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Missing Link in Speaker Operation

Parts 1 & 2

by D. J. Tomcik—Chief Electronics Engineer, Electro-Voice, Inc.

PART 1

THE AMPLIFIER DAMPING FACTOR AND ITS APPLICATION TO SPEAKER PERFORMANCE

IN AUDIO REPRODUCTION, a subject of considerable importance to the high-fidelity enthusiast is amplifier damping factor and its effects on speaker operation. Misconceptions have arisen concerning this subject, and vague and incomplete answers have too often been given to the many questions involved.

Are the high damping factors found in present high-fidelity amplifiers by-products of high-feedback circuits and, as such, unimportant in the operation of the system? Or is the ultimate, as some loudly proclaim, to have the highest possible damping factor built into the amplifier? Why does a particular speaker sound better with amplifier A than with amplifier B, although both show identical frequency response and power capabilities under bench checks? Why does that $2.00 speaker with the 6-ounce magnet (inefficiency and distortion included) seem in some cases to have more bass than the high-fidelity unit with the 5-pound magnet? Why is it that one enthusiast found reproduction more pleasing when he used a little current feedback from the output circuit yet another didn't when using the same circuitry?

Some simple laboratory experiments and straightforward analysis can answer these questions and clear the air.

SPEAKER MECHANICS

The speaker can be considered, for the moment, a purely mechanical device. As such, the cone with its inherent mass and the cone suspension with its compliance or stiffness make up a resonant system. Some mechanical damping is present but such a slight amount that the system can be considered highly underdamped —if the cone is displaced and then released, it oscillates about its normal resting position for several cycles at its natural resonant frequency. This oscillation decreases in amplitude and finally reaches a state of rest due to the small amount of damping.

If this underdamped speaker is driven by a voltage source having a very high internal impedance so as to maintain the underdamped condition, the cone will vibrate at a greater amplitude at frequencies close to its natural resonance. (This action is similar to pushing a swing or pendulum "in time" with its natural period so as to obtain large amplitudes.) The frequency-response curve of the speaker under these conditions will show a peaked output near cone resonance, usually between 30 and 80Hz. Operation in this manner produces high transient distortion and is undesirable in high-fidelity systems. This can be shown by pressing and then releasing the cone. The oscillation which results is all distortion, since the cone does not follow the applied square waveform of depressing and releasing it.

THE SPEAKER AS A TRANSDUCER

To reduce the transient distortion as well as the peaked bass response, it is necessary only to damp the cone. If the speaker were purely a mechanical device this would be difficult. But since it is an electromechanical transducer, damping is obtained easily. In analyzing the electrical portion of the speaker we find a coil of wire wound around a form and attached to the cone. The coil is placed in a magnetic field and in this way constitutes a simple motor or generator.

If a voltage is applied to the coil, it moves in the magnetic field which in turn moves the cone. If the cone is mechanically moved, the motion of the coil in the magnetic field generates a voltage in the coil. From this it can be seen that cone damping can be obtained by using the magnetic braking action present when the coil terminals are externally closed through a resistance. The motion of the cone in trying to oscillate generates a voltage in the coil. This voltage produces a current flow through the coil and external resistance. The current flow tries to move the cone by motor action, but opposite in direction to the motion producing the current. Therefore the cone is damped in its free motion.

For a given speaker, the amount of damping can be varied by changing the value of the external resistance and consequently the value of the braking current. There is one value of damping at which the cone returns to rest in the quickest possible time without going past the rest position. This condition is called the critically damped state. Transient distortion is greatly reduced and the low-frequency response is more nearly uniform.

Excessive damping returns the cone slowly to its rest position. If the speaker is driven by a voltage source with very low internal resistance, the low-frequency response lacks intensity. (The action now is similar to pushing a pendulum while it is submerged in grease or heavy oil.)

Fig. 1 shows the extent to which a speaker's output is affected by various damping values. Actual speaker performance is shown for overdamped, critically damped and underdamped conditions. To obtain these curves, the amplifier driving the speaker had means for varying its internal resistance. The method for accomplishing this will be discussed later.

SPEAKER-DAMPING VARIABLES

The easiest method for determining these factors as well as their effect on the damping action is to resort again to the magnetic brake. First, we know that the induced voltage in the coil is directly related to the amount of flux cut by the coil. Therefore a larger magnet or smaller gap volume will induce a higher voltage. As a result, a larger external resistance is needed to limit the current so that the desired braking action is retained.

Second, the amount of induced voltage is directly related to the length of conductor cutting the magnetic field. Since both the coil diameter and the number of turns are directly proportional to the length of wire, we may conclude that these factors also enter into the determination of the critical damping resistance (R_{CD}).

Third, the R_{CD} is made up of two components. The d.c. coil resistance as well as the external resistance limits the amount of braking current. So the R_{CD} is the sum of the coil resistance and the external, or amplifier, resistance. Conditions might exist, and they surely do, where the d.c. coil resistance of a given speaker itself is greater than the resistance necessary to critically damp the cone. Nothing can be done externally to remedy this situation short of using a negative resistance amplifier output impedance.

The fourth factor, which is a little more difficult to explain without mathematical illustration, is the effect of the cone mass and suspension stiffness on the value of the R_{CD}. It is logical that to stop a heavier cone from moving in a given time, a greater force in opposition to the motion is required. To increase the opposing force, it is necessary to have a larger braking current, obtainable by lowering the circuit resistance. Also, the stiffer suspension, when displaced, possesses a greater restoring force. The tendency for the cone to overshoot its rest position is increased. Therefore, the damping force necessary to overcome this restoring force must be increased proportionately and can be obtained by again decreasing circuit resistance. It must be remembered that the effective mass and stiffness of a speaker are dependent to some extent on the type of enclosure in which the speaker is housed.

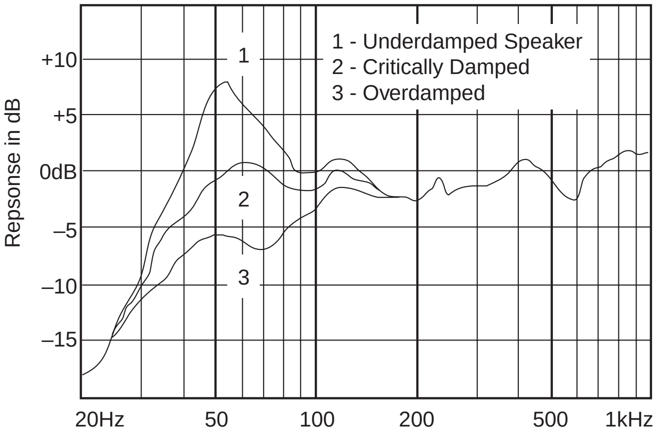


Fig. 1. The effect on frequency response of various values of damping

To summarize, the factors that determine the R_{CD} can be mathematically expressed as follows:

$$R_{CD} = C\frac{(Bl)^2}{\sqrt{kM}}$$

where R_{CD} is the critical damping resistance; B, flux density; l, length of conductor in the magnetic field; k, effective stiffness; M, effective mass, and C is a constant.

This formula is not given to encourage experimental calculations—the test equipment necessary is far beyond the means of the average audio enthusiast. Rather, it is used to indicate the relationship of the various factors in determining the critical damping resistance.

EXPERIMENTAL RESULTS

Figs. 2, 3 and 4 show actual response curves of three speakers for various values of damping resistance. Infinite baffles were used in obtaining all curves. The speaker whose curves are shown in Fig. 2 is an inexpensive unit with a 6.8-ounce magnet and 1-inch coil diameter. By referring to the equation we can expect the R_{CD} to be low because of the low values of B and l. The curves bear this out since both show the speaker in an underdamped condition. The d.c. coil resistance of this speaker is greater than the R_{CD} and, even though the amplifier resistance is 0.5 ohm for the lower curve, the speaker is still underdamped. Fig. 3 shows curves for a high-fidelity 12-inch speaker with a 3-pound magnet and a 2½-inch voice-coil diameter. As expected, the R_{CD} is much higher than in the first case. The overdamped, critically damped and underdamped curves show plainly that the smoothest response occurs when the speaker is critically damped. Fig. 4 indicates that this 15-inch speaker with a 5-pound magnet and large

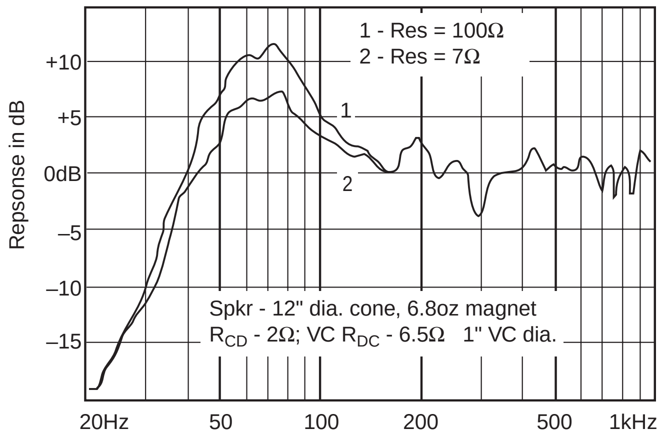


Fig. 2. Frequency response curves for an inexpensive speaker with different values of "damping resistance."

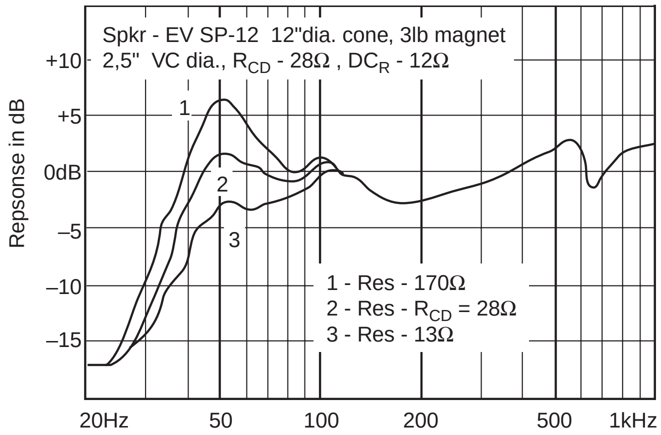


Fig. 3. Frequency response curves for a hi-fi speaker speaker with different values of "damping resistance."

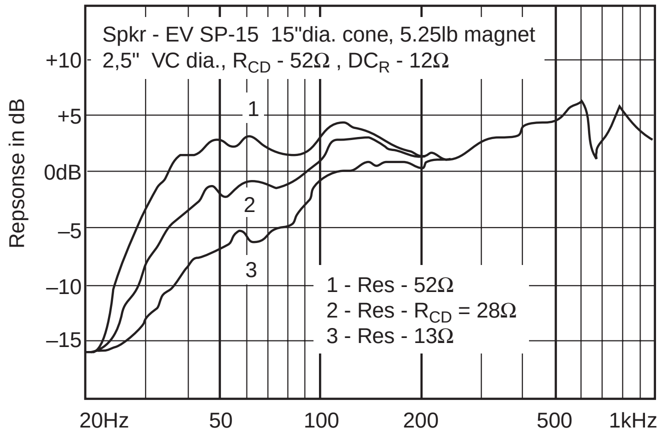


Fig. 4. Frequency response curves for a 15" speaker with different values of "damping resistance."

voice coil has still a higher R_{CD}. The overdamped curve, No. 3, shows what can be expected from the speaker when the amplifier damping factor is 10 or greater, commonly considered to be the criterion of a good high-fidelity amplifier. However, to obtain critical damping with this particular speaker, the amplifier damping factor had to be adjusted to a value of 0.4—an internal resistance of 40 ohms on the 16-ohm tap! The increase in efficiency by operating this speaker critically damped instead of overdamped is 9dB or 8 times the acoustic power output.

CONCLUSION

To return to our questions in the early part of this article, let us now see how many can be answered. High damping factors should not be considered by-products of inverse feedback, but should be controlled. They play a very important part in the reproducing chain. Neither should an amplifier be designed with very high damping factors only. A good high-fidelity amplifier demands that the damping factor be variable within wide limits. It is important not only to present the correct load impedance to the amplifier, but also to present the correct load impedance to the speaker. These two load values are seldom the same. The means of true amplifier-to-speaker matching is obtained with the aid of correct amplifier damping factor selection. The answer to the question of why amplifier A works better than amplifier B with a given speaker is that the damping factor of amplifier A more nearly critically damped the speaker than did amplifier B. During the bench test with resistive loads, the two performed in an identical manner. With the variable load of the speaker, the operation was entirely different. The inexpensive speaker seemed to have more bass than the high-fidelity unit because it was working in an underdamped condition, even with a high amplifier damping factor, whereas the hi-fi speaker was heavily overdamped. And finally, the man who improved his speaker performance with current feedback was merely altering his amplifier damping factor to suit his speaker combination. Your speaker, being entirely different, did not perform with that particular value of damping as it would with critical damping. It's all as simple as that.

From the foregoing we see that speakers vary greatly in their requirements of source impedances to critically damp the cone and achieve optimum speaker performance. It also has been conclusively shown with laboratory curves that best speaker performance occurs with critical damping. No one value of amplifier internal impedance can satisfactorily match all speakers and enclosures. The missing link has been found in critically damping the speaker.

PART 2

OBTAINING VARIABLE DAMPING FACTORS IN AMPLIFIERS; DETERMINING CRITICAL DAMPING FACTORS

PART 1 OF THIS ARTICLE (December, 1954) discussed the effects of various damping factors on the operation of cone type speakers, particularly in the region of cone resonance. It was determined that a given speaker performs best only when critically damped. The matched reproducing system therefore requires the speaker as well as the amplifier be terminated in their proper loads. The amplifier is matched over the greater portion of the frequency spectrum by proper design, so the speaker should be matched to its desired load by proper amplifier design.

As was shown, the proper speaker load for critical damping is the numerical difference between the critical damping resistance (R_{CD}) and the d.c. resistance of the voice coil. This value should be equal to the amplifier internal impedance. Of course, the speaker can be critically damped by using an amplifier of very low internal impedance and putting a fixed resistor in series with the speaker. However, this method results in a power loss in the resistor which may be much greater than that supplied to the speaker. The correct and efficient method of matching is by controlling the amplifier internal impedance, which does not absorb power. (The amplifier nominal impedance should not be confused with the amplifier internal impedance. The nominal impedance, 4, 8 or 16 ohms, is what the amplifier should work into whereas the amplifier internal impedance refers to regulation, as explained later in this article. The two values are seldom the same.)

DAMPING FACTOR

To simplify matters and eliminate the variable of nominal impedance, the term amplifier damping factor is often used. The damping factor is equal to the nominal impedance divided by the internal resistance of the amplifier. For example, an amplifier whose internal resistance on the 16-ohm tap is 8 ohms has a damping factor of 2.

For a given speaker there is one value of internal resistance and consequently one value of damping factor which results in critical damping. This value can be called the critical damping factor (CDF).

Fig. 1. Equivalent output circuit.

Fig. 2. Schematic of the equivalent plate circuit of the output stage.

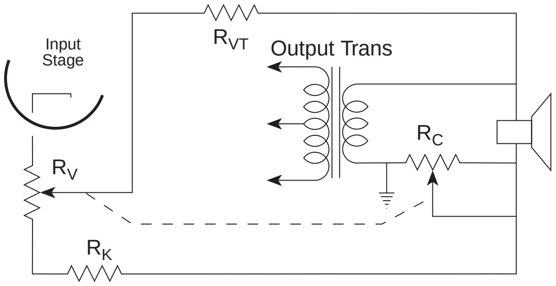


Fig. 3. Circuit using variable feedback.

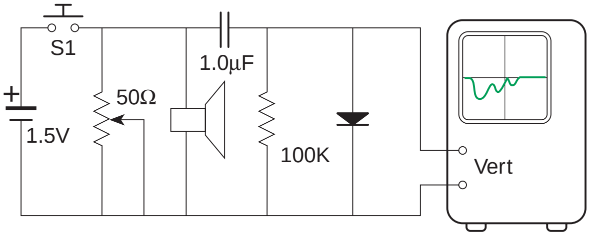


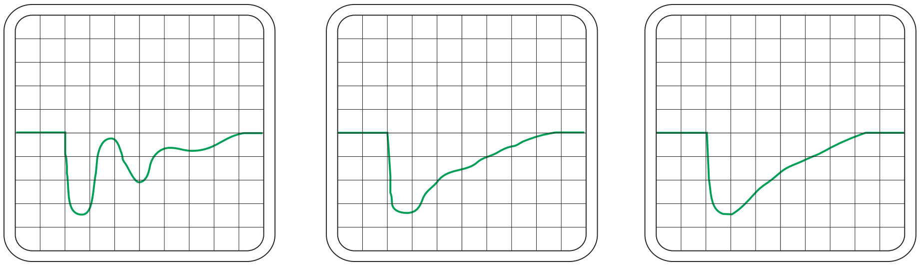
Fig. 4. Circuit for determining CDF.

To visualize the damping factor concept better, consider the amplifier output terminals a voltage source with zero impedance in series with a resistor equal in value to the internal impedance. Fig. 1 shows this arrangement with the proper amplifier load. The amplifier may be push-pull, cathode follower, or any other type, since the equivalent output circuit for all can be considered to be the same as that in Fig. 1. To measure the damping factor of any amplifier it is necessary only to measure the output voltage under no-load and rated-load conditions. The formula for damping factor then becomes:

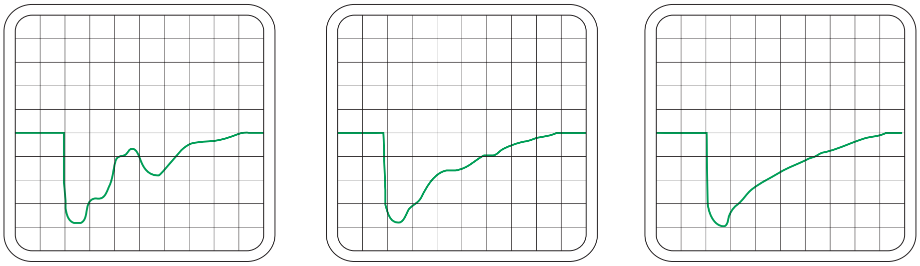
$$DF = \frac{E_{RL}}{E_{NL} - E_{RL}}$$

where E_{RL} = rated-load voltage and E_{NL} = no-load voltage.

From this formula we see that the damping factor is also a measure of the output regulation—how far the output varies from a constant-voltage source with changes in load. Amplifiers with high damping fac-



Drive unit mounted on an infinite baffle



Drive unit mounted in a bass reflex enclosure

Fig. 5. Three time responses for differing values of damping. The upper traces were taken with the drive unit mounted on an "infinite baffle" while the lower ones were taken with the unit mounted in a bass reflex enclosure.

tors act more like constant-voltage sources than those with lower damping factors. Conversely, amplifiers with low damping factors act more like constant-current sources than those with higher damping factors. Hence a means is provided to vary the damping factor simply by controlling the regulation. This is easily done by using feedback in the circuit to obtain more or less constant-voltage or constant-current amplifiers. But, first, what damping factor requirements are necessary in a really good high-fidelity amplifier?

We have seen in Part I that all speakers classed as high-fidelity units require positive values of amplifier resistance for critical damping. Only inefficient speakers in the very low price range require negative resistances. It is possible to obtain negative-resistance characteristics from an amplifier by using positive feedback. But since the speaker that requires this type of damping is mediocre at best, and since positive feedback may result instability and increased distortion, negative-resistance amplifiers are unnecessary in the present state of the reproducing art.

The highest practical damping factor is approximately 10 to 15. Since the d.c. coil resistance of a speaker generally makes up more than 75% of the total nominal impedance, amplifier damping factors greater than 10 or so have no appreciable effect on speaker damping. For example, a 16-ohm speaker with a 12-ohm d.c. coil will have a total series resistance of 13.6 ohms with a damping factor of 10, and a total series resistance of 12.4 ohms with a damping factor of 40. The difference in frequency response is not noticeable to the ear and hardly measurable.

The lowest damping factors found in today's high-fidelity speakers range from around 0.3 or 0.4. A good low limit for amplifier design would be 0.1 or 160 ohms on the 16-ohm tap.

We have now established the limits to be between 0.1 and 15 to cover amply the range in modern-day speakers. The damping control should be calibrated directly in damping factor or internal resistance to simplify adjustment to a given speaker.

OTHER CONSIDERATIONS...

A good high-fidelity amplifier should also have a constant sensitivity with rated load applied, as the damping factor is varied. This results in a constant negative feedback which maintains the distortion and hum figures at constant low levels. In addition, the damping-factor control system should not be frequency-discriminating. Frequency discrimination will affect sensitivity more at some frequencies than at others and produce an undesirable tone-control action in the system.

An effect which might be noticed in a non-frequency-discriminating system is that of high frequency accentuation at low damping-factor values where a single wide-range speaker is used. This high-frequency boost is caused by the speaker inductive reactance becoming appreciable and affecting the gain of the amplifier at high frequencies. The effect is not present in multiple-speaker systems since the reproducing components are designed to present the nominal impedance over their working range of frequencies and are then cut off by the crossover network above their range. However, in a single-speaker system, the several decibels of treble boost are not serious and probably complement the high-end speaker roll-off due to the single-cone operation. In any event, if desired, the treble control can nullify this effect.

AMPLIFIER DESIGN

With the requirements mentioned, we can proceed to design the output circuit of the amplifier, remembering the criterion that negative voltage feedback lowers the internal resistance while negative current feedback raises the resistance. We will probably want to settle on some minimum value of negative feedback to take care of the frequency response, distortion and hum. This usually falls between 15 and 20dB of loop feedback. It may turn out that we will need more than this minimum value, depending on the circuit and particular constants used.

The circuit is first considered without loop feedback so as to determine the starting-point damping factor. The equivalent circuit shown in Fig. 2 applies to all types of circuits as long as rp is considered the effective plate resistance and R_L the load impedance referred to the primary of the output transformer. For example, the damping factor for push-pull 6V6's pentode-connected, with rp = 64,000 ohms and R_L = 8,000 ohms, is:

$$DF = \frac{8,000}{64,000} = .125$$

without loop feedback. To obtain the high damping factor of 10, negative voltage feedback is used around the loop until that value is obtained, say 18dB. Then if 9dB of negative current feedback is added while 9dB of negative voltage feedback is removed, the total negative feedback remains at 18dB; but the damping factor is now 0.125 as with no feedback. However, the sensitivity, frequency response, distortion and hum remain constant. This amplifier covers approximately the desired range of damping factors while the set requirements are maintained. The design procedure is applicable to all types of amplifiers, the only difference being the initial value of damping factor with no loop feedback. The value of r_p will vary greatly with the type of circuit. A cathode-follower output stage results in a very low value of r_p, approximately equal to the reciprocal of the transconductance. Generally, pentodes in push-pull have high values. Triodes fall in between pentodes and cathode-followers. The ultra-linear circuit is a combination midway between pentode and triode operation. The Electro-Voice Wiggin's Circlotron circuit using two 6V6s in a bridge arrangement results in an r_p equal to 2kΩ and an RL equal also to 2kΩ. Under these conditions, no loop feedback or equal voltage and current feedback results in a damping factor of 1. Over-all negative voltage feedback increases the damping factor to values greater than 1, and over-all negative current feedback to values less than 1.

Fig. 3 shows an arrangement in which the current and voltage feedback can be varied in any amount while the total feedback remains a constant. Resistor R_c permits maximum desired current feedback when it is fully in the circuit. The value of R_{vf} is such that the total required voltage feedback is obtained when the slider of R_v is at the cathode position. The ratio of R_v to R_k is chosen so that the voltage feedback is equal in value to the maximum current feedback when the movable arm of R_v is at the R_k end. The two potentiometers are ganged in such a way that an increase in voltage feedback causes a decrease in current feedback.

DETERMINATION OF CDF

With the Fig. 3 circuit arrangement it is possible to obtain various damping factors by the turn of a knob. It is now necessary only to determine the CDF of the speaker to be used and then adjust the amplifier damping factor to that value.

The Electro-Voice line of high-fidelity speakers includes the CDF value in their specifications. For those who would like to determine the CDF of their present speaker system, the equipment needed includes an oscilloscope, a calibrated variable resistance of about 50 ohms maximum, a flashlight battery, a momentary pushbutton switch, a 0.5-μf capacitor, a type 1N34 germanium diode and a 100kΩ resistor. The components are arranged as in Fig. 4. Carefully observe the polarity of the flashlight cell and the 1N34. Mount the speaker under test in its permanent enclosure since the baffle has some influence on the CDF value. The amount of coupling between the speaker cone and enclosure is not very great. The cabinet resonances will not be appreciably affected by changing damping on the speaker, but the enclosure does contribute to the effective mass and stiffness of the speaker, which directly affects the value of CDF.

The circuit of Fig. 4 operates as follows. When the switch is closed, the speaker cone is displaced due to the current flowing through the voice coil. The switch is then opened and the cone returns to the rest position. The voltage it generates in so doing is observed on the oscilloscope. The external resistance shunting the speaker is adjusted so that the scope trace indicates critical damping. This value of resistance is then equal to the necessary amplifier resistance to critically damp the cone. Thus the CDF is determined. The capacitor and 100kΩ resistor act as a filter to stabilize the scope trace when the switch is repeatedly opened and closed. If they weren't included, the trace would bob up and down on the screen, making observation almost impossible.

This effect is due to the slow charge and discharge of the input capacitor of the oscilloscope. The 1N34 diode shorts out the positive voltage surge when the switch is closed so that only the motion of the cone on opening the switch is analyzed on the scope.

In performing the test, start with the variable resistance high so the speaker is underdamped. Decrease resistance slowly until critical damping is obtained. In so doing, the point where the second and succeeding cycles just barely disappear is more easily seen. Approaching critical damping from the overdamped state is more difficult to observe. The switch should be continuously operated several times a second and the horizontal sweep adjusted to a low sweep rate.

The upper curves in Fig. 5 show the traces obtained for a speaker in an infinite baffle for the underdamped and critically damped states. Notice the absence of any second cycle when critically damped. In the lower curves of Fig. 5, the speaker was mounted in a very large bass-reflex box. Notice how the enclosure resonance remains even after the speaker is critically damped. In small bass-reflex enclosures, the resonant frequency of the port is close to the cone resonance and does not show distinctly on the curve. In this case, the patterns appear as in Fig. 5a. The point of critical damping is reached when the second full cycle is just barely eliminated in all cases. The wave form for a slightly overdamped condition looks the same as that for the critical damping, the only difference being an amplitude decrease in the overdamped wave.

CONCLUSION

The CDF of any speaker can now be obtained and the amplifier matched to give optimum performance. Errors of ± 50 % in CDF do not appreciably change the performance of the speaker, so it is unnecessary to determine the needed amplifier resistance down to the last ohm. In fact, the point at which critical damping occurs will be rather broad when the above procedure is followed.

However, great mismatch can result in a very appreciable loss of bass power—as much as eight or nine times. It is therefore worth the time and effort to determine the CDF and match the speaker-amplifier combination. You will have the satisfaction of knowing that the components are performing at their best and in this way providing more listening pleasure.

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