A New Approach to Loudspeaker Damping

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Modestly styled by the author as "the hottest thing in audio," positive feedback added to a negative-feedback amplifier is shown to reduce output impedance to zero or below, achieving a damping factor of infinity.

IS APPRECIABLY BETTER LOUDSPEAKER damping really attained by increasing the damping ratio of amplifiers higher and higher? The answer, sadly enough, is "No!" Some lowering of the otherwise very high impedance of a pentode amplifier is desirable, and there are other concurrent benefits obtained from the use of the same negative feedback which reduces apparent output impedance. However, it appears that there is a widespread misunderstanding of the principles involved.

In this article, the author will endeavor to show that we have been deluding ourselves to a great extent about the merits of a high damping ratio, and that there is a way to achieve high damping other than by the application of more and more negative feedback. By the method to be described herein, it is possible to take the damping ratio right up to infinity and beyond. In fact, it is in the region well beyond infinite damping ratio that an amplifier must operate in order to provide theoretically perfect speaker diaphragm control. By the addition of only one inexpensive part, your own amplifier may be transformed to operate either at infinite damping ratio, or at a condition of near-perfect electrical damping.

Let us examine the principles involved in amplifier-damping of loudspeakers. Take an ohmmeter or bridge to the nearest speaker and measure the d.c. resistance of the voice coil. Ten ohms is a representative value for a 16-ohm speaker. Now measure the resistance of 16-ohm secondary of an output transformer. Another ohm or so. Now add the 11 ohms thus obtained to the tiny apparent output impedance—0.6 ohms, maybe?—you have obtained in your amplifier, perhaps with considerable expense and circuit complexity. Doesn't look so good, does it? For instance, if you have been successful in doubling your damping ratio from 4 to 8—thus cutting output impedance from 4 ohms to 2 ohms—you have, for your pains, cut *total* effective generator resistance only from 15 ohms to 13 ohms. Actually you haven't even done that well because in either case additional damping has been contributed by the mechanical resistance of the cone suspension.

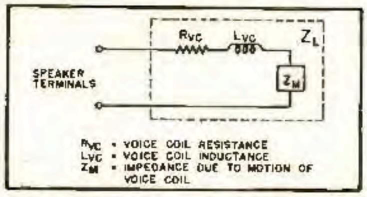
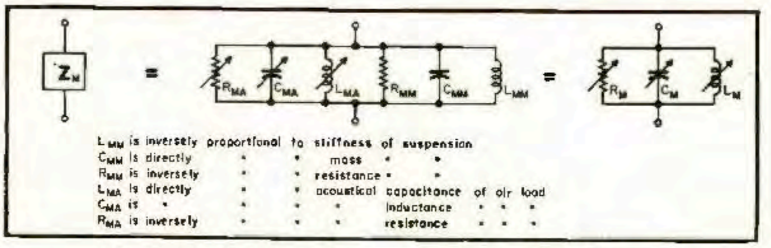


Fig. 1. Electrical equivalent of loudspeaker load.

It is justifiable to take voice-coil resistance, normally considered as part of the load, and add it to the source, for two reasons. First, as in the case of motor rotor windings, resistance and self-inductance of the voice-coil are necessary evils and contribute nothing to performance. Second, the voice-coil parameters are effectively in series with, not shunted across, the "business" part of the load. If one measures the electrical impedance of a speaker at a given frequency and then impedes the motion of the voice-coil, the impedance is seen to go *down*, being lowest with the voice-coil completely blocked. At this point the voice-coil shows the same impedance that it would if completely removed from the speaker except that its inductance is affected somewhat by the metal surrounding the gap. Conversely, if a weightless voice-coil could be suspended in the gap so that it could move freely without encountering stiffness or friction, the electrical impedance of the speaker would be infinity. The total electrical impedance of the circuit will always be greater than that of the voice-coil alone unless the speaker is inoperative. Clearly, then, the equivalent circuit is the series one of *Fig.* 1.



L_{MM} is inversely proportional to stiffness of suspension
C_{MM} is directly " " mass " "
R_{MM} is inversely " " resistance " "
L_{MA} is directly " " acoustical capacitance of air load
C_{MA} is " " " " inductance " " "
R_{MA} is inversely " " " resistance " " "

Fig. 2. Equivalent circuit for motional impedance of loudspeaker.

Transient Response

Good transient performance is often equated to the reduction of overshoot or "ringing." There is more to it than that, but the yardstick thus suggested is a useful one for underdamped systems. Certainly ringing contributes largely to the characteristic "loudspeakerish" sound from which all direct-radiator speakers seem to suffer. To induce ringing in any underdamped system it is only necessary that an impulse be introduced which contains components higher in frequency than the resonant frequency of the system. The familiar "mouth-harp" is an example of such a system. The pitch of the vibrating part of the mouth-harp does not vary. Yet when placed in the performer's mouth, tunes are produced by tuning the cavity (formed by the mouth) which the initial transient starts ringing. Circuit switching can produce widely differing sounds in different speakers. This writer once arranged a half-dozen speakers of various sizes and makes so that he could play a simple tune with the thumps created by closing toggle switches connected between the respective voice-coils and a dry-cell. Fine tuning was accomplished by changing baffling. In no case was the speaker installation any different from one which might have been intended for sound reproduction. This experiment suggests one reason why two-way systems are likely to not *sound* good to the layman. If the pitch of the click of the high-frequency speaker bears an inharmonic relation to the pitch of the thump of the low-frequency speaker, a disagreeable noise is produced on every transient—which is to say on at least every note of music and syllable of voice reproduced.

It is clear that damping is a desirable objective, but it is also clear that beyond a certain point inverse feedback does virtually nothing toward attaining this objective. Actual tests with pulses

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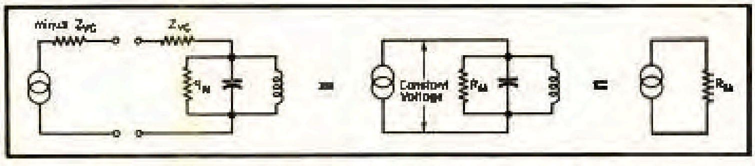

Fig. 4. Method of using negative impedance to achieve perfect damping.

and interrupted wave-trains show that a triode output *without* feedback represents about the point of vanishing return. A lower output impedance than that thus represented is of very little importance in restraining the ringing of a typical diaphragm assembly. Direct-radiator speakers will ring at their resonant frequency even if fed by a generator of zero internal impedance. Just how badly they will ring under that circumstance will depend on the amount of flux in the gap and upon the amount of damping inherent in the diaphragm suspension. The role of mechanical damping, which takes place mostly in the outer roll, is illustrated in *Fig.* 2. The power that goes into R_{ma}, shown in the middle circuit of that figure, is the power that counts—the power that represents acoustic output. The shunting reactances are necessary evils. Any power lost in R_{mm}, the edge damping, is power wasted from the standpoint of efficiency. Nevertheless it can be seen that a low value of R_{min} will do much to minimize the effects of the shunting reactances.

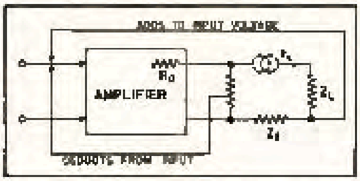

Fig. 3. Arrangement for applying voltage-proportional negative feedback simultaneously with current-proportional positive feedback.

It is impossible to get all of the way to zero apparent output impedance by means of negative feedback. Even assuming that it were possible, the speaker would still not be cured of ringing, because of the intervening impedance of the voice-coil. High flux-density in the gap can reduce the effect of the voice coil, but cannot eliminate it. But suppose that it were possible to make the amplifier exhibit *negative* impedance as viewed from the output terminals. The negative impedance would subtract from the voice-coil impedance. If the two just matched, the effect of the latter would have been eliminated entirely. This is no idle dream, but is, in fact, quite easy of attainment. The means is *positive* feedback. Readers will recall that constant-*voltage* inverse feedback from an output causes apparent output impedance to decline, while constant-*current* feedback causes it to rise. With *positive* feedback the opposite holds—voltage-proportional feedback causes the output impedance to rise and current-proportional feedback lowers it. Furthermore, current-proportional positive feedback will take the output impedance right down past zero and into the negative region if desired. The ideal setup, then, is to use voltage proportional negative feedback *plus* current-proportional positive feedback.

Direct and inverse feedback can thus be used simultaneously without cancelling each other out, although cancellation occurs insofar as the distortion-reducing and frequency-response-smoothing effects of inverse feedback are concerned. But with regard to reducing apparent output impedance, the effects of the inverse and direct feedback are additive. Referring to the block diagram of *Fig.* 3, it will be seen that any voltage developed only in the load causes the input voltage to be modified in the *same phase* by the resultant out-of-phase voltages in the two respective feedback circuits. The operation of the circuit is as follows: starting with negative feedback alone, the apparent output impedance goes down as positive feedback is applied. It requires only a slight amount of positive feedback to bring it to zero. Damping-ratio at this point is, of course, infinity. As more positive feedback is added, the apparent output impedance becomes negative and starts to "erase" the series part of the speaker load impedance. At some point the voice-coil impedance is exactly matched by the negative impedance of the amplifier and theoretically perfect damping is achieved, as illustrated in *Fig.* 4. If positive feedback is increased considerably beyond this point, oscillation will eventually occur. In actual installations it may take place before the midband gain gets up to what it would be with no feedback at all. This is due to the difficulty of securing an exact phase match between the load impedance and the negative impedance. This last consideration is of only academic interest, however. There will always be an ample safety margin before oscillation, even if the inductance of the voice-coil is ignored and the amplifier is made to exhibit a pure negative resistance.

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Fig. 5. Waveforms across output of negative-impedance amplifier with 30-cps square-wave input. Speaker resonant frequency = 120 cps.

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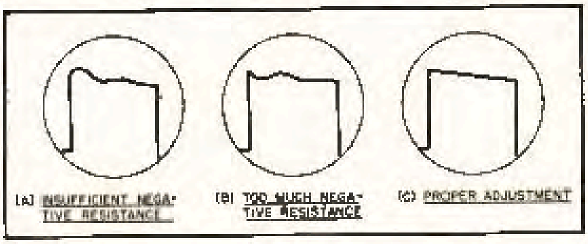
(A) INSUFFICIENT NEGATIVE RESISTANCE
(B) TOO MUCH NEGATIVE RESISTANCE
(C) PROPER ADJUSTMENT

"Perfect" Damping

Thus perfect damping is arrived at long before the benefits of the negative feedback have been cancelled out. The exact amount of positive feedback necessary varies with the installation. With a typical high-efficiency speaker and a fairly high amount of negative feedback, the ideal amount of positive feedback to be added will be found to be that amount which just about doubles the gain. Circuit algebra shows that this means the effective negative feedback will have been cut in half. In other words, the principle is applicable to any circuit from which you can get roughly 6 db more of feedback than you really need from a standpoint of distortion. This will include most high-quality amplifiers and practically *all* triode amplifiers. *Figure* 5, drawn from actual 'scope traces, shows that the combined feedback principle works out as neatly in practice as it does in theory. It also illustrates the quickest and easiest way to adjust the amount of positive feedback applied when one of the circuits to be described is added to an amplifier. Note that if too much positive feedback is used, ringing resumes, but is now reversed in phase.

Figure 6 shows a circuit that has been recommended for applying positive feedback to the popular Williamson amplifier. It would seem that this circuit has several drawbacks. Since it applies feedback before even-order harmonics have been bucked out, it increases the magnitude of those harmonics and lessens the likelihood that they will be perfectly cancelled. Since it introduces constant-current negative feedback, it defeats its own purpose up to a point and requires high output from the driver tubes. Finally, since ordinary ganged potentiometers run well above 10 per cent "tracking error," the signal balance of the output stage is likely to be rather bad.

The circuit of *Fig.* 7 was devised by the writer in 1949 and is believed to be far superior to that of *Fig.* 6. It is easy to apply to existing amplifiers using any of the popular circuits and the single adjustment has no effect on push-pull balance. It may be seen that a split-load type of phase inversion is applied to the positive feedback, permitting it to be returned to the same point at which the negative feedback is applied. This keeps phase shift identical in the amplifier part of both positive and negative feedback loops. If desired, the phase-inversion feature can be left out and the positive feedback applied to grid of same stage, as shown in *Fig.* 8. This circuit is satisfactory where the damping is desired only at the lower frequencies. The stray and interelectrode capacitance to ground from the top of the grid resistor prevents the higher frequencies from

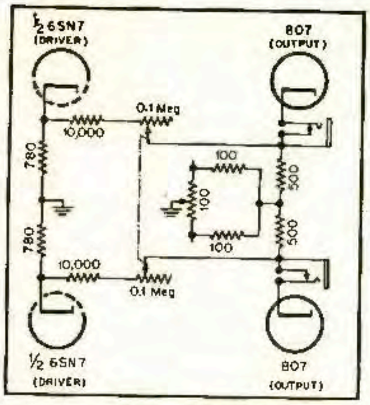

Fig. 6. One method of obtaining current-proportional positive feedback.

being fed back, even without the inclusion of R and C. R_g may be a volume control if desired.

Negative Inductance

An interesting refinement on the negative-output-resistance amplifier is to make it display negative *inductance* as well, thereby cancelling out the inductance of the voice-coil and improving high-frequency response and stability. This can be done by including an inductance in series with the positive-feedback rheostat, as shown dotted in *Fig. 7*. The optimum value for this inductance is given by the formula:

$$L_f = \frac{L_{vc}}{A' - 1}$$

Where A' is gain of part of amplifier enclosed by feedback loop, with *negative feedback only* and *unloaded*. To apply this formula, you need to know L_{vc}, the blocked voice-coil inductance of your speaker (or speakers). Unfortunately, I know of no way to block the voice-coil of a speaker securely without injuring it, so even if a means of measuring inductance is available it will do no good unless the speaker has an electromagnetic field. In that case the effect of blocking can be achieved by simply leaving off the field current.

If you are prepared to tackle it on a cut-and-try basis, you can assume that the blocked voice-coil inductance of a 16-ohm speaker is about 1 millihenry and start from there. Such a coil should be toroidally wound of #16 wire on an air core. Connect the coil into the circuit and add or remove turns until a value is found that permits R_f to be advanced the furthest (greatest resistance) without oscillation taking place. Actually there is nothing critical about this inductance. If it permits R_f to be turned at all further than it could be without the coil in the circuit, it will improve the operation of the circuit. After turns on coil are adjusted, R_f can then be adjusted to its final setting by means of square waves applied to amplifier and 'scope across speaker terminals, as in *Fig. 5*. It is also possible to do a fairly good job by ear with program material consisting of male speaking voice by adjusting for the least boominess. When you are through, you will have an outfit that provides the cleanest reproduction you have ever heard from direct-radiator speakers. This is, of course, provided that other things are right. Bear in mind that no amount of damping in one circuit will dampen another resonant circuit that is but loosely coupled to it. For instance, if a room resonance is present—it is almost impossible to get away from it in small rooms—no amount of speaker damping will obviate it. Look out also for acoustic feedback to turntable or microphonic tubes.

Limitations

Now for the bad news. A generator of low or negative internal resistance is in some regards not an ideal device with which to drive a loudspeaker. Some writers, describing the performance of amplifiers of high damping ratio, have spoken of the "apparent" lack of lows and have gone on to imply that the ear of the listener needs retraining; that the lows are there all right, just less conspicuous because of lack of resonance. Actually the lows *are* attenuated more and more as damping is applied. With the circuits of *Figs.* 6 and 7 the loss of lows will be very pronounced with some speaker arrangements, though negligible with others, as will be explained.

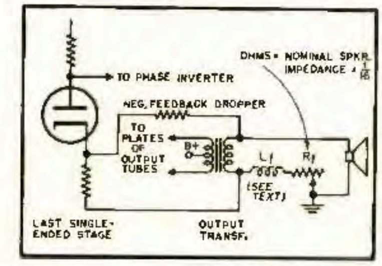

Fig. 7. Preferred method of applying positive feedback.

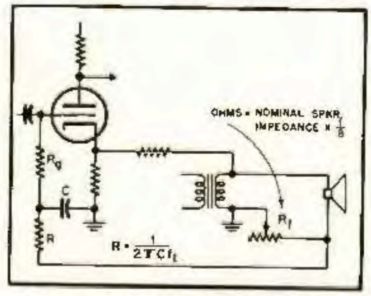

Fig. 8. Variation of Fig. 7 that produces low-frequency boost but damps speaker only at one low frequency, which may be set to be resonant frequency of the speaker.

It has to do with variation, with frequency, of the air loading on the speaker cone. In (B) of *Fig. 2*, the resistance and reactance contributed to the equivalent electrical circuit of the motional impedance by the mass and mounting of the voice-coil and cone have been depicted as fixed. On the other hand, resistance and reactances arising from air loading have been depicted as variable. In general, the circuit values due to definable *mechanical* parameters are relatively fixed. Those due to *acoustic* values may vary with frequency, even the equivalent inductance and capacitance. Over a wide range of frequencies where the speaker (if considered as a perfect piston) gets a big enough "bite" of air, the loading due to air is almost purely resistive and is constant with frequency. For the equivalent circuit within this range C_{ma} and L_{ma} could be left completely out, and R_{ma} could be shown as fixed. However, if the applied frequency is lowered far enough, the "bite" will cease to be big enough at some frequency that depends on the size of the cone and the resistive loading will start to change. Whether it may be said to go "up" or "down" depends upon the acoustical-electrical analogy one uses (e.g. force-current or force-voltage). At any rate, the net effect is that the resistance "seen" by the electric circuit, R_m in *Figs.* 2 and 4, goes *up* with decreasing frequency.

Figure 9 shows the variation of R_m with frequency on the assumption that R_m is entirely due to the air loading on the cone. (In different speakers, the contribution of R_{mm} will flatten the actual rise of the curve to various degrees.) The "turnover" frequency, f_1, will vary from about 520 cps for a 15-in. speaker to about 1,660 cps for a 5-in. speaker. It can be seen that loudspeaker response will drop off about 6 db per octave below this frequency if an effective constant voltage is applied across Z_m (since the power output will then be inversely proportional to R_m). But the ordinary amplifier, with considerable output resistance adding its effect to that of the voice-coil, will drive a speaker in such a manner that there will not, in general, be such a low-frequency attenuation. The reason is that the reactive part of the motional impedance, as at (C) of *Fig. 2* "looks", above resonance, like a capacitance shunting the load. Together with output resistance and voice-coil resistance it forms a power-eating tone control circuit that flattens out the response be-

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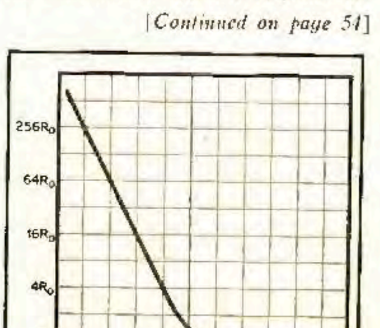

Fig. 9. Variation with frequency of resistive component of air loading on diaphragm, using the force-current analogy.

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[from page 22]

tween speaker resonance frequency and f_t. Then above f_t, where the tone-control effect is no longer bucked by a changing radiation resistance, one would expect a falling-off of response. There is less than might be anticipated, however, because speaker cones are designed to quit functioning as rigid pistons at about this point.

At any rate it can be seen that some apparent internal resistance in the amplifier is essential for flat frequency response from the usual direct-radiator speaker. This should make it clear why it is that some speaker manufacturers have specified limits on the amount of feedback to be employed in amplifiers suitable for use with their respective speakers. It also explains why exponents of a high damping-ratio sometimes contradict themselves by placing a pad between amplifier and speaker.

But suppose that the benefits of perfect damping are desired without reduction of low-frequency response. The speaker system must be given a big enough bite of air so that loading will remain constant down to the lowest frequency to be reproduced. Horn loading presents one possibility. But with a horn (or horns) pains must be taken to see that the mouth area is adequate at frequencies well below taper cutoff. To fulfill this condition down to 100 cps or below requires a huge installation. Horn systems designed for home use are mostly short on mouth area and as a result the diaphragm loading fluctuates violently with frequency. This may do no harm where there is series resistance to smooth out the output, but, as has been shown, with the negative-impedance amplifier the output will fluctuate exactly as the cone loading does. Another possibility is to use a large number of direct-radiator speakers. Theoretically, to be down not more than 4 db at 60 cps would require a cone area of 5,900 sq. in. in an infinite wall. This would correspond with the staggering total of fifty-four 15-in. speakers. But it is not as bad as that. By mounting in a corner near the ceiling or floor, one-fourth as much radiating area will suffice. By making use of the effective radiating area of a bass-reflex port, the number of speakers can be cut in half again. As it figures out, six 15-in. speakers in a bass-reflex cabinet in a

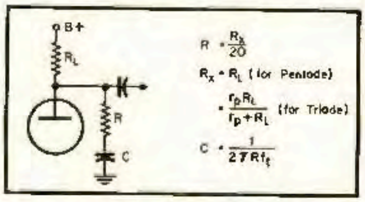

Fig. 10. Bass-compensation circuit for use at low level in preamplifier.

corner will do very well. Since the power each speaker will be required to handle will be small, bargain-basement speakers will do; the total investment can be quite small.

If space or purse does not permit a cone area large enough for constant air loading, the only recourse left is to add some bass-boost, to decrease the amount of damping, or to compromise and do both. The proper turnover frequency, f_t, for the boost and the amount of boost required will vary with the speaker and with the installation. The circuit of *Fig.* 8 will give a mild amount of bass-boost, depending on the setting of R_f. The circuit of *Fig.* 10 will give the maximum amount that could possibly be needed and has the advantage that it may be adjusted separately from output damping. However, it may be preferable to adjust the present bass-boost control and the damping control, R_f, together until the settings that *sound* the best are determined.

If the reader is impressed by the lure of improved damping, he may still want to adapt for negative impedance just for its novelty value. When the indicated simple changes have been made, it will result in an amplifier whose output voltage actually goes *down* when the load is removed. This phenomenon is so fascinating that the writer has had to demonstrate it for friends over and over again.

Loudspeaker damping is an extensive subject and this article is probably not really the "last word." But it should finally lay the ghost of some old fallacies, and it does point the way to securing perfect damping by electrical means. It would be hard to ask for anything more in this direction. In the writer's opinion, it's hard to improve on perfection.

CANNON ELECTRIC OPENS LARGE EASTERN PLANT

Accenting its expansion to the Atlantic seaboard, Cannon Electric Company, Los Angeles, recently began operations in a new 10,000-sq. ft. plant located in the East Haven district of New Haven, Conn.

At present the new plant will provide engineering and design consultation services for Cannon's eastern customers; however, the company intends to add warehousing, assembly, sub-contracting, and eventually manufacture, in order to give overnight service to the east coast, according to Robert J. Cannon, president.