Variable Damping Factor Control

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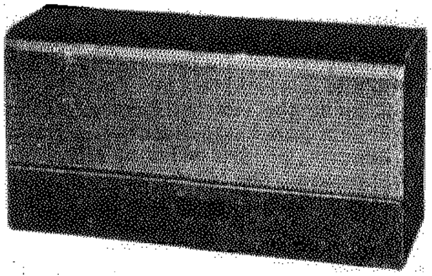
The virtues of a high damping factor in an amplifier have been the subject of unending discussion. *The circuit presented here enables the user to determine for himself the damping factor which will result in optimum reproduction through his own speaker system.*

ENTHUSIASTS OF HIGH-QUALITY reproproduction seem to hold either of two widely divergent opinions on the desirability of high damping for loudspeaker loads. Those in favor claim that a high damping factor (low amplifier output impedance) increases the magnetic damping of the motion of the voice coil thereby reducing spurious excursions caused by mechanical and acoustical resonances and improving the transient response, while those against claim that a high damping factor degrades either the high- or low-frequency *response (or both) of the speaker* thereby degrading the transient response.

Let us examine these claims by referring to the equivalent circuit of an enclosed-cabinet single-cone loudspeaker shown in *Fig.* 1. Constant-voltage generators are shown in the electrical equivalent circuits at (a) and (c), and a constant-force generator in the mechanical equivalent circuit at (b). Equation (*4*) represents the total resistance R_D acting in series with the reactive components of motional impedance Z_M to produce damping. Any increase in the value of R_D will increase the damping on motion of the speaker cone. Inspection of both Eq. (*4*) and (b) of *Fig.* 1 shows that an increase in radiation resistance R_A, *mechanical resistance* R_S, or gap flux density B will increase the damping. Conversely, a decrease in amplifier source resistance R_G or d.c. voice-coil resistance R_C will increase the damping. Horn loading will increase R_A. R_S is designed into the speaker and inspection of Eq. (*5*) shows that as R_S is increased the efficiency μ of the speaker decreases. This makes it desirable to have R_S as small as possible in relation to R_A if damping can be obtained from another source. B can be increased by using a larger more expensive magnet than is obtainable in speakers of moderate cost. The winding length l can be increased by using more turns of wire on the voice coil, but since there is only a *limited amount of space in the voice*-coil gap and resorting to smaller diameter wire will increase R_C, there is an optimum wire size and winding length beyond which little improvement can be gained. R_G can be decreased by decreasing the amplifier source resistance, and as far as damping is concerned, a decrease in R_G is *exactly* equivalent to increasing the gap flux density B.



The Bogen DO30A, which incorporates the damping factor control described in this article.

The damping factor of an amplifier is defined as

$$DF = \frac{Z_L}{R_G} \qquad (6)$$

where Z_L is the impedance of the amplifier load, and R_G is the amplifier source resistance. If the load is a speaker system $Z_L = Z_C + Z_M$ at high frequencies and $Z_L = R_C + Z_M$ at low frequencies. It is seen that DF increases as R_G decreases, and when R_G equals zero DF equals infinity. If R_G should be made a negative value, DF would also become negative.

Optimum Damping

It has been shown that a high DF is equivalent to higher magnetic damping of motional impedance Z_M and that given a DF sufficiently high the damping of Z_M may be made equivalent to *perfect* horn loading. The question that remains is how much damping can we use profitably? The ultimate limit is imposed by the occurrence of oscillation in the LCR circuit comprising Z_M. If R_D is made infinite, Z_M will become critically oscillatory. This condition can be produced by making R_G equal to $-R_C$ and corresponds to an amplifier DF of -1. This is the same as saying that R_C is exactly cancelled out by a negative R_G.

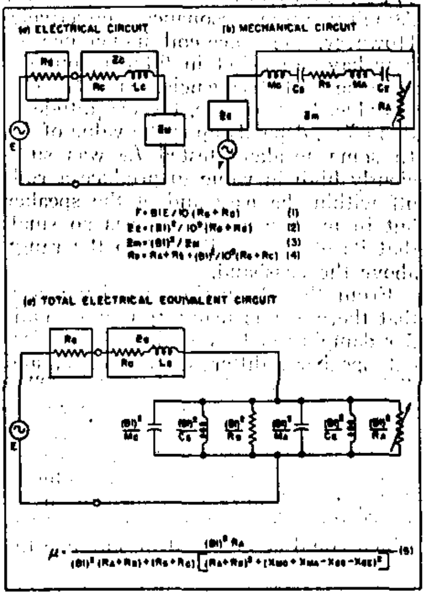


Fig. 1. Electrical and mechanical equivalent circuits of loudspeaker driven by amplifier.

Another limit we can observe, if all that interests us is damping of cone or enclosure transients at resonance, is the reduction of the Q of Z_M at resonance. When the Q of a resonant circuit is made equal to 1, the frequency response is flat throughout the range of resonance but there is some transient overshoot. If the Q is made equal to 0.5, the circuit is said to be *critically damped* and there is no transient overshoot but the frequency response begins to droop below the range of resonance. This effect is shown in *Fig.* 2. The droop below resonance is explained by considering (b) of *Fig.* 1. The R_A of the speaker diaphragm (or apparent diaphragm at the horn mouth if the speaker is horn loaded) begins to decrease as the square of the wavelength below the critical wavelength (the wavelength that is equal to the circumference of the diaphragm). This effect alone will produce a 12 db/octave droop in sound output below the critical wavelength. The reactance of C_B, the compliance of the air in the enclosure, and C_S, the compliance of the cone suspension, become increasingly large below the fundamental resonant frequency and account for an additional 6 db/octave droop below resonance. (M_C is the mass of the cone and M_A is the mass of the air.) The Q of the resonant circuit can be decreased by increasing the value of either R_A or Z_E. An increase in R_A can be produced by horn loading and will result in a higher critical wavelength. On the other hand, an increase in Z_E will not alter the critical wavelength but will have the same effect on damping as horn loading. So we see that in a speaker system that has its critical wavelength at a higher frequency than its fundamental resonant frequency, the effect of resonance may be used to reinforce the response between these two critical frequencies. By making the Q equal to 1, we will

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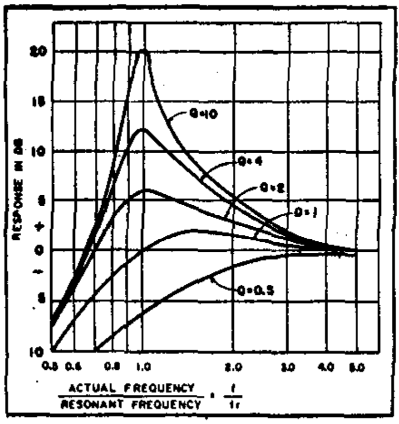


Fig. 2. Relative response of loudspeaker for different values of G.

achieve optimum flatness in the frequency response. The Q of the mechanical equivalent circuit of (b) in *Fig.* 1 may be expressed as

$$Q = \frac{X_M}{Z_E + R_A + R_S} \qquad (7a)$$

where X_M represents the total inductive reactance of $(M_A + M_D)$. In the total electrical equivalent circuit of (c) in *Fig.* 1, the equivalent expression for the Q is

$$Q = \frac{\frac{(Bl)^2}{X_M}}{R_G + R_C + \frac{R_A}{(Bl)^2} + \frac{R_S}{(Bl)^2}} \qquad (7b)$$

If we have an *ideal* exponential horn of infinite length, infinite mouth area, and zero rate of flare, we can expect R_A to be infinite throughout the frequency range, making the critical wavelength infinite (zero cps). The effect of C_E and C_S will be eliminated, the Q at resonance will be reduced to zero, and the damping will be perfect. But since such an ideal condition is impossible, let us examine what will happen on the other hand if we take a less than perfect system (with or without horn loading), and make Z_E infinite by employing a *DF* of −1. The effect of C_E and C_S will be eliminated, the Q at resonance will be reduced to zero, the damping will be perfect, but the critical wavelength will remain unchanged. At frequencies below the critical wavelength, the response will droop at a rate of 12 db/octave. The critical wavelength can be made to occur at a sufficiently low frequency either by employing a speaker with an adequate diaphragm area, or by employing a horn with an adequate mouth area. For such a large area as would be needed, say, for a 30- to 50-cps cutoff, the horn offers the better solution—and the effect of infinite Z_E would be a great advantage in damping the violent resonances that occur in a less-than-perfect horn. There is, however, another mode of attacking the problem. The 12-db/octave droop could be equalized electrically if the critical wavelength occurs at too high a frequency. If we can reduce the distortion attendant with the degree of equalization that would be required to restore the low frequencies, this method would be a legitimate mode of attack. It will be shown later that a *DF* of −1 will result in a drastic reduction of all types of distortion in the speaker system.

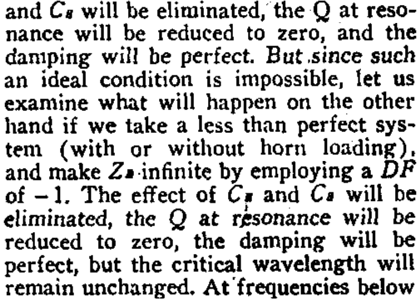


Fig. 5. Equivalent circuit of amplifier with positive current feedback driving loudspeaker load (for purpose of distortion analysis).

High-Frequency Damping

The foregoing analysis, while based on the low-frequency range, is valid for the complete speaker range, providing allowances are made for the voice coil inductance L_C and for the coefficient of coupling between the voice coil and the resonances due to cone break-up. Generally speaking, the coupling between break-up resonances and voice coil is small, thereby minimizing the benefits *deriving from a high DF. Horn loading* of the cone for high frequencies appears to be the only means at our disposal for damping these resonances effectively. However, the voice-coil inductance L_C *may* have an effect in filtering out the *extreme high frequencies* as $(R_G + R_C)$ is reduced. Of course, the magnitude of this effect depends upon the value of L_C. In some speakers tested L_C was sufficiently high in value to produce a roll-off within the passband of the speaker but in most speakers L_C was so small *that its effect was limited to the range* above the passband.

From this discussion, we have seen that there are as many optimum amplifier damping factors as there are different speakers, different enclosures, and different *combinations of the two.* This is a *fact*, regardless whether optimum *DF* is defined as that required to reduce the Q of the system to 1, or to 0.5, or that required to cancel out R_C. It follows that it would be of great benefit to incorporate a control into an amplifier which could be adjusted to optimize the *DF* for each individual speaker system. Such a *Variable Damping Factor* control has been incorporated into Bogen Models DB20-DF and DO30A. The bare bones of the circuit are shown in *Fig.* 3.

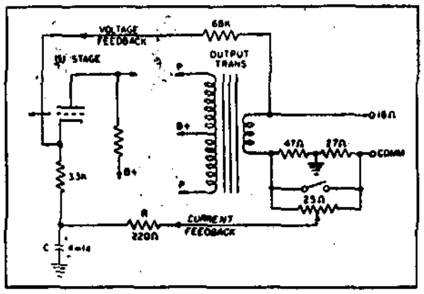


Fig. 3. Simplified schematic of the Bogen Variable Damping Factor circuit.

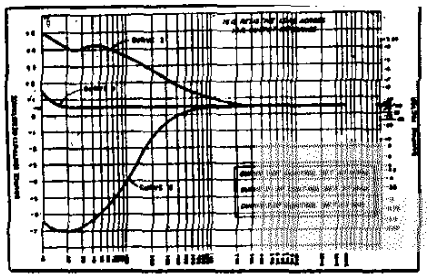


Fig. 4. Variation of amplifier source resistance permitted by DF control when using a resistive load.

Circuit Description

The circuit employs a simple bridge circuit inserted into the common side of the output transformer secondary. A voltage is developed across the 0.47-ohm and the 0.27-ohm resistors that is proportional to the current flowing through the speaker load. This current-proportional voltage is sampled by the slider on the 25-ohm potentiometer and fed back through low-pass filter RC as current feedback to the cathode of the first stage where it is added with the over-all negative voltage feedback. At a certain position of the potentiometer slider, there will be no voltage developed between slider and ground and, therefore, no current feedback. On either side of this position the slider will sample either a positive or a negative current-proportional voltage depending whether the slider is moved toward the 0.47-ohm or the 0.27-ohm resistor, respectively. By this means the effective source resistance of the amplifier may be varied between wide limits in the positive (negative current feedback) as well as the negative (positive current feedback) direction. *Figure* 4 shows the range of variation plotted for both source resistance and *DF*. Inasmuch as these curves were taken for the purpose of calibrating the *DF* control, a 16-ohm resistive load was used across the 16-ohm secondary. With a speaker load, the range of variation will be a function of the R_C and Z_E of the speaker. For a speaker with a rated impedance of 16 ohms, the R_C will be much less than 16 ohms and the Z_E

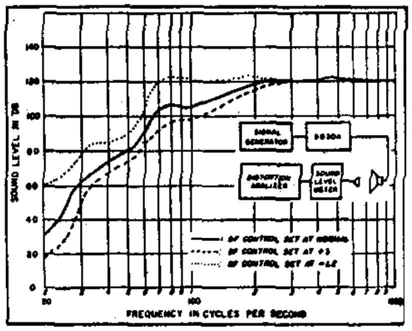
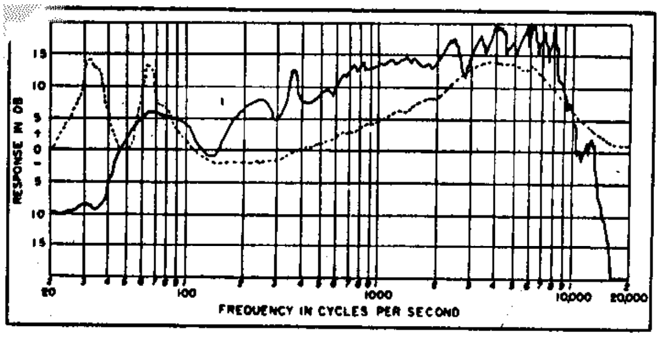


Fig. 6. Curves showing the effect of amplifier DF on distortion generated by loudspeaker system. 5% harmonic distortion contours are shown. (NORM. DF is equal to +30.)



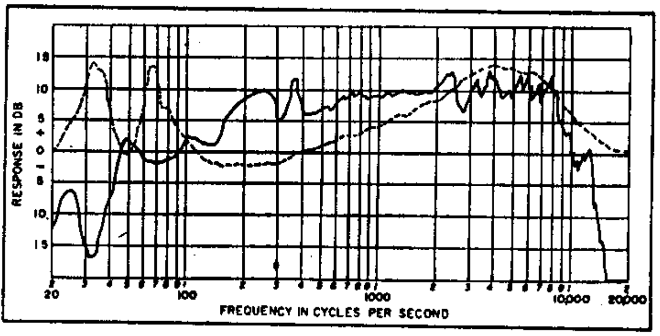


Fig. 8. (left). Sound pressure response of 15-in. coaxial speaker mounted in 8 cu. ft. bass-reflex enclosure with amplifier DF set at +3. Dotted line represents impedance of speaker. Fig. 9 (right). Sound pressure response of speaker of Fig. 8 with amplifier DF set at −1.2.

will be a function of frequency. So we can state that with a speaker load the action of the *DF* circuit is two-fold. With the *DF* control set to introduce negative current feedback, the source resistance is *greater* than the basic R_a of the amplifier (R_a with no current feedback) and the voice-coil drive voltage is *directly* proportional to the speaker system impedance. With the *DF* control set to introduce positive current feedback, the source resistance is *less* than the basic R_a of the amplifier and the voice-coil drive-voltage is *inversely* proportional to the speaker system impedance. The matter of degree depends on the *DF* control setting.

The RC filter limits the effect of the control to frequencies below 300 cps—(1), to avoid the possibility of the speaker oscillating at its frequency of minimum impedance (usually between 200 and 400 cps); (2), to restrict the damping to the low-frequency range where it is most needed and most effective; and (3), to avoid the possibility of the tweeter oscillating at its resonant frequency (if a tweeter is used).

The type of curves shown in *Fig.* 4 were found desirable to compensate for both the rise in low-frequency sound output produced with low damping and the roll-off produced with high damping by changing the *apparent* efficiency μ of the speaker system. This can be seen clearly by inspecting Eq. (*5*) in *Fig.* 1. If the term $(R_a + R_c)$ increases in value, the efficiency is reduced. Conversely, if $(R_a + R_c)$ decreases, efficiency is increased. However, this change in efficiency is only apparent since it requires that additional power be dissipated in $(R_a + R_c)$ for its accomplishment.

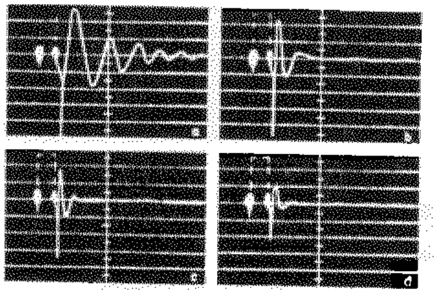


Fig. 7. Sound pressure waveforms showing the effect of amplifier DF on acoustical transient response of loudspeaker system. Solid line shows motion of speaker cone after application of square pulse (dashed line). (a) DF = +0.1, (b) DF = +3, (c) DF = ∞, and (d) DF = −1.2.

Distortion Reduction

One of the most important benefits gained from the use of positive current feedback is the drastic reduction of all types of distortion in the speaker system. *Figure* 5 shows the equivalent circuit of an amplifier driving a speaker load. E_o is the useful voltage developed across the radiation resistance R_A of the speaker system. Any non-linear element that produces distortion and frequency discrimination can be represented as an impedance *Z* in parallel with R_A. The current through R_A and *Z* develops a voltage across R_f. This voltage is added with the input signal voltage e_s as positive current-proportional feedback.

The total current through R_f is the sum of the useful current through R_A and the distortion current through *Z*

$$I = i_i + i_s \qquad (8)$$

The voltage developed across R_A and *Z* is

$$E_o = -A(e_s + IR_f) + IR_a + IR_c + IR_f \qquad (9)$$

which can be arranged as

$$E_o = -Ae_s + I(R_a + R_c) - IR_f(A-1) \qquad (10)$$

To make E_o a faithful replica of e_s we must make

$$E_o = -Ae_s \qquad (11)$$

This can be done by making

$$R_f(A-1) = R_a + R_c \qquad (12)$$

so that these two terms will cancel. The value of R_f required is

$$R_f = \frac{R_a + R_c}{A-1} \qquad (13)$$

and is the value that will produce a *DF* equal to −1 by making R_a sufficiently negative to cancel the effect of R_c and R_f. This also checks the conclusion made earlier that if Z_s were made infinite, the effects of C_s and C_e on the frequency response would be eliminated.

The curves of *Fig.* 6 show actual sound pressure measurements made on a typical 12-inch coaxial speaker housed in a 5 cu. ft. bass-reflex enclosure. The speaker was driven by a Bogen DO30A amplifier which was adjusted to give different damping factors. These curves represent 5 per cent harmonic distortion contours for different values of *DF* and show the effect of *DF* on maximum sound power obtainable at 5 per cent distortion in the low-frequency range. From *Fig.* 6 we see that with a *DF* of −1.2 this speaker can be driven about 30 db harder at 20 cps than is possible

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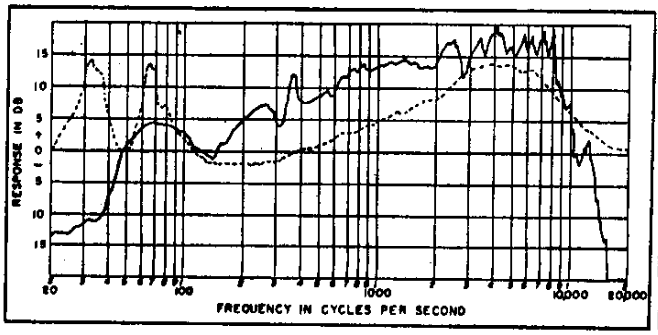

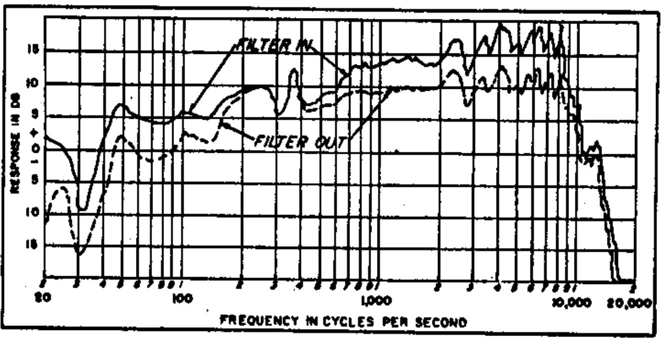

Fig. 10 (left). Sound pressure response of speaker system of Fig. 8 driven by commercial laboratory standard amplifier which has fixed DF of +10. Compare with Fig. 8. Fig. 11 (right). Sound pressure responses of speaker system of Fig. 8 showing effect of 300-cps filter. Dashed curve is same as solid curve of Fig. 9.

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with a fairly average *DF* of +30 *or* about 40 db harder than is possible with a *DF* of +3 (representative of triodes with no negative feedback)—with no increase in distortion! We repeat: this is a typical speaker system, not specially selected. The reduction of distortion below 200 cps is even more drastic for contours of high distortion. The value of 5 per cent was selected as the maximum that can be tolerated in a high-quality system.

Figure 7 shows the *acoustical* transient response of the speaker system to a square pulse (dashed line) for different damping factors. The ringing (hang-over) is at 55 cps. As the *DF* is increased the wave-train decays more rapidly, the amplitude of the ringing decreases, and overshoot decreases.

The effect of *DF* on the sound pressure response of a typical 15-inch coaxial speaker housed in an 8 cu. ft. bass-reflex enclosure is shown in *Figs.* 8, 9, and 10. The response curves were taken with a 10 ft. axial free-space between speaker and microphone at a reference level of 5 watts at 300 cps. The impedance curve of the speaker system is superimposed as a dashed curve on *Figs.* 8, 9, and 10 to visualize the effect of impedance as discussed earlier. It may be seen clearly in *Fig.* 8 that with a low positive *DF*, the response curve follows the impedance curve. *Figure* 9 shows that with a high *DF*, the response curve has an inverse relationship with the impedance curve. *Figure* 10 is included for comparison and shows the response curve of the speaker fed by a commercial laboratory standard amplifier that has a fixed *DF* of +10. Note the similarity between *Fig.* 10 and *Fig.* 8. Incidentally, the harmonic distortion generated at 30 cps by the speaker measured 95 per cent in *Figs.* 8 and 10 and only 20 per cent in *Fig.* 9 for equal sound levels. The curves of *Figs.* 8 and 9 were taken with the 300-cps RC filter out of the circuit. *Figure* 11 shows that the essential effect of the 300-cps filter on sound pressure response is to raise the over-all level and improve sound output below 25 cps.

Summary

In conclusion, let us summarize the benefits of adjusting the *DF* to optimize the performance of *each* speaker system.

1. Improved transient response from damping the low-frequency speaker and enclosure resonances by reducing the Q to 1 or less.
2. Flatter low-frequency response from complete damping of speaker-system resonances.
3. Extended low-frequency response by cancelling the droop caused by C_s and C_s below the fundamental resonance if extremely high *DF* is employed.
4. Drastic reduction of low-frequency distortion caused by any non-linearities in the speaker system if extremely high *DF* is employed.
5. Increased power handling capacity of the speaker system by eliminating low-frequency resonance peaks. The maxim of the chain and its weakest link holds true. If the speaker system has a resonant peak, the system will be over-driven at the frequency of the peak before being over-driven at other frequencies. A reduction or elimination of peaks by adjusting the *DF* to reduce the Q of the fundamental speaker and enclosure resonances to 1 or less will increase the over-all power-handling capacity of the system.

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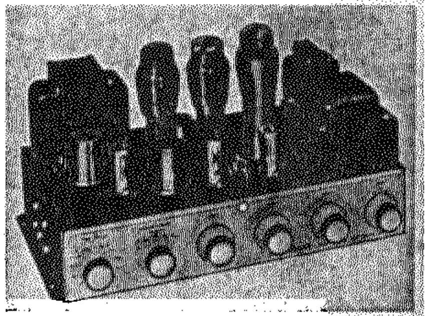

Fig. 12. Bogen DB20DF—A complete self-contained amplifier incorporating damping factor control.