend upon the enclosure used, the frequency of the apparent resonance, the characteristics of the loudspeaker proper, and other factors. It is suggested that relatively high values of output impedance be employed wherever opposing considerations do not interfere. This will guard against unwanted effects from an as-yet-unmentioned source, namely the blocked voice coil reactance. In any even, very low or negative output impedances should be avoided.

It is not the purpose of the present invention to produce damping effects. Consequently, the idealized theory given herein is based on the simplifying assumption that amplifier output impedance is infinite. To embrace the production of damping effects, a more extended analysis can be made. Such an analysis will show that it is possible to achieve a given value of pseudo mass no matter how low an output impedance is employed; and that, furthermore, the value achieved will be independent

of frequency, at least under the usual circumstances wherein the effects of the voice coil reactance are not important. (One skilled in the art will comprehend that such an extended analysis can be based upon the principle of superposition. A low resistance shunted across a constant-current generator can be made equivalent to an infinite resistance by supplying it with an extra current component of suitable value. Such an extra current must in the present case be in phase with the drop across the motional impedance and hence has resistive, but not reactive, effects.)

Acceleration is a vector quantity; consequently so is the auxiliary current that represents it in the amplifier output. According to Eq. C the phase of the auxiliary current is the same as that of the acceleration. However there remains a choice of directions in which the current may be caused to flow through the voice-coil. In other words there is a choice of polarities available; a switch in polarity as viewed from the voice-coil being equivalent to a 180° phase shift. It is desirable that i_x have proper polarity with regard to the other current to be found in the voice-coil, namely the one that flows in response to the program signal. If this polarity relationship is reversed, the pseudo-mass that is developed will be negative and will in effect subtract from the true mass of the moving system rather than adding to it. A small negative pseudo-mass will raise the resonant frequency and increase distortion. A large negative pseudo-mass will cause instability.

In practice the proper polarity may readily be determined by trial-and-error. It can also be determined analytically, by proceeding from the following premise: For positive pseudo-mass, i_x must be opposite in phase to the definable current component that develops the force component that matches the force developed by the true mass. Taken with regard to the program current as a whole, i_x will correctly be generally opposed at frequencies above that of the apparent or pseudo resonance and generally aiding at frequencies below said resonance.

Re-arranging Eq. C:

$$M_x = BL \frac{i_x}{a} \quad (D)$$

Or, with given loudspeaker characteristics, the amount of the pseudo-mass developed is a function of how much auxiliary current flows in response to a given acceleration. One skilled in the art will be able to control this ratio in the design process so as to achieve the required response characteristics. It may be desirable to make said ratio variable rather than fixed in given equipment, as for instance to permit the accommodation of differing loudspeakers or differing listening circumstances with the same electrical equipment. The ratio may readily be made variable by means of the incorporation in the equipment of one or more simple attenuators. It is even possible, with the aid of simple circuitry, to provide for optional change-of-sign of the ratio to permit raising the resonant frequency somewhat for special purposes.

The amplifier considerations just discussed apply in a general way to the amplifiers used in all the embodiments illustrated and to be described.

In one embodiment of my invention, illustrated in Fig. 1, the auxiliary signal generating means is a direct-reading accelerometer 10. An accelerometer is here defined as a device adapted to produce an electrical signal output of magnitude instantaneously proportional to the measure of the acceleration of the mechanical element to which it is applied. It should be carefully noted that, so defined, an accelerometer includes a transducer plus any necessary auxiliary equipment for same, but does not include the visibly readable meter that the term literally might imply. My usage here is that preferred in the fields of vibration and strain measurement. Modern transducers in the latter fields are so commonly used in conjunction with separate electronic recording

means that they are considered to deliver their measurements or indications in terms of electrical signals, rather than visually. The most basic type of accelerometer (as just defined) is one in which acceleration is determined through measurement of the forces exerted on a small test mass which is arranged to move with the surface or object under test. I will hereinafter call such a basic accelerometer a "direct-measuring" type to distinguish it from other types in which neither stress nor strain due to acceleration are measured directly.

For use in my invention a small, lightweight unit is required. A small piezo-electric type of accelerometer is suitable for this service, where the electrical load provided for it can be of high impedance. Such an accelerometer should be cemented by its proper support point directly to the diaphragm 11 of the loudspeaker 12, preferably near the center. Electrical connections can be made by means of flexible leads.

An excellent brief summary of the principles of operation of piezo-electric accelerometers is given in *The Engineer*, vol. 201 page 382, April 1956, under the title, "Barium Titanate Accelerometers and Strain Gauges." The same paper also gives exemplary constructional details. Evidence that this type of accelerometer is small enough in mass for use in the present invention is the fact that models already commercially available weigh as little as 3 grams. (Glennite models A322 and A323, Gulton Mfg. Co., Metuchen, New Jersey.) Evidence that this type of accelerometer can eventually be made very low in price is the fact that structurally speaking it is even simpler than the familiar "crystal" phonograph cartridge. (Incidentally, phonograph cartridges of the displacement-sensitive type can be made to function as accelerometers by virtue of the mass of their needles; indeed they do so function every time a user inadvertently taps his pickup arms on the side while changing records.) For use in the present invention a type with a cylindrical mounting base is to be preferred, said base being properly dimensioned to be cemented inside a forward extension of the voice coil form.

The left end of the amplifier rectangle in Fig. 1 represents the input end of the amplifier and the right represents the output. The auxiliary signal is introduced into the signal channels of the amplifier somewhere prior to the output circuitry as shown and previously discussed.

Besides direct-measuring accelerometers, there also exist differentiating types. The latter types are made possible by the fact that just as excursion or velocity measurements of alternating motion are mathematically translatable into acceleration measurements, so the signals depicting those same excursion or velocity measurements translatable electrically into signals depicting acceleration. For instance acceleration is the derivative (with respect to time) or velocity. A signal depicting velocity when fed through a "differentiating circuit" becomes a signal depicting acceleration. Thus it is possible to use as an accelerometer an instrument that is really basically a velocity meter. Velocity-meters have the advantage that the body or housing, the heaviest part of such instruments, may be fixedly mounted, with only a small component part being required to move with the mechanical element under test. (Like "accelerometer," the term "velocity-meter" is borrowed from those fields in which it is most commonly applied. The previous warning against too literal interpretation of "meter" holds in the present case.)

An embodiment of my invention utilizing a velocity-meter and an electrical differentiator as (or in place of) an accelerometer is diagrammed in Fig. 2. The velocity-meter shown may be of any suitable type. The heavy line 13 indicates a mechanical connection or mechanical integrity between the moving system of the loudspeaker 12 and the moving element of the velocity meter. The output of the instrument is run through a differentiating circuit, as shown, after which it is identical for practical

purposes with the signal that would be supplied by a direct-measuring accelerometer and is similarly introduced into the signal channels of the amplifier.

One type of velocity meter suited for this service is the moving-coil type. In this type the moving element is a conductor arranged to move in a magnetic field and the electrical output is taken from said conductor. The voltage developed in the conductor is proportional to the velocity, but the current is not necessarily so related. The signal produced by this type of velocity-meter is thus a "voltage-coded" one.

The differentiator shown may be one that utilizes a capacitor. The instantaneous current through a capacitor is proportional to the derivative (with respect to time) of the voltage across it. To utilize a capacitor as a differentiator, one of suitable value is chosen and it is connected so as to constitute practically the entire load (internal included) "seen" by the source of the signal to be differentiated. If the voltage of said signal represents the quantity to be differentiated, then the current through the capacitor is proportional to the differentiated quantity. Such a current can be used directly to feed current sensitive, low impedance components, e.g. transistors. To feed high impedance, voltage sensitive components it is necessary to develop a voltage proportional to the current just mentioned. This is accomplished by including a resistor, of value too small to substantially affect the current, in series with the capacitor. Then the voltage across that resistor is taken as the output of the differentiating circuit.

Thus the capacitor differentiator can be adapted to produce either a "voltage-coded" signal or a "current-coded" signal. (In the former the significant magnitude is the strength of the voltage, in the latter the significant magnitude is the strength of the current. But the magnitude of the input signal to the differentiator can be specified only by the voltage of that signal, which should be substantially independent of the current over the range of operating frequencies. Since a moving-coil type velocity meter produces a voltage-coded signal and its internal impedance may be made relatively low, the combination of this type of velocity-meter with a capacitor differentiator works out fine. (Other combinations are possible, for instance an electrostatic velocity-meter with an inductor differentiator.)

A differentiating circuit may be more elaborate than the types just mentioned; for instance, it is possible to incorporate a vacuum tube or a transistor for the sake of improved performance. Certain considerations must be mentioned that apply to any differentiating circuit that may be employed in my invention. Whatever the circuit, it must ultimately depend on the relationship between voltage and current in a reactance. It necessarily follows that in order to take out a differentiated signal without appreciably disturbing that voltage-current relationship, considerable signal strength must be sacrificed. In general it can be said that for any given type of differentiator, the more perfect the differentiation, the greater the loss of signal strength. "Perfect" differentiation would involve infinite attenuation and the strength of the resultant differentiated signal would be zero.

Therefore it becomes important to indicate how great a degree of imperfection can be tolerated, for the sake of economy, in a differentiating circuit to be used in my invention. Experimentation indicates that a wide degree of latitude is permissible. As differentiation is made less and less perfect, the first deleterious effect to appear seems to be a variation in level of high-frequency response. The point at which this effect becomes objectionable will, of course, depend upon the bandwidth sought to be covered, as well as upon a number of other variables. Hence, a precise quantitative statement is impossible. Qualitatively, however, it is possible to state that it is permissible for differentiation to be nearly non-existent at the top of the reproduced band, provided that

it is reasonably good by midband (differentiation will normally improve with falling frequency).

Therefore, herein and in the claims when I speak of a "differentiator," a "differentiating circuit," or a "circuit for developing a signal component having magnitude proportional to the derivative-with-respect-to-time . . ." I do not mean to imply that mathematically perfect differentiation need be achieved, for that would be impossible. I do mean to imply only the use of a means having performance that is sufficiently good for the purposes of the invention, as specified herein.

For compactness the velocity-meter may be constructed integrally with the loudspeaker, its moving element thus becoming a part of the moving system of the loudspeaker. As a further condensation and as an economy move, the magnet that supplies the necessary magnetic field for the loudspeaker may also be made to supply the field required by the velocity meter, assuming the latter to be of the moving-coil type. As a still further condensation, the winding for the velocity meter can be made to move in the same magnetic gap with the loudspeaker's voice-coil. This is equivalent to saying that the velocity-meter represented in Fig. 2 may consist simply of an extra winding on the voice-coil of the loudspeaker. This extreme simplification is possible and highly satisfactory within certain limitations.

It can be shown that any ordinary moving-coil type loudspeaker in the sound reproducing situation constitutes a velocity-meter by itself without the benefit of extra windings or magnetic gaps. From loudspeaker theory we have,

$$e_m = BLv \quad (E)$$

where e_m is the motional voltage and v is the velocity of the voice-coil and hence of the moving system. The motional voltage is simply a back voltage developed in the voice-coil that makes itself felt over and above the voltage drop that would be predicted from the "blocked" (true) voice-coil impedance according to Ohm's law. In order to account for the extra voltage drop it is customary to postulate an extra impedance, called the motional impedance, in the electrical circuit of the loudspeaker. The resultant equivalent circuit has the motional impedance in series with the blocked voice-coil impedance, with the motional voltage, e_m , represented by the drop across said motional impedance.

By means of this equivalent circuit it is possible to deduce a method for extracting a signal of magnitude proportional to the motional voltage from the amplifier output circuitry. Let K be an arbitrary constant. Then, from the circuit described, by Kirchhoff's law,

$$Ke_0 - KZ_v i_0 = Ke_m \quad (F)$$

where e_0 is the output voltage of the amplifier, i_0 is the output current and Z_v is the blocked voice-coil impedance. The amplifications of Eqs. E and F can be stated as follows: The combination in proper ratio and in a generally opposing sense of a signal of magnitude proportional to the amplifier output voltage with a signal of magnitude proportional to output current will yield a composite signal of magnitude proportional to the velocity of the moving system. This composite signal can be differentiated and injected into the signal channels of the amplifier in the same manner as would be the signal from a separate velocity-meter.

The "proper ratio" referred to above in the italicized sentence is dependent upon the value of Z_v . Strictly speaking this ratio should vary with frequency, as Z_v has a reactive component due to the inductance of the voice-coil. It is a simple matter to make the ratio vary as prescribed, through the means used to develop the signal representing the second term of Eq. F. However the reactive component of Z_v is negligible at the lower frequencies and so for equipment not intended to reproduce the higher frequencies the proper ratio is substantially a fixed ratio.

The simplest differentiating circuits tend to affect relations between voltage and current in a signal supplied to them. Therefore such a signal should either have its intelligence coded as voltage, said voltage being substantially independent of the current, or have its intelligence coded as current, said current being substantially independent of the voltage. In certain cases one must choose, in applying the method Eq. F to my invention, between having the terms of that equation represent voltages or currents.

One skilled in the art will be able to accomplish it either way. For use with a capacitor differentiator it is preferable to provide voltages to represent the terms of the equation. The voltage called for by the first term can be obtained from a voltage divider of ratio K across the output of the amplifier. The resistance of this voltage divider should be kept reasonably low in anticipation of the varying load presented by the differentiator. The voltage called for by the second term of Eq. F can be obtained as the drop across an impedance in series with the output, inserted for the purpose and having the value KZ_v . To conserve power it is advisable to make the value of K much less than one. For reasons of economy and easy adjustment it may be desirable to make the series element strictly resistive. This is justified in equipment that will not be used at the higher frequencies, as explained above. However, where required, it is a simple matter to include the proper value of series inductance.

An embodiment utilizing a loudspeaker as its own velocity-meter is represented in Fig. 3. The rectangle 14 represents a means, such as the one already suggested, for developing a signal of magnitude proportional to the output voltage. The rectangle 15 represents a means, such as the one already suggested, for developing a signal of magnitude proportional to the output current. Means 14 and 15 are located in the output circuitry of the amplifier, preferably housed with the amplifier rather than with the loudspeaker. Note that one of these means could be located in the primary of the output transformer (if an output transformer is used) and the other in the secondary, provided that proper relative signal values be maintained and that precautions be taken to keep non-signal (D.C.) currents where they belong. In any event, the signals from means 14 and 15 are combined, differentiated, and introduced into the amplifier, as shown in the figure.

The combination of these two signals must be in a generally opposing sense. Also the two signals must have proper relative values as called for by Eq. F and the proper combined value as indicated by Eqs. C and D. As regards balance between the two signals, one of the means 14 and 15 may be made adjustable to permit adjustment in the field by the operator of the equipment. An adjustment procedure may be based on the fact that if the motional impedance is made zero, under otherwise operative conditions, then the combined signal supplied to the integrator should total zero. The motional impedance can be temporarily eliminated by blocking the movement of the voice-coil or by connecting a dummy load having the electrical characteristics of the blocked voice-coil in place of the loudspeaker.

The velocity-proportional signal generated by the means suggested by Eq. F and embodied in the version of Fig. 3 is only a means to an end. That end is the provision of an acceleration-proportional signal. It will now be shown that it is possible to get a signal of the latter type without having a definable velocity signal as an intermediate product. Differentiating Eq. F:

$$K \frac{de_0}{dt} - KZ_v \frac{di_0}{dt} = K \frac{de_m}{dt} \quad (G)$$

Eq. G shows that the signal of magnitude proportional to output voltage and the signal of magnitude proportional to output current may be differentiated before they

are combined rather than after, in arriving at a signal proportional to the derivative of the velocity, i.e., one proportional to the acceleration. The first two terms of Eq. G taken separately say nothing about velocity and taken together indicate acceleration.

Fig. 4 represents an embodiment which utilizes the principle of Eq. G. As before, 14 is the means for developing a signal of magnitude proportional to the output voltage and 15 is the means for developing a signal of magnitude proportional to the output current. Note that there are two differentiators, one each for means 14 and 15.

This embodiment has the advantage that each of the two differentiators used can be tailored to the characteristics of its respective signal source. For instance, consider some specific circuitry that can be used for means 14 and its differentiator. Suppose that a voltage-type signal is required for injection into the amplifier. Then we can conveniently start with a current-type signal from means 14. If a resistor be connected across the output of the amplifier, the current through that resistor will be proportional to the output voltage and so will constitute the signal required. The differentiator can consist of an inductor inserted in series with the resistor and having a value so-chosen that its reactance is small compared with the value of the resistance used at the highest frequency to be reproduced. The presence of the inductance thus will not seriously affect the described relationship of resistor current to output voltage. According to a well known rule, the voltage across an inductor is proportional to the derivative (with respect to time) of the current through it. Thus the voltage across the inductor under discussion represents the first term of Eq. G and is ready for introduction into the earlier stages of the amplifier. The amplifier circuitry involved should be designed so as not to draw enough current to upset the relations just arrived at.

Next, consider corresponding circuitry that can be used for means 15 and its differentiator. If we ignore the small effect of the voice-coil inductance, the second term of Eq. G simply calls for a signal of magnitude proportional to the derivative of the output current. For the present purpose such a signal can be obtained by inserting an inductance, of value too small to appreciably affect the output current, in series with the output and by taking the voltage across this inductance as the required signal. In this case, as well as in a certain case applying to means 14, it is impossible to separately distinguish signal source means and differentiator; in other words they are combined. Fig. 4 must not be construed as showing that a differentiator responsive to a signal providing means is necessarily separately distinguishable therefrom.

If the two signals obtained by the means just suggested or by equivalent means do not have the proper ratio demanded by Eq. G, a gross correction can be made by introducing each into the amplifier at a different level of amplification. In this case the amplifier will differ from that usable in other embodiments to the extent that provision must be made for mixing in one additional signal. The representation used for the amplifier in Fig. 4 is intended to convey the sense that the two signals under discussion may be injected at the same or at different levels of amplification. If both are to be injected at the same level it makes no difference, of course, if they are combined prior to injection. Electrically speaking it amounts to the same thing. In any event, two auxiliary signals can be defined, one emanating from each differentiator.

For resolving the polarity and magnitude relationships between the two auxiliary signals, some point of reference wherein both signals are present is required. Since both must be introduced into the amplifier prior to the output circuitry, the signal components in the output respectively ascribable to each may be used as the first two terms of Eq. G.

It might be advisable to provide a conveniently adjustable balance control for setting the relative intensities of the two signals, as for instance to free given electrical equipment from the necessity of always being used with a loudspeaker of exact specific voice-coil impedance. Adjustment can be made by the operator of the equipment according to the following directions: First temporarily eliminate the motional impedance by one of the methods previously suggested. Supply as a program signal a steady test signal of fixed frequency. Arrange to connect and disconnect both auxiliary signals from the amplifier while measuring the output voltage. Adjust the value of one or the other of the auxiliary signals by the means provided until the output remains constant regardless of whether both are connected or both are disconnected.

In practice the embodiments of Figs. 3 and 4 both seem to tolerate considerable departure from ideal balance conditions. The chief effect of excessive unbalance is to provide an inequality of response at various frequencies. This suggests that under certain circumstances it might be desirable to introduce some imbalance deliberately in order to compensate for opposing frequency discrimination originating elsewhere. By "signal" I mean any electrical effect which can be used to convey the instantaneous measure of a rapidly varying quantity. By "electrically embodied intelligence" I mean one or more signals generically.

It is convenient and in accordance with current practice to speak of a signal as being "amplified" or "differentiated." The identity of a signal before and after being so operated upon should not be taken too literally, however. The identity is one of cause and effect, while the character of the information transmitted and the identity of the currents representing that information may be changed in the process.

By the "magnitude" of a signal I mean that time-varying measurement of said signal which embodies the information transmitted. In the case of the type of signal conventionally used, the measurement in question is that of the instantaneous value of either the voltage, the current, or the square-root of the power. Other systems are possible, wherein the measurement in question might be that of such values as envelope amplitude or frequency deviation.

In speaking, of the polarity relationships between combined signals, I take the 90° phase angle mark as the borderline between "generally aiding" and "generally opposing" or between "generally in phase" and "generally out of phase."

I use the word "circuitry" in a sense in which it is commonly used in electronic and allied arts, namely as generic to both "circuit elements" and "circuit wiring." Examples of circuit elements are resistors, transformers, and vacuum tubes.

I am aware that in the prior art there exists a feedback system sometimes called motional feedback wherein a voltage proportional to the velocity of the moving system is fed back in a negative sense. My invention differs from this system in important respects. Most important of these is the fact that insofar as my invention can be regarded as a feedback system it teaches the feeding back of a signal or signals defining acceleration, not one proportional to velocity. Velocity information can be defined in versions of my invention, but it is not fed back. Needless-to-say, velocity and acceleration are different quantities. One may be negative when the other is positive; one may be zero when the other is at a maximum. Also they vary with frequency in different fashions.

Differences in structure and/or method are reflected in differences in function. The older system tends to eliminate the resonant peak in response and with it much of the useful low-frequency response as well. My system retains the useful low-frequency response while moving the resonance to a lower frequency.

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I specifically do not claim herein any method or construction in which electrical intelligence directly denoting the velocity of the moving system of a loudspeaker is introduced into the pre-output signal circuitry of an amplifier driving that loudspeaker.

Also I do not claim herein any method or construction in which electrical intelligence directly denoting the excursion of the moving system of a loudspeaker is introduced into the pre-output signal circuitry of an amplifier driving that loudspeaker for I claim such an arrangement in my co-pending application Serial Number 588,020, filed May 29, 1956.

It should be apparent that my invention resides largely in the realm of principle. My disclosure has necessarily been largely diagrammatic. Where I have become specific to the point of suggesting certain components and arrangement details, it has been only for illustrative purposes; a great variety of specific constructions may be resorted to without departing from the spirit and the scope of the invention as hereinafter claimed.

I claim:

1. In sound reproducing apparatus, in combination: an amplifier; a loudspeaker connected to the output of said amplifier; means for developing electrically embodied intelligence instantaneously depicting the acceleration of the moving system in said loudspeaker; and connections for introducing said electrically embodied intelligence into the pre-output signal channels of said amplifier.

2. In sound reproducing apparatus, in combination: an amplifier; a moving-coil loudspeaker connected to the output of said amplifier; a mechanical-to-electrical transducer system adapted to develop a signal having magnitude instantaneously proportional to acceleration of the moving system in said loudspeaker; and connections for introducing said signal into the pre-output signal channels of said amplifier.

3. The combination set forth in claim 2 further characterized in that said transducer system comprises a velocity meter plus a differentiating circuit.

4. The combination set forth in claim 3 further characterized in that the sensing element of said velocity meter is an extra winding on the voice coil of said loudspeaker.

5. The combination set forth in claim 2 further characterized in that said transducer system utilizes a direct-measuring accelerometer.

6. A marketable component of sound reproducing apparatus comprising a moving-coil type loudspeaker and a direct-measuring accelerometer, said accelerometer being built into said loudspeaker in such a manner as to be responsive to vibrations of the moving system thereof.

7. In sound reproducing apparatus, in combination: an amplifier adapted to be supplied with a program signal; a moving-coil loudspeaker connected to the output of said amplifier; a mechanical-to-electrical transducer system adapted to develop an auxiliary signal having magnitude instantaneously proportional to acceleration of the moving system in said loudspeaker; and connections arranged to introduce said auxiliary signal into the pre-output signal channels of said amplifier in that polarity according to which said auxiliary signal will generally buck or oppose said program signal at frequencies above that of the loudspeaker resonance.

8. In sound reproducing apparatus, in combination: an amplifier; a loudspeaker connected to the output of said amplifier; circuitry for deriving from the voltage and the current in the output of said amplifier electrically embodied intelligence instantaneously depicting the acceleration of the moving system in said loudspeaker; and connections for introducing said intelligence into the pre-output signal channels of said amplifier.

9. In sound reproducing apparatus, in combination: an amplifier adapted to be supplied with a program signal; a moving-coil loudspeaker connected to the output of

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said amplifier; circuitry for deriving from the voltage and the current in the output of said amplifier electrically embodied intelligence instantaneously depicting the acceleration of the moving system in said loudspeaker; and connections arranged to introduce said intelligence into the pre-output signal channels of said amplifier in that polarity relationship according to which the sum of said intelligence will generally buck or oppose the effects of said program signal at frequencies above that of the loudspeaker resonance.

10. A marketable component of sound reproducing apparatus comprising at least: an amplifier; circuitry for developing a definable signal component having magnitude proportional to the derivative-with-respect-to-time of the output voltage of said amplifier; circuitry for developing a definable signal component having magnitude proportional to the derivative-with-respect-to-time of the output current of said amplifier; and connections for introducing both of said signal components into the pre-output signal channels of said amplifier.

11. A marketable component of sound reproducing apparatus comprising at least: an amplifier; circuitry for developing a signal of magnitude proportional to the output voltage of said amplifier; circuitry for developing a signal of magnitude proportional to the output current of said amplifier; connections for combining the two last-named signals in a generally opposing sense to produce a combined signal; a differentiator circuit for differentiating said combined signal to produce an auxiliary signal; and connections for introducing said auxiliary signal into the pre-output signal channels of said amplifier.

12. A marketable component of sound reproducing apparatus comprising at least: an amplifier; circuitry for developing a first auxiliary signal of magnitude proportional to the derivative-with-respect-to-time of the output voltage of said amplifier; circuitry for developing a second auxiliary signal of magnitude proportional to the derivative-with-respect-to-time of the output current of said amplifier; and connections for introducing both of said auxiliary signals into the pre-output signal channels of said amplifier.

13. The combination set forth in claim 1 further characterized in that the apparent output impedance of said amplifier is more than two-and-one-half times the nominal impedance of said loudspeaker.

14. The combination set forth in claim 1 further characterized in that the apparent output impedance of said amplifier is more than four times the nominal impedance of said loudspeaker.

15. In sound reproducing apparatus: a moving-coil loudspeaker; mechanical-to-electrical transducing means arranged to be responsive to vibrations of the moving system of said loudspeaker; amplifying means connected in driving relationship to said loudspeaker; and connections for delivering the electrical output of said transducing means to an input of said amplifying means, said transducing means and said amplifying means being arranged to deliver to said loudspeaker a component of current having magnitude instantaneously proportional to the acceleration of said moving system.

16. A marketable component of sound reproducing apparatus comprising: an amplifier; circuitry for deriving from the output voltage and current in said amplifier electrically embodied intelligence instantaneously depicting the acceleration of the moving system in any suitable moving-coil loudspeaker which may be connected to the output of said amplifier; and connections for feeding back said electrically embodied intelligence to the pre-output signal channels of said amplifier.

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