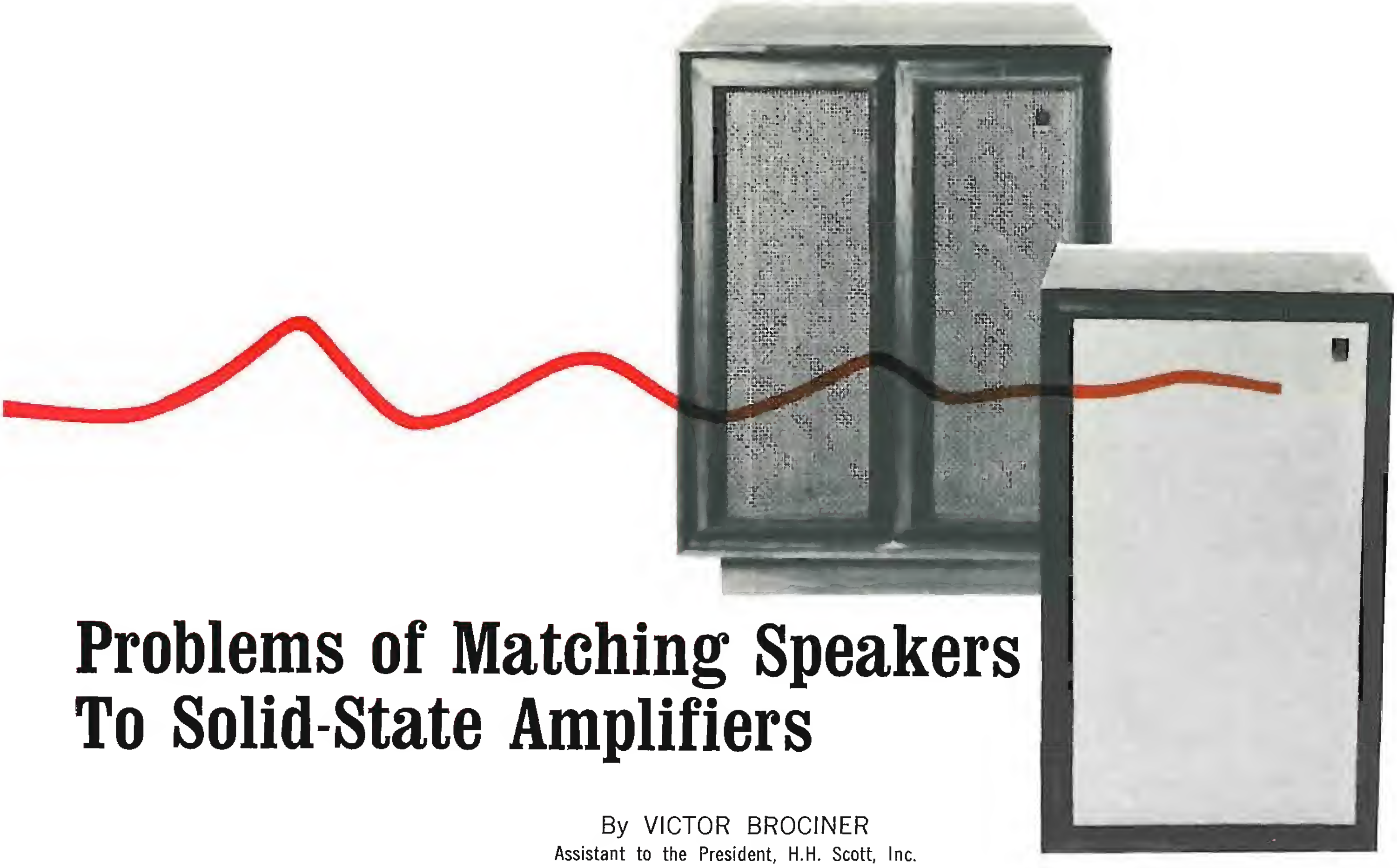


Problems of Matching Speakers To Solid-State Amplifiers

By VICTOR BROCINER
Assistant to the President, H.H. Scott, Inc.

Transistor amplifiers are very sensitive to changes in load, especially to lower-than-rated values. Therefore, careful attention must be paid by the speaker designer to the impedance of his system over the entire audio range. Here is how one manufacturer solves this problem. Details on adding loudspeakers to an existing hi-fi system are also covered.

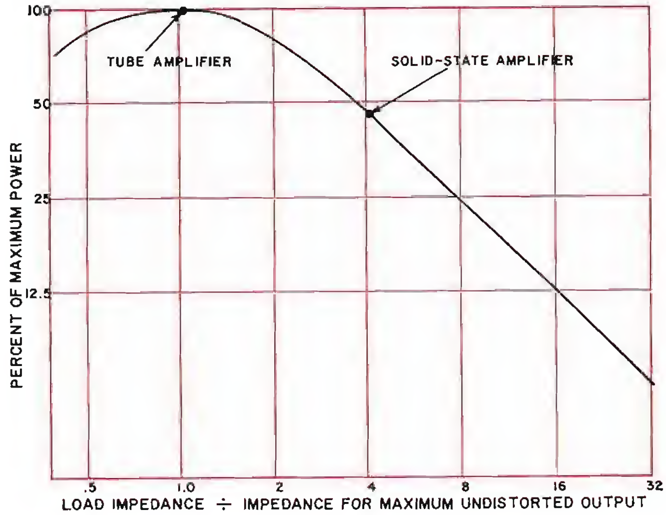
UNLIKE a tube amplifier, the transistor amplifier cannot be operated at the peak of its power *vs* load curve because the transistors are incapable of dissipating the heat that would be generated internally under these conditions. The variation of power output for a given value of distortion as the load resistance is changed on a solid-state amplifier is shown in Fig. 1. Solid-state amplifiers are operated at a point well to the right of the peak shown in Fig. 1. A serious consequence is that if the load resistance is decreased below the minimum value for which the amplifier is designed, there is danger of blowing out the transistors or their protective devices.

Typical silicon power transistors in current use can dissipate 100 watts continuously at a case temperature of 50° C. In an amplifier with a 70-volt power supply, designed for slightly over 75 watts of continuous power output into an 8-ohm load, the maximum dissipation with sine-wave signals is 40.6% of the output power or about 15 watts per output transistor. (This is for the ideal case, with a perfectly regulated power supply and no losses except in the transistors.) With square waves this increases to about 20 watts. For very low frequencies for which dissipation has to be calculated as it is for a d.c. amplifier, the dissipation rises to 38 watts per transistor for sine waves.

All this is well within the safety limits. Such an amplifier would be equipped with a 2-ampere speaker fuse which, being capable of carrying nearly 3 amperes for short periods corresponding to the loudest transient passages in program material, allows the amplifier to operate at its full power output. For 4-ohm resistive loads, the fuse rating could be increased to permit operation at full power.

But what happens at a lower load, say at 1 ohm? At peak input, on an instantaneous basis, half the supply voltage is connected across the load in series with the

Fig. 1. While a tube amplifier is usually operated at a load impedance producing maximum power output at a given distortion, solid-state amplifiers are usually operated at several times this value. The shape of the curve shown is for solid-state amplifiers; curve for tube amplifiers is somewhat different.



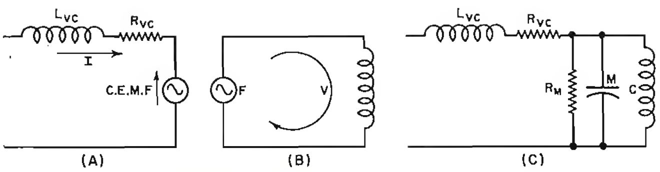


Fig 2. Electrical and mechanical equivalent circuits of speaker.

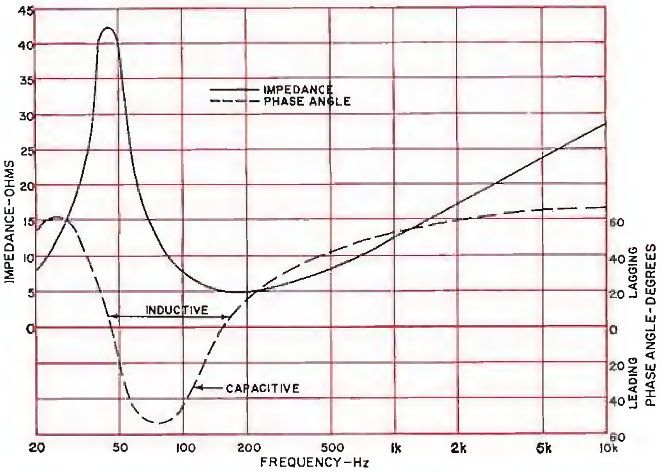


Fig. 3. Typical impedance and phase angle curves of speaker.

internal resistance of the transistor plus its emitter resistor, say 1 ohm.

$$\textit{Inst. current} = \frac{\textit{power supply voltage}}{\textit{resistance}} = \frac{70/2}{1+1} = 17.5 \text{ A}$$

This is above the 15-ampere maximum current rating of the transistor and will blow a fuse, but very likely not in time to protect the transistor.

If the load is of correct value but reactive instead of resistive, all of the power drawn from the supply must be dissipated in the transistor and its emitter resistor. The maximum peak dissipation for the two output transistors occurs when the voltage across each transistor is 0.75 times the supply voltage and the current is 0.866 times I_{max}, or

$$P_{dis,max} = 0.75E_{bb} \times 0.866\, I_{max} = 0.65\, E_{bb}I_{max}$$

I_{max} is equal to its value for full power output into rated resistive load $= E_{bb}/2R_L = 70/(2 \times 8) = 4.37$A; then $P_{dis,max} = 0.65 \times 70 \times 4.37 = 199$ W. This also exceeds the maximum rating of the transistor.

The situation with actual amplifiers and loads is not quite as bad as the foregoing calculations indicate because power-supply voltages decrease as the power output increases, the dissipation calculations have neglected the presence of the emitter resistors, and loads are not usually purely reactive. *Nevertheless, it is quite apparent that for reliable operation of solid-state amplifiers, careful attention must be paid to the magnitude and to the character of the load impedance that is used.*

Loudspeaker Impedance

The circuit across the terminals of a dynamic speaker can be viewed as the voice-coil resistance in series with its inductance, and both in series with a generator (see Fig. 2A). The generator represents the counter-e.m.f. generated by the motion of the voice coil in the magnetic field. This voltage depends on the flux density, the length of the active voice-coil conductor, and the velocity of the voice coil.

At frequencies well above resonance, the motion is mass-controlled, that is, the speaker acts as if the stiffness of its suspension were nearly zero and the mechanical resistance due to friction and acoustic resistance of the air load were likewise negligible. The simplified analog circuit is shown in Fig. 2B. By analogy with an electric circuit, the velocity, V (current), lags the force F (voltage), because the circuit is "inductive." Also, the force is in phase with the driving current, I, since the force is directly proportional to the driving current. Then the velocity lags driving current, which means that the generated voltage also lags the driving current. Consequently, the source generator in Fig. 2A sees a circuit in which the current is leading the voltage. This means that the motional impedance (an electrical impedance substituted for the generator) is *capacitive*. This is represented as M (for mass) in the complete equivalent circuit shown in Fig. 2C.

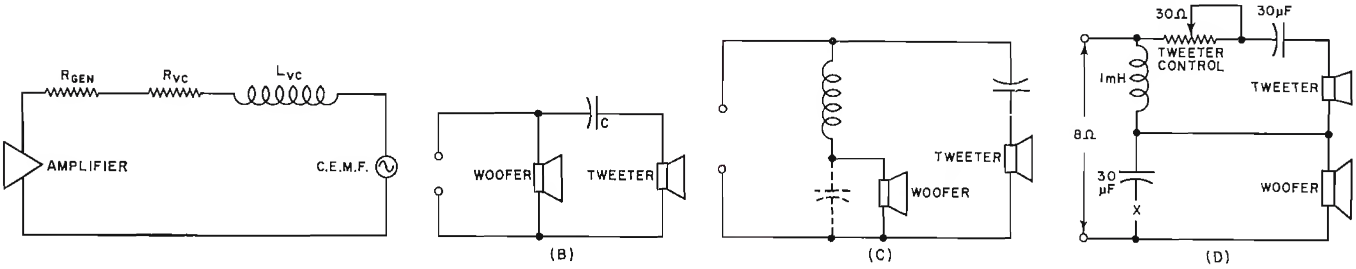
Below resonance, the stiffness controls and this appears in the electric circuit as an inductance. This is represented as C (for compliance) in Fig. 2C. The resistive element corresponds to an in-phase voltage and is an electrical resistance (R_M). Now, are these elements in series or in parallel? We know that at resonance the impedance rises, so they must be in parallel as shown.

The complete impedance curve of a typical loudspeaker is shown in Fig. 3. The trough of the curve occurs near 400 Hz in direct-radiator woofers and wide-range speakers, with a value of impedance only slightly greater than the voice-coil resistance. The amount of difference is a measure of the electromechanical efficiency of the speaker. Since the increase in impedance is caused by the motionally generated counter-e.m.f., a large increase would be caused by the high velocity and this represents high efficiency. Since direct-radiator speakers have typical efficiencies from less than one percent to only a few percent, one would not expect a large rise in mid-frequency impedance over the resistance. So, in effect, the minimum value of impedance of a speaker is determined primarily by the resistance of the voice coil.

The rise at higher frequencies is caused by the voice-coil inductance. In a wide-range speaker it is undesirable because for an essentially constant-voltage driving source it reduces the voice-coil current at high frequencies, with a resultant drop in response. The most effective means of reducing this effect is to cover the center pole of the magnet structure with a copper cap which acts as a shorting ring and minimizes the voice-coil inductance. Since the cap takes up some space that would otherwise be occupied by the magnet structure, flux density is reduced somewhat, with some reduction in over-all efficiency.

The peak at resonance is primarily determined by the flux density and the resistance losses (damping) of the speaker. At resonance the mechanical system acts like a

Fig. 4. (A) Equivalent circuit of speaker connected to amplifier. (B), (C), and (D) Two-way speaker systems and networks.



resistance. If there were no losses and no air load, the velocity would be infinite. With a given amount of resistive loss, the velocity is proportional to the active flux, as are the counter-e.m.f. and motional resistance. Thus, the more powerful the magnet, the higher the impedance peak at resonance. This seems to conflict with the idea that a speaker with a powerful magnet is well-damped, but it really does not.

When the speaker is connected to an amplifier of low source impedance (high damping factor), there is an additional damping element—the electrical damping provided by the amplifier. The counter-e.m.f. generated by the motion of the voice coil now works into a closed circuit (Fig. 4A). The motional voltage opposes the voltage applied by the amplifier, reducing the net voltage that drives current through the voice coil. This, in turn, decreases the current, which reduces the velocity. So the counter-e.m.f. acts in such a way as to oppose its own action, with the result that the damping of the system is increased.

Multi-Speaker Systems

With multi-speaker systems, the matter of impedance becomes considerably more complicated. Consider the simplest possible two-way system of Fig. 4B. The dividing network consists only of a capacitor in series with the tweeter. The woofer response falls off at higher frequencies and, in the interests of economy, no electrical means are used to keep these higher frequencies out of the speaker. Fig. 5 shows the impedance curves of the woofer alone, that of the tweeter with its capacitor, and the system impedance. It is seen that over a considerable range of frequencies the impedance is far below the rated value for the system. This is caused by the fact that a 4-ohm tweeter is used in an 8-ohm speaker system. This sort of thing comes about when the speaker designer attempts to obtain flat response with a tweeter that is not as efficient as the woofer. The lack of efficiency is made up by forcing more current through the lower impedance tweeter. The alternative is to design a more efficient tweeter, but this usually requires a heavier magnet structure which increases the cost. With tube amplifiers this practice merely resulted in reduced available power over part of the frequency range, but as has been explained previously, the consequences are more serious with solid-state amplifiers.

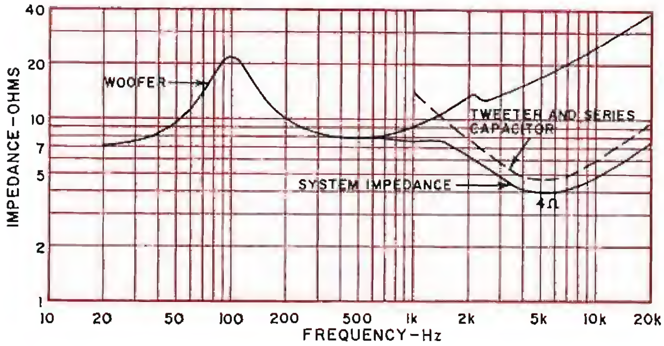


Fig. 5. Impedance of 2-way speaker system consisting of an 8-ohm woofer and a 4-ohm tweeter along with series capacitor.

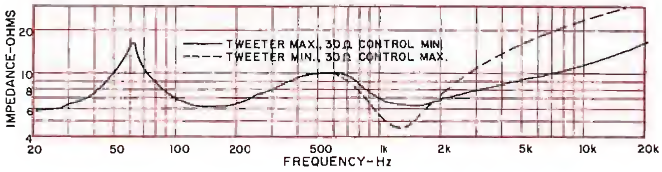


Fig. 6. Impedance curves at two settings of tweeter control.

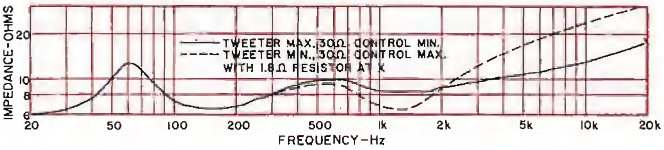


Fig. 7. Impedance curves with the 1.8-ohm resistor added.

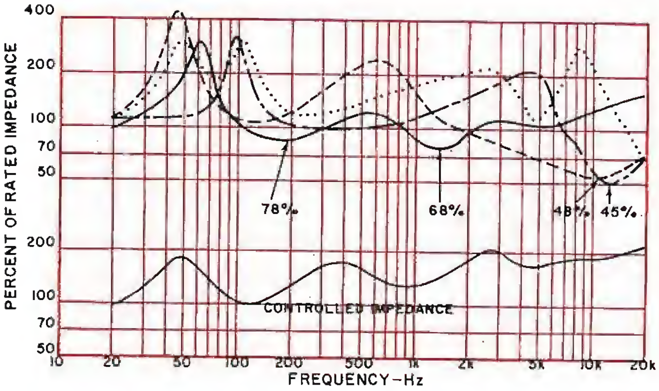


Fig. 8. (Above) Impedance curves of a number of commercially available speaker systems. (Below) Curve of controlled-Z system.

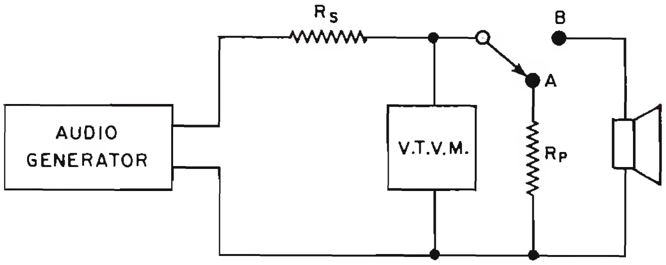
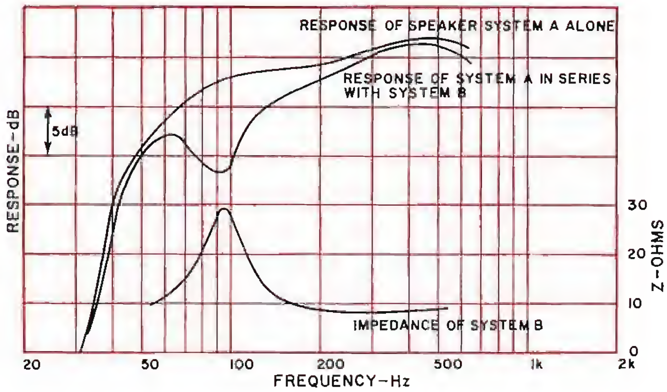


Fig. 9. Test-equipment setup used to measure speaker impedance.

Another way in which low impedance can occur is illustrated by the arrangement in Fig. 4C. This two-way system may have a bump in its frequency-response curve because the woofer is not cut off sharply enough. The situation is remedied by shunting the woofer with a large capacitor, shown dashed. The bump is now gone, but the impedance in the 2000-Hz region may be way below its rated value. A properly designed dividing network, with a larger value of inductance and a smaller capacitor, smooths the response just as well but maintains the impedance near its correct value.

An interesting example of how low impedance can occur in an unexpected manner is shown with the series-type network of Fig. 4D. In Fig. 6 we have the impedance curve (solid line) which shows a minimum of 6.5 ohms—acceptable for a system rated at 8 ohms. One would be inclined to disregard the effect of turning down the tweeter control because this inserts 30 ohms into the circuit. The dashed line, however, shows that the minimum value of impedance has now dropped to less than 5 ohms. The explanation is that with the tweeter at maximum (control

Fig. 10. Effect of adding inexpensive speaker system (B) to hi-fi speaker system (A) using a simple series connection.



at minimum resistance), the 1-mH choke, the upper 30-μF capacitor, and the tweeter form a parallel-resonant circuit with "Q" great enough to maintain the impedance at a high value around the crossover frequency. With the tweeter turned down and the 30-ohm control inserted in the circuit, this effectively leaves only the choke, the bottom capacitor, and the woofer in the circuit, with a lower impedance than before. The remedy is to insert a resistor of 1.8 ohms at "X" in Fig. 4D. This has very little effect on the woofer cut-off curve but keeps the impedance up to an acceptable level, as shown in Fig. 7.

In multi-speaker systems it is sometimes necessary to use two or more speakers in parallel for a given frequency range to provide wider distribution or greater power-handling capability. These speakers should have a higher impedance than the other speakers in the system so that their impedance when paralleled is equal to the rated impedance. Sometimes it is impossible to obtain units of suitable impedance values or it may be uneconomical to manufacture them. The result is too low an impedance over part of the frequency range. A matching transformer would solve the problem, but it must be a high-quality transformer with a high primary inductance and this may not be economical either.

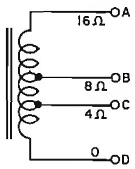
A large number of commercial speaker systems were measured and their impedances plotted. Some of the curves are shown in Fig. 8 with impedance indicated as a percent of its rated value. We have called out the points at which these have minimum impedances that were found to be unacceptably low. In order to be sure of safe high-level operation of solid-state amplifiers with these speakers, they should be operated in series with a 2-ohm resistor. In contrast to these, one curve is that of a system that has been designed especially to have controlled impedance.

Measuring Speaker Impedance

Speaker impedance can be measured quite easily using only an audio generator and a vacuum-tube voltmeter. The only other components needed are two resistors: a high-power (5 to 10 watts) series resistor (R_S) at least 20 times the value of the impedance to be measured, and a precision resistor (5% or better). The precision resistor (R_P) should preferably have a value equal to the rated speaker impedance but it can be any known value from about half to double this figure. The equipment is connected as shown in Fig. 9.

The first step is calibration. With the switch at "A" the precision resistor is connected across the v.t.v.m. terminals. The output of the generator is adjusted to produce a 1000-Hz voltage across the precision resistor that is one-hundredth the value of the resistor. For example, if R_P is 8 ohms, adjust the voltage to 80 mV. (If the v.t.v.m. range does not extend this low, a higher value may be used but it must be remembered that the generator is putting out a much higher voltage and distortion may be produced.) The calibration permits the v.t.v.m. to be read in ohms by multiplying its reading in volts by 100. (If a higher voltage is used, the corresponding ratio is used to read the v.t.v.m.)

Fig. 11. Use of a matching transformer for multiple speakers.



AMPLIFIER		SPEAKER(S)	
CONNECT TO	FOR LOAD VALUE	IMPEDANCE	CONNECT TO
B—D	8Ω	16Ω	A—D
B—D	"	4Ω	C—D
A—D	"	2Ω	C—D
B—D	"	1.44Ω	A—B
B—D	"	.64Ω	B—C
A—D	"	.32Ω	B—C

The speaker is then substituted for the precision resistor by switching to position "B". A series of impedance readings is then made over the entire operating frequency range and the results plotted as a curve of impedance *vs* frequency. The minimum value of impedance is easily observed. It should be within 10% of the rated impedance of the system.

If the speaker system is equipped with level controls for the different channels, such as tweeter and mid-range, impedance curves should be plotted for various combinations of settings of the controls since these can affect the impedance of the system considerably.

It should be pointed out that the impedance at or near resonance varies with power level, and the results obtained by this method may not be exactly the same as those given by measuring at a "standard" power input to the speaker of one-tenth of its rated power. However, we are not particularly interested in accuracy in this region because the impedance is usually well above rating here.

Manufacturers' Specifications

It is often inconvenient to measure the impedance of a speaker system, especially before it is purchased. How, then, can the audiophile determine the suitability of a speaker before acquiring it? The answer is to demand that the speaker manufacturer specify not only the rating or nominal impedance but also the minimum value of impedance attained within the audio range or, preferably, a curve of impedance *vs* frequency.

The definition of *rating impedance* for a speaker is not as widely known as it should be. As defined by both the IEEE and EIA standards (61 IRE 30.RPI "Recommended Practices on Audio and Electroacoustics: Loudspeaker Measurements" and RETMA Standard SE-103 "Speakers for Sound Equipment"), it is "the value of a pure resistance, specified by the manufacturer, in which the electrical power available to the speaker is measured." It is intended to indicate to which tap of an (output-transformer coupled) amplifier a speaker should be connected. It is not the impedance of the loudspeaker at a designated reference frequency. It is, *ideally,* the average impedance over the frequency band transmitted by the speaker, weighted by the spectrum of the signal with which the speaker will be used. For direct-radiator loudspeakers it may be estimated by adding 10% to the minimum value of the magnitude of the measured impedance in the frequency range above cone resonance, or by adding 20% to the voice-coil d.c. resistance.

The EIA Standard also states that speaker impedance (not rating impedance) shall be presented in terms of magnitude and phase angle as a function of frequency. This is exactly the information that is required to determine whether or not safe operation can be obtained with a solid-state amplifier.

Of course, in the long run, it will hardly be necessary for the audiophile to go through all this information. Loudspeaker manufacturers are aware of the problem and it is assumed that in their own interests as well as those of their customers and of manufacturers of solid-state equipment, they will revise their designs where required so that all the speakers available on the market will be perfectly safe for use with solid-state amplifiers.

Installing Additional Speakers

Since a solid-state amplifier requires that the load impedance be kept above a certain minimum value, it follows that when a number of speakers are to be operated at one time, provision must be

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made to meet this requirement. It would be a simple matter indeed if speakers were available in any desired impedance. These could then be selected so that their impedance in parallel is above the desired minimum impedance. Unfortunately, speakers are made with nominal rated impedances of 4, 8, or 16 ohms and a given type is not made in a choice of impedances.

Means for connecting speakers in parallel can be considered in two classes: those built into the amplifier and those external to the amplifier. Some amplifiers include provisions for paralleling main and remote speakers. To take care of situations where the paralleled speakers provide too low a load value, a series resistor is provided in the amplifier. Suppose, for example, that the minimum safe value of impedance for a given amplifier is 3 ohms and we want to operate two 4-ohm speakers in parallel, making their combined impedance 2 ohms. A one-ohm series resistor will provide the required protection. Unfortunately, it will also decrease the damping factor and provide a slight peak at resonance in a speaker designed for flat response with an amplifier of high damping factor. (In an over-damped speaker this would improve the bass response.) In order to avoid this effect, some amplifiers use negative feedback around the series resistor to maintain a high damping factor.

Series Operation

Why not operate the speakers in series? If they are identical this is perfectly all right. If they are not, there can be all kinds of undesirable interaction between them. The simplest case is where they are of different rated impedance. If an 8-ohm and a 4-ohm speaker are connected in series, the same current will flow through both and, since power equals I^2R, the 8-ohm speaker will receive twice as much power as the 4-ohm speaker. This, however, is a gross oversimplification of what occurs since the impedances of the two speakers vary over the frequency range.

To illustrate the effect, consider the extreme case of an inexpensive, replacement-type speaker in series with a good hi-fi system, both of nominal 8-ohm impedance. The latter probably resonates around 45 Hz and has its minimum impedance of about 6 ohms in the 100-400 Hz region. The inexpensive speaker may resonate at 90 Hz in its cabinet and present a resonant impedance of 30 ohms.

At 90 Hz the two speakers in series are 36 ohms. The hi-fi system has ⅙th the amplifier output voltage across it. In the mid-frequency range the impedances are equal and the hi-fi speaker gets ½ the output voltage. The relative input voltage at 90 Hz is about ⅓, producing a hole in response of almost 10 dB. Fig. 10 shows actual measurements on such a connection. In addition, since the hi-fi speaker electrically "looks into" a source impedance consisting of the other speaker in series with the amplifier, the effect on the damping factor can well be imagined.

Use of Transformer

There is a well-known device for changing impedances, even if somewhat discredited in hi-fi circles. This is the transformer. When operating at low impedance with fairly small transformation ratios and without d.c. in the primary (unlike an amplifier output transformer), this is a very efficient and not too costly device which can be designed for very wide frequency range and freedom from phase shift. This does not mean that transformers designed for public-address applications can be used. Indeed, these are likely to be dangerous because they usually have poor low-frequency response due to low values of primary inductance.

In the equivalent circuit for a transformer, the primary inductance is a shunt element. A low value results in a virtual short circuit at very low frequencies and a predominantly reactive load for the range immediately above this. Both conditions are exactly what we are seeking to avoid in loading the amplifier. A high-quality transformer must be used. It is interesting to note that a very large number of taps are not needed for a great variety of transformation conditions (Fig. 11). A 16-8-4 ohm transformer can be used for loads of 4, 2, 1.44, 0.64, and 0.32 ohms if the amplifier will safely accept an 8-ohmn load.

Unequal power to different speakers may not be undesirable. In some cases it is desirable to operate the remote speakers at reduced loudness. In this case a remote speaker of higher impedance than the main speaker should be used. An alternate means is a fixed or adjustable L-pad or a simple potentiometer. The latter should have a resistance about five times the impedance of the remote speaker. If operated for reduced loudness, it will place a large value of resistance in series with the speaker, reducing the loading of the amplifier.

In this article we have pointed out some of the problems that may occur when connecting speakers to solid-state amplifiers. It behooves the user to be aware of these problems and to know how to solve them. ▲