Loudspeakers and Negative Impedances*

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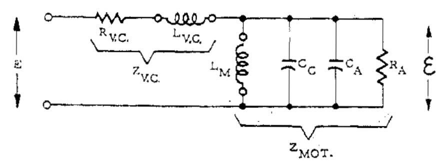
Summary—A direct radiator moving coil loudspeaker driven by an amplifier whose output impedance approaches the negative of the blocked voice-coil impedance can be made to exhibit extended low-frequency response with reduced distortion. The results are not to be confused with the effects of a negative resistance source. In a typical case, neutralization of 70 per cent of the blocked voice-coil impedance completely damps the cone resonance, as well as substantially reducing the nonlinear distortion below resonance. When the amplifier is compensated for the falling radiation resistance at low frequencies, uniform output can be obtained to any arbitrary low frequency, limited only by the ultimate power-handling capability of the amplifier and speaker. In this system, no additional amplifier power is required at frequencies down to the speaker resonance; additional power is required below that point.

Introduction

DIRECT radiator, moving-coil loudspeakers are basically inefficient transducers. The influence of the mechanical impedance upon the electrical input impedance is very slight as is typical of most "wide-band" electromechanical transducers. Even the magnitude of a mechanical resonance is often strongly masked by the electrical impedance. Because the electrical impedance of the blocked voice-coil is large compared to the average reflected mechanical impedance, the transfer characteristic of the transducer is largely influenced by the nature of the mechanical impedance.

A commonly used equivalent circuit for a direct radiator, moving-coil loudspeaker is shown in Fig. 1. Useful radiation is assumed to take place from one side of the cone as is the case wherein the loudspeaker is mounted in a totally enclosed box. The reflected radiation resistance, R_A, is inversely proportional to the square of the signal frequency for frequencies below that for which the diameter of the loudspeaker cone is approximately equal to a half-wavelength (the frequency of ultimate radiation resistance). For low frequencies, the air load upon the cone becomes essentially that of a constant mass.

For acoustic output independent of frequency, it is necessary that the voltage across R_A be inversely proportional to frequency at low frequencies. Therefore, the compliance of the moving system, L_M, is made very large so that its resonance with C_A and C_C occurs at the lowest possible frequency. Unfortunately, for loudspeaker cones and cabinets of convenient size, this resonance appears within the range of musical frequencies; and, by virtue of its lack of resistive loading, is insufficiently damped to avoid "ringing" on transient signals. Below the resonant frequency, the loudspeaker cone becomes stiffness-controlled and the acoustic output falls at a rate of 12 db per octave.



E = Input voltage
$\mathcal{E}$ = BLV

where:
B = Magnetic flux density
L = Length of voice—coil wire
V = velocity of voice—coil motion.

Reflected Motional Impedances

$$L_M = B^2L^2 \frac{C_S C_B}{C_S + C_B}$$

where:
C_S = Compliance of cone suspension
C_B = Compliance of air load in box.

$$C_C = \frac{M_C}{B^2L^2}$$

where:
M_C = mass of cone and voice-coil.

$$C_A = \frac{M_A}{B^2L^2}$$

where
M_A = mass of air load on loudspeaker.

$$R_A = \frac{B^2L^2}{r_A}$$

where:
r_A = radiation resistance presented to loudspeaker.

Electrical Impedances
R_{VC} = resistance of blocked voice-coil
L_{VC} = inductance of blocked voice-coil.

Frictional losses are assumed negligible.

Fig. 1—Common equivalent circuit for direct radiator moving-coil loudspeaker.

In addition to frequency and transient distortions, the direct radiator loudspeaker is subject to considerable nonlinear distortion at low frequencies. Below the resonant frequency, where the motion of the cone is determined principally by the compliance of the system, the nonlinearity of the compliance produces distortion in the radiated sound. There are other factors contributing to nonlinear distortion in a loudspeaker but the nonlinearity of the compliance is the principal offender.

There appears to be an unlimited variety of ways to modify the performance of a loudspeaker. The major effort has been concentrated on the design of the

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speaker enclosure, some of which have taken rather bizarre forms. Reflex cabinets, multistage reflex cabinets, column resonators, labyrinths, folded horns, and "semihorns," even cabinets with vibrating walls, have made their appearance. Some of the more serious designs have produced really noteworthy improvements in performance over the somewhat ill-defined "basic loudspeaker."

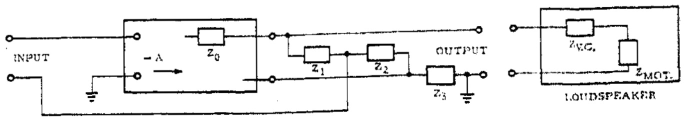
Recently, a design has become very popular in which the loudspeaker is provided with a heavy moving system so as to obtain a low-frequency resonance with its small enclosure. The compliance of the suspension is sufficiently high that the enclosure stiffness is the controlling element below resonance. This virtually eliminates the distortion caused by a nonlinear suspension. Unfortunately, the heavy moving system reduces the sensitivity of the loudspeaker and also requires that a separate speaker be employed for high-frequency reproduction. These limitations are unimportant in some applications but for general use the cost is prohibitive.

Some improvement in low-frequency performance can be obtained by acoustically damping the typical loudspeaker. If this is accomplished by stuffing the enclosure with fibrous material the speaker sensitivity is reduced only in the vicinity of resonance. This method is difficult to control accurately and the results are not always predictable if heavy damping is attempted. Once effective damping is achieved acoustically, the loudspeaker will become deficient in low-frequency response. In this case the amplifier must be equalized and the low-frequency power rating increased, which may not be economically feasible.

If the loudspeaker can be damped electrically by the output impedance of the driving amplifier, unnecessary losses are avoided and a more economical system results. This has long been realized, but so too has the fact that the blocked voice-coil impedance presents an effective barrier, isolating the motional impedance from an external "short circuit." If the blocked voice-coil impedance can be "reduced" by subtracting from it the output impedance of the amplifier, a more effective short circuit of the nonlinear, resonant motional impedance should result.

Within the last ten years the interest in negative-output impedance amplifiers has grown and died a number of times. The idea looked all right but there was always something overlooked and as a consequence the publicity has been largely unfavorable.[1–4] Perhaps a good close look at the problem will stimulate new interest in "negative damping factors."

[1] W. Clements, "Loudspeaker damping," *Audio Eng.*, vol. 35; August, 1951.
———, "Positive feedback," *Audio Eng.*, vol. 36; May, 1952.
[2] U. J. Childs, "Loudspeaker damping with dynamic negative feedback," *Audio Eng.*, vol. 36; February, 1952.
———, "Positive current feedback," *Audio Eng.*, vol. 36; May, 1952.
[3] "A new hi-fi speaker system," *Radio & TV News*, vol. 57, pp. 54–55, 82; April, 1957.
[4] N. H. Scott, "Power amplifiers for music reproduction," *J. Audio Eng. Soc.*, vol. 3, pp. 138–142; July, 1955.



$$Z_1 + Z_2 \gg Z_0$$

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

$$Z_0 = \frac{Z_0 + Z_3 - \dfrac{Z_1 Z_3 A}{Z_1 + Z_2}}{1 + \dfrac{Z_2 A}{Z_1 + Z_2}}$$

$-A$ = open circuit voltage gain of basic amplifier.
Z_0 = output impedance of basic amplifier.
A' = open circuit voltage gain with negative impedance circuit.
Z_0' = output impedance with negative impedance circuit.
If A is very high, and

$$\frac{Z_1}{Z_2} = \frac{Z_{VC}}{Z_3}$$

(a bridge balanced against Z_{VC}), then $Z_0' = -Z_{VC}$. Bridge may take form of:

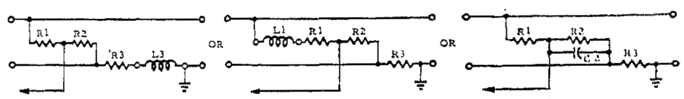


Fig. 2—Basic negative impedance circuit.

Basic Circuit

A particularly suitable circuit for obtaining an output impedance composed of a negative resistance and inductance is shown in Fig. 2. In this circuit, positive current feedback and negative voltage feedback are combined in a bridge and fed in a common feedback path through the amplifier. This system avoids complications resulting from gain and phase shift variations which may be encountered if separate feedback paths are employed.

The equations for operation of the circuit indicate that the output impedance is quite independent of the amplifier gain and phase shift when the loop gain is high and the phase shift not severe. With the bridge circuit balanced against the blocked voice-coil impedance, there will always be a net negative feedback at audio frequencies. At the extremes of the frequency spectrum where the reflected motional impedance becomes zero there will be no feedback produced by the circuit. The balanced bridge will, therefore, produce a stable negative output impedance which in no way detracts from the quality of the basic amplifier.

A close look at Fig. 2 will disclose the identity between negative-output impedance amplifiers and "motional feedback" or "motion control" systems. With the bridge of Fig. 2 accurately balanced against the blocked voice-coil impedance, the feedback voltage is proportional to the "generated back EMF," *i.e.*, the motional impedance. For the more likely condition of some degree of unbalance in the feedback network, the feedback voltage is a mixture of either negative voltage, or positive current feedback plus the "motional feedback."

The impedance concept offers certain advantages over the other analogies when it comes to equivalent circuitry or when studying the amplifier and loudspeaker individually, and is preferred by the author.

Practical Considerations

There are a few fundamental precautions which merit special attention, not because they are particularly complex but because they are vital to success.

Loop Gain

It is desirable that the loop gain of the circuit be as high as possible. For conventional high-quality amplifiers employing considerable feedback, this necessitates the use of additional stages of amplification which may result in stability problems at the frequency extremes when the loudspeaker is disconnected and the feedback voltage is maximum. If oscillation so results, the amplifier may be damaged and such a potential disaster is to be avoided if possible.

Perhaps the simplest solution to this problem is to restrict the circuit to a two-stage amplifier with little, if any, inherent feedback. The quality of the basic amplifier may be poor compared to a feedback amplifier but its performance with a loudspeaker can actually be superior. Improved results are to be obtained, however, if the basic amplifier is provided with some inherent feedback. The circuit of Fig. 3 is illustrative of one of the many successful approaches. The two-stage circuit provides a loop voltage gain of approximately 20 for the negative impedance circuit. Rated output power was achieved with less than ¼ per cent distortion at 40 cps in a model employing this circuit. This performance has been achieved through the use of positive feedback around the low-level stage which raises the gain of the main feedback loop to essentially infinity. The feedback factor of 1/20 is slightly more than sufficient to reduce the gain of the circuit to its initial value under loaded conditions. The distortion of the low-level stage is thus reduced slightly and the distortion and output impedance of the final stage are reduced essentially to zero.[5]

Voice-Coil Inductance

A factor requiring especial attention is the nature of the loudspeaker's blocked voice-coil inductance. This inductance is far from ideal in nature, being influenced by assorted hysteresis and eddy-current losses associated with the mass of iron structure surrounding it. Accurate cancellation of an impure inductance such as this may involve considerable complication of the bridge circuit. And, since the actual motion of the voice-coil has little precise bearing upon the radiation of higher frequencies, accurate cancellation of the voice-coil inductance is of doubtful value. However, neutralization of a large percentage of the voice-coil resistance alone raises the Q of the voice-coil inductance and this is almost certain

[5] J. M. Miller, Jr., "Combining positive and negative feedback," *Electronics*, vol. 23, pp. 106–109; March, 1950.

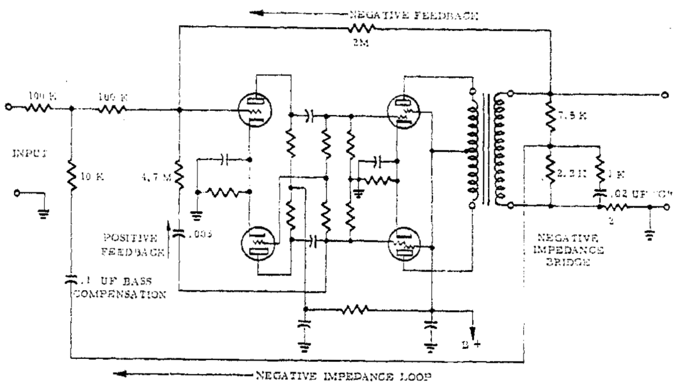


Fig. 3—Practical negative output impedance amplifier.

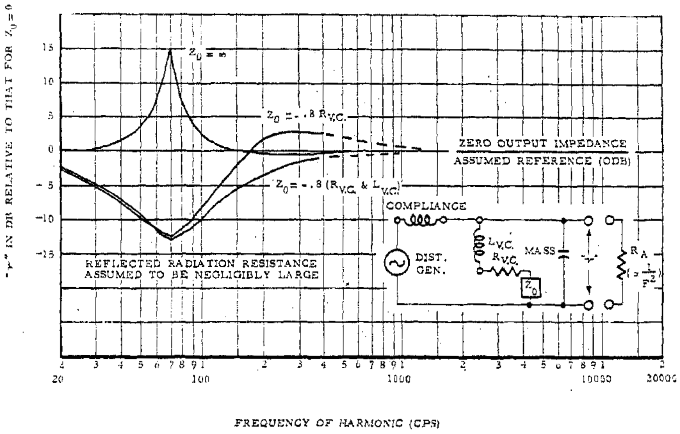


Fig. 4—Effect of output impedance on distortion of cone velocity relative to distortion for zero output impedance.

to result in disappointing performance. The new "High Q" voice-coil inductance in parallel with the reflected motional stiffness resonates with the reflected mass of the moving system accentuating the response and transient distortion in the mid-low-frequency range. At higher frequencies the response will be weakened as is expected from a look at the equivalent circuit (Fig. 1). Some negative output *resistance* circuits bypass the feedback at middle and high frequencies to compensate for this loss, but the resonance remains as evidenced by a more or less sharp knee which incidentally makes equalization for the reduced bass response difficult. Although the effects on response may be more noticeable, the lack of inductive cancellation can result in significantly increased nonlinear distortion. Redrawing the equivalent circuit of a loudspeaker to show the effect of the amplifier output impedance upon the distortion yields the circuit of Fig. 4. The distortion components produced in the nonlinear stiffness pass through a low-pass filter before appearing across the radiation resistance of the loudspeaker. With the resistance in the circuit reduced, the filter accentuates the harmonics appearing in the vicinity of the cross-over frequency. The curves of Fig. 4 illustrate the effect of output impedance upon the magnitude of the distortion components as compared to the reference condition of zero output impedance. The hypothetical speaker illustrated is typical of full range speakers. An efficient low-frequency "woofer" having a heavier moving system and more inductive voice-coil will exhibit this effect to a more pronounced degree and at a considerably lower frequency. It is then possible that a tone as low as 20 cps may show increasing distortion as the source *resistance* is lowered from a high positive value through zero into negative values. Such a speaker can be expected to benefit more from the use of a negative *inductance* source than from the occasionally specified positive *resistance* source.

Sufficient inductive neutralization is produced in the circuit of Fig. 3 to provide reduced distortion at all frequencies and some treble boost is incorporated to maintain the high-frequency response of the speaker within one db of the constant voltage reference. The treble boost is inherent in the bridge circuit employed in Fig. 3 because the capacitor, C, reduces the amount of open circuit feedback at high frequencies resulting in an open circuit response which rises at high frequencies. In practical applications, the amount of negative inductance and treble boost can be chosen to correct for certain general trends in the high-frequency characteristics of the loudspeaker. In applications involving coaxial or "woofer-tweeter" speakers, neutralization of the combined voice-coil impedance can be very complicated. A convenient remedy in the case of simple capacitor coupled tweeters, however, is to neutralize for the low frequency speaker and connect the tweeter through its capacitor directly to the output transformer—avoiding the series current feedback resistor. More complicated multi-speaker systems may require individual amplifiers for each speaker.

Bass Equalization

If neutralization of the voice-coil impedance is sufficient to reduce the Q of the fundamental resonance to less than unity, some bass boosting will generally be desired. Optimum flatness of response is obtained when a 6 db per octave bass boost is employed in the region where the motion is resistance controlled and 12 db per octave for the lower frequencies where the cone resumes stiffness control. Usually the additional boosting in the stiffness control region is unnecessary with the available program quality and places a needless strain on the amplifier's output power at rumble and "compressor-thump" frequencies. Often it will be desirable to limit the amount of the 6 db per octave boost to prevent the amplifier from assuming too heavy a low-frequency burden. If the damping is beyond critical ($Q<0.5$) the turnover of the usual bass boost circuit will complement the speaker response nicely. All of this assumes that the radiation impedance of the loudspeaker is as predicted for infinite baffle, free field conditions. The use of the loudspeaker in a living room may considerably modify its radiation impedance at low frequencies as well as the propagation of its sound. These effects are usually beyond the control of the equipment manufacturer[6] and compensation for them is best left for the listener to attempt with tone controls and selection of speaker location. Presuming for the moment that perfect low-frequency response is obtainable directly from the loudspeaker by application of these principles, it follows logically that additional modification of the response by enclosures which allow radiation from the rear of the cone must necessarily result in a less perfect response. It is, however, conceivable that reflexing an enclosure at a very low frequency can further improve the performance of a modestly designed negative impedance system.

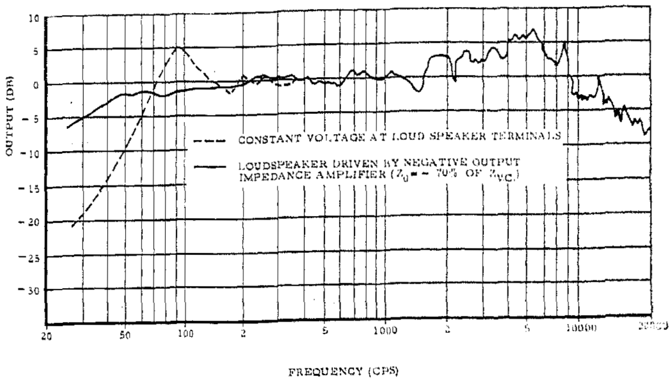


Fig. 5—Response-frequency characteristics on ℄ of RCA SL-12 loudspeaker in 3-cubic-foot box.

In the circuit of Fig. 3, the bass compensation for rising reflected radiation resistance is accomplished in the negative impedance loop, but the circuit parameters are chosen so that there is negligible effect on the efficiency of the negative impedance circuit. The bass boost is effected by frequency-variant loading of the input circuit to the main amplifier.

Performance

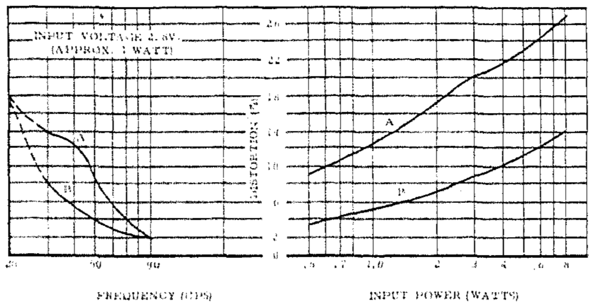
Loudspeaker in a Large Box

The loudspeaker chosen for these tests is a high quality 12-inch single-cone unit mounted in a totally enclosed 3-cu-foot box. Resonant frequency in the box is 89 cps.

Frequency Response: The response-frequency characteristic of this loudspeaker is shown in Fig. 5. The negative impedance amplifier is seen to level and extend the low-frequency response.

Distortion: The loudspeaker distortion was measured with a ribbon microphone of essentially flat response above 40 cps and a total rms distortion meter. The microphone's sensitivity was low at frequencies below about 30 cps resulting in an apparent noise level comparable to the distortion. Therefore, the distortion measurements below 30 cps are approximate. The distortion characteristics of the loudspeaker are shown in Figs. 6

[6] A different form of feedback loudspeaker in which the feedback voltage is derived from the acoustic output (by a microphone) rather than from the voice-coil motion can minimize the effects of variations in radiation impedance upon the radiated power.



(a) (b)

Fig. 6—Total harmonic distortion of RCA SL-12 loudspeaker in 3-cubic-foot box vs (a) frequency at 1 watt, and (b) input power at 40 cps. A = loudspeaker alone, B = loudspeaker driven by negative output impedance amplifier ($Z_0 = -70$ per cent of Z_{VC}).

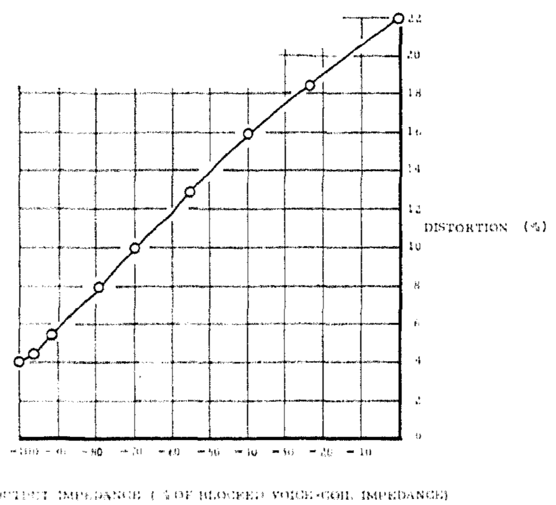
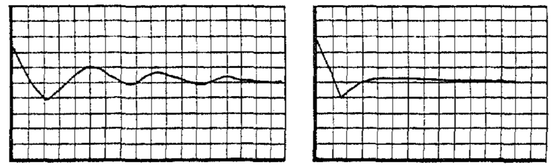


Fig. 7—Total harmonic distortion of RCA SL-12 loudspeaker in 3-cubic-foot box at 4 watts of 40 cps input vs amplifier output impedance.

and 7. In Fig. 6, the distortion is plotted vs frequency at 1 watt and vs power at 40 cps. Measurements were not recorded for powers above 8 watts because the loudspeaker began "ticking" the limits of its maximum excursion. Above 8 watts at 40 cps, the measured distortion did not nearly indicate the increase in listener annoyance due to the "ticking." Driving the loudspeaker with a negative impedance amplifier results in a substantial reduction in low-frequency distortion.

Another possible source of distortion in a loudspeaker is the nonlinearity of the flux density in the voice-coil gap. If distortion due to this cause were of important magnitude, there might be a limit upon the amount of desirable impedance cancellation. Fig. 7, however, shows that the loudspeaker distortion continues to decrease as the cancellation is increased to 100 per cent. The percentage cancellation indicated is true only for the resistive component of the voice-coil impedance. The inductance was somewhat less effectively cancelled. The values of cancellation above 80 per cent were accomplished in this amplifier by unbalancing the negative impedance bridge, under which condition the amplifier



(a) (b)

Fig. 8—Response to step function input, RCA SL-12 loudspeaker in 3-cubic-foot box. (a) Loudspeaker terminals shorted. (b) Loudspeaker connected to negative output impedance amplifier ($Z_0 = -70$ per cent of Z_{VC}).

experienced a net positive feedback from the bridge. Therefore, Fig. 7 illustrates, in part, the excellent immunity of the circuit to critical adjustment.

Transient Response: The response of the loudspeaker to a step-function signal is shown in Fig. 8. To obtain these patterns a dry cell was connected directly to the loudspeaker in one case and in series with the amplifier output terminals in the other case. The battery was shorted to obtain the step function input. The radiated sound was detected by a condenser microphone, amplified, and fed to a long-persistence screen oscilloscope. No attempt was made to correct for the effects of successive differentiation by the uncompensated radiation impedance of the loudspeaker, microphone, amplifier, and oscilloscope responses; or for possible room reflections.[7] Ringing is evident at the resonant frequency for the shorted voice-coil condition but not for the negative impedance condition. Adjusting the amplifier output impedance showed aperiodic damping to occur at about 54 per cent cancellation of the blocked voice-coil impedance.

Loudspeaker in a Small Box

Another loudspeaker of the same type was mounted in a totally enclosed box of $\frac{1}{2}$ cubic foot. The resonance of the speaker in this box, which was just large enough to hold the loudspeaker, occurred at 200 cps. The negative impedance amplifier used to obtain the following frequency and transient responses was an inexpensive 10-watt unit possessing no feedback other than that due to the negative impedance loop. The amplifier is typical of the type used in home and automobile radios. The net negative feedback due to the negative impedance loop is about 6 db at midaudio frequencies; and the distortion at 100 cps is about 2 per cent at 5 watts. This distortion is of the same order of magnitude as that due to the loudspeaker. For this reason, the distortion measurements for the loudspeaker in the small box were made using the previous amplifier (similar to Fig. 3).

Frequency Response: The response-frequency characteristics of the loudspeaker mounted in the small box are shown in Fig. 9. The improvement obtained with the negative impedance source is more pronounced fo

[7] Measurements of the actual cone motion indicate a nearly per fect square wave response of a loudspeaker driven by a negative output impedance amplifier. (R. E. Werner, "Loudspeaker performance as affected by a negative output impedance amplifier," unpublished

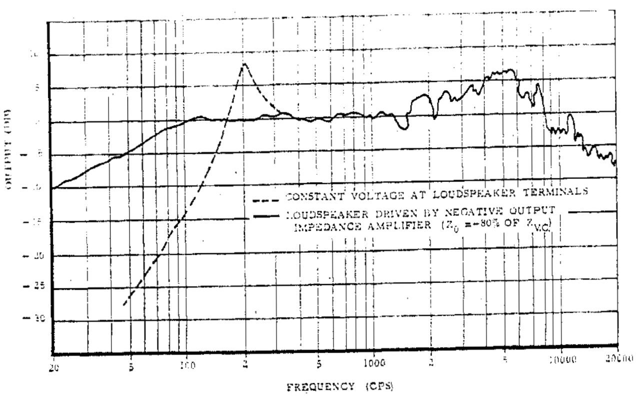


Fig. 9—Response-frequency characteristic on ℄, RCA SL-12 loudspeaker, ½-cubic-foot box.
--- = loudspeaker alone
— = loudspeaker driven by negative output impedance amplifier ($Z_0 = -70$ per cent of Z_{VC})
0 = 66 cps
x = 100 cps.

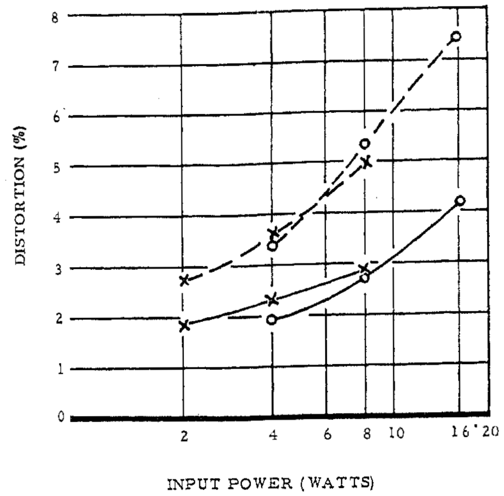


Fig. 10—Total harmonic distortion RCA SL-12 loudspeaker, ½-cubic-foot box.

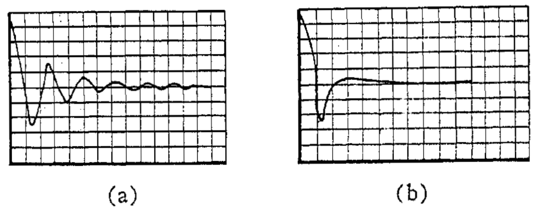


Fig. 11—Response to step function input RCA SL-12 loudspeaker in ½-cubic-foot box. (a) Loudspeaker terminals shorted. (b) Loudspeaker connected to negative output impedance amplifier ($Z_0 = -84$ per cent of Z_{VC}).

the small box than for the larger box as one may have anticipated. It is unlikely that any form of acoustical treatment of a ½-cubic-foot box could produce such a response from a 12-inch loudspeaker.

Distortion: The distortion characteristics of the loudspeaker in the small box are shown in Fig. 10. The distortion produced by the loudspeaker is again materially reduced by the use of a negative output impedance amplifier.

Transient Response: The response of this system to a step-function input signal is shown in Fig. 11 and is similar to that measured for the loudspeaker in the larger box. In this case, however, the Q of the resonance is higher and aperiodic damping is achieved at about 73 per cent cancellation of the blocked voice-coil impedance.

Subjective Tests

Subjective tests are a necessary assessment of value in a consumer product, particularly an acoustical product. In order to subjectively evaluate the performance of a sound system affecting only the lower frequencies, it is necessary to precondition inexperienced observers so that their attention will be adequately focused on the generally unobserved low-frequency accompaniment. This assumes, of course, that music is chosen for the program material. The use of selected noises and sound effects may be more effective; but the end use is with voice and music and the system must be so evaluated. About the two systems herein presented: it is difficult to find an adequate music recording to evaluate the performance of the loudspeaker in the 3-cubic-foot box with an inexperienced audience, but equally difficult to find unsuitable program material for evaluating the performance of the loudspeaker in the ½-cubic-foot box.

The system was demonstrated before the Delaware Chapter of the Acoustical Society of America on June 7, 1956. A number of loudspeakers were employed including a 4-inch "Drive-In Theater" loudspeaker in its normal enclosure and a 15-inch "Woofer-tweeter" loudspeaker in a 3-cubic-foot box. In all instances, an improvement over the normal system was noticed by all members present at the meeting. The effect was most startling in the case of the "Drive-In Theater" loudspeaker, as would be expected. The 15-inch loudspeaker was made utterly flat to below 20 cps by its negative impedance amplifier and is an excellent example of a situation in which a reflex or horn type of enclosure would be undesirable.

The power-handling capability of a sound system is one characteristic which demands subjective listening tests. Because the use of a negative impedance amplifier in no way modifies the efficiency of the loudspeaker, no additional power is required in the spectrum above the loudspeaker resonance. The amplifier is required to deliver additional power below the resonance determined by the amount of equalization desired. Subjective tests reveal that a 10-watt amplifier is more than adequate for home use even with the 12-inch loudspeaker mounted in the ½-cubic-foot box. Musical program material appears to have a power-frequency distribution such that the 10-watt amplifier overloads at the same volume whether wired normally or with a negative output impedance equalizing to 80 cps.

Over 8 years of subjective evaluation have convinced the author that the low-frequency performance of a loudspeaker can be made superior to that of the majority of available program sources.

Conclusions

The results of the foregoing measurements encourage the following conclusions:

1) The use of a properly designed negative-output impedance amplifier will greatly extend the low-frequency response, reduce the nonlinear distortion, and eliminate the resonant frequency hangover of a direct-radiator moving-coil loudspeaker.

2) The improvement in frequency and transient response obtained with this system is most dramatic when the loudspeaker is mounted in a small box wherein the resonant frequency will be higher in the music spectrum.

3) The music power-frequency spectrum is such that no increase in amplifier power capability will be required in using this system for most applications.

4) The improvement in loudspeaker performance obtainable with this system allows the use of less expensive loudspeakers and smaller speaker enclosures in high-quality sound systems.

5) Because of the poor quality of loudspeakers in comparison with present-day amplifiers, the use of a negative impedance circuit can provide improved performance even with a reduction in quality (and cost) of the amplifier.

6) The use of negative output *resistance* amplifiers with loudspeakers is to be avoided unless very careful analysis indicates that the results will be as desired.

7) Claims regarding the performance of a loudspeaker with a resistive source impedance should not be carelessly extrapolated to the conditions of reactive source impedances, in particular negative impedances.

8) A loudspeaker driven by a negative output impedance amplifier should always be mounted in a totally enclosed box unless careful attention reveals that a different type of enclosure will augment rather than detract from the performance.

Correspondence

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A Compatible Method of Recording and Reproduction of Stereo Sound*

There is currently much interest among audiophiles concerning the introduction of stereodisks. Reports from various audio shows indicate that the 45 degree–45 degree orthogonal groove system is quite acceptable. At least one other method of recording two audio channels on disks has been described, namely that of recording the second channel as a high-frequency FM signal superimposed on a normal audio channel.

One of the shortcomings of the orthogonal groove method is that it is not compatible with existing monaural records and audio systems since a special stylus is required. This difficulty is overcome with the FM method with the addition of rather complicated and critical equipment. The following describes another method of recording stereophonic sound which largely eliminates the above mentioned difficulties.

More than one audio channel can be recorded on a single information channel by simply heterodyning the additional audio channels into frequency bands above the normal audio spectrum but still within the range of existing recording and reproducing equipment. The audio channels thus combined are recorded and then reproduced by separating and demodulating the heterodyned channels. Drift-free operation of the additional channels is possible by also recording the heterodyning local oscillator frequencies and using these same frequencies for local oscillator signals in the demodulating process. Such a method is compatible with existing monaural records.

This system is in the process of evaluation by an independent group of engineers. Tests are not yet complete. However this subject is timely and it seems advisable to present a detailed description of operation at this time.

Fig. 1 shows a block diagram of the recording system for a two-channel stereo program. Channel 1 is a normal audio frequency spectrum, as is channel 2. The local oscillator frequency fo is slightly greater than the highest frequency in either channel 1 or channel 2. The resultant sum frequencies are selected by a high-pass filter and combined with the audio of channel 1 and the local oscillator fo in an adding circuit. Thus at the input of the recorder a signal consisting of audio channel 1, $f'1$ to $f'2$, the local oscillator frequency fo, and the sum signal obtained by heterodyning the local oscillator and the audio of channel 2, $fo+f1$ to $fo+f2$ is presented to the recording device, either a tape recorder or disk cutter.

* Received by the PGA, August 4, 1958.