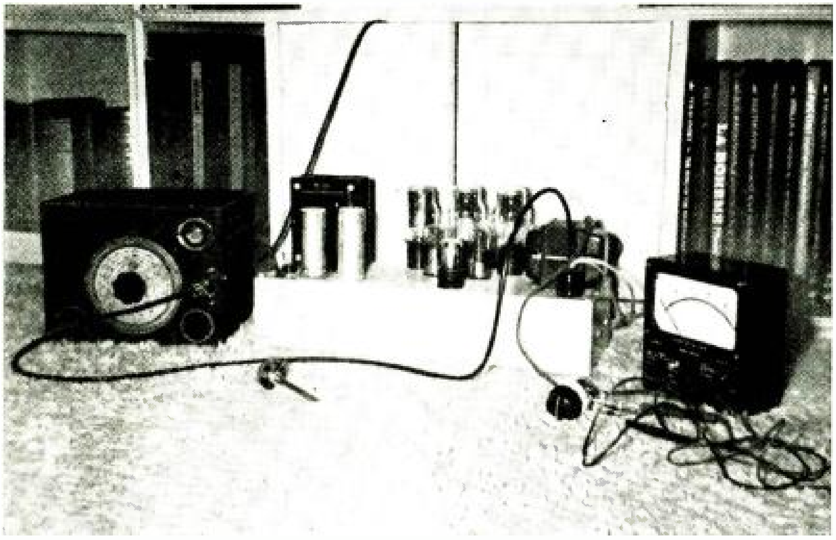
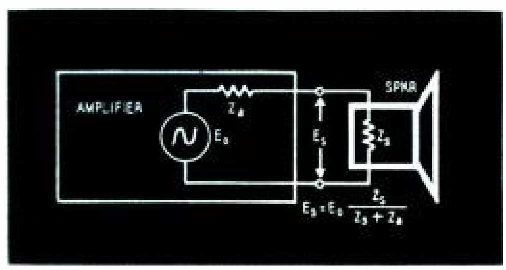
AUDIO IMPEDANCE MEASUREMENT

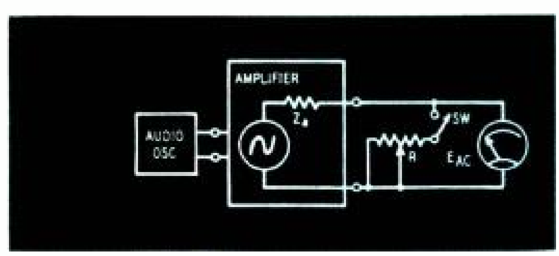


A complete setup for measuring amplifier impedance.

Simple measurements with minimum equipment provide answers to audio problems.

By JAMES A. MITCHELL





Figs. 1 and 2—Basic impedances and measurement circuit.

THE measurement of impedances in audio equipment has become a potent tool in our sound trouble-shooting kit since an audio enthusiast came to us with a puzzler. Let's call it "The Case of the Screwy Bass." He claimed that after he had installed a high-fidelity Williamson-type amplifier, his sound system actually had *less* bass than with an inexpensive PA amplifier. He had run response curves on each amplifier, and while both were flat in the middle range, the PA amplifier *fell off* in output below 100 cycles but the Williamson was perfectly flat down to 20 cycles. Our friend demonstrated the problem by switching his speaker from one to the other. There was no doubt that we heard more bass from the PA amplifier in spite of the measured response curves.

In checking the problem, we found the response curves had been measured with a *resistor* load. However, when we checked the response of the amplifiers with the *speaker* as the load, two high peaks in the bass range were found with the PA amplifier. These peaks were entirely absent when the Williamson-type amplifier was tested. The two amplifiers were affected quite differently by the change in the type of load. By a few measurements we were able to show that this was a matter of differences in impedances. The Williamson-type amplifier had a very different internal impedance characteristic from the PA amplifier.

The impedance of any device is its tendency to oppose the flow of current when an a.c. voltage is applied to it. In many devices this is simply resistance, but in equipment such as speakers, transformers, and amplifiers there are elements of inductive and capacitive reactance as well as resistance. These all affect the flow of alternating current. Impedance is the effective sum of these three elements. The inductive and capacitive elements in audio equipment cause impedance to change with frequency. This curve of impedance versus frequency tells us a good deal about the performance of an audio unit.

When an audio amplifier drives a speaker system there are two impedances which affect the performance. The first (Z_a in Fig. 1) is the internal impedance of the amplifier. The second (Z_s) is the impedance of the speaker. It can be seen that the voltage across the speaker is not the full voltage of the amplifier (E_0) because the internal impedance of the amplifier is in series with the speaker. If the amplifier's internal impedance is big enough to be significant and if the speaker impedance varies with the frequency, the voltage across the speaker will not be uniform at all frequencies but will have peaks at the impedance peaks in the speaker. The voltage across the speaker will differ from the fundamental voltage of the amplifier by the ratio indicated in the formula of Fig. 1. This is one reason why an audio amplifier should have a low internal impedance.

The damping factor

The internal impedance of an amplifier may be measured at any one of the amplifier's output taps. A more useful unit is the *damping factor*, which is equal to the rated output impedance divided by actual internal impedance. This makes it unnecessary to state at which output taps the measurements were made. The internal impedance is not a constant value but depends on the frequency at which it is measured. The complete description of an amplifier's internal impedance is a curve showing the damping factor versus frequency.

Normally an audio amplifier will have an internal impedance of 1/2 to 1/20 its rated output impedance. The damping factor will therefore be in the range of about 2 to 20. This damping factor is determined by the plate resistance of the output tubes, the circuit in which they are used, and the design of the output transformer. The use of feedback around the output stage reduces the effective internal impedance. Amplifiers with triode output tubes such as 2A3's or 6B4-G's without feedback and using traditional transformer design, have damping factors of 2 to 3. Feedback will increase the damping factor. Beam power tubes such as the 6L6 give an amplifier a very high internal impedance. Feedback is essential with these types, and their high gain makes considerable feedback feasible.

There are several ways of measuring electrical impedance. Many of them require bridge circuits or that hard-to-find item, an a.c. milliammeter. The methods to be described have been limited to the simplest equipment possible. An audio oscillator is needed as well as an a.c. voltmeter, a couple of rheostats of about 10 and 25 ohms and a few 10-watt resistors between 10 and 50 ohms. The oscillator should be capable of covering the audio range in which you are interested with reasonably low distortion. The voltmeter is preferably of the electronic type, though good results can be obtained with a sensitive volt-ohm-milliammeter with a.c. scales in the 0.5- to 3.0-volt range. Just remember to make all measurements on the same scale if your meter isn't uniformly calibrated on all scales.

One of the simplest methods of measuring the internal impedance of an amplifier is to use the scheme shown in Fig. 2. The plan is to measure the output voltage with no load across the amplifier; then with an adjustable resistor as a load to find at what load resistance the output voltage will be one-half the no-load voltage. The audio oscillator is connected to the amplifier input, and an on-off switch and rheostat are connected in series to the amplifier output terminals. These should be the impedance taps used in your particular installation. The rheostat should be capable of covering a range down to about 1/20 of the nominal output impedance. The voltmeter is placed across the output taps. With the switch open, the amplifier gain or oscillator input is adjusted until a conveniently measurable voltage is obtained, say 2.0 volts. The switch is then closed and the rheostat adjusted until the voltage drops to 1.0. The switch can now be opened and the resistance of the rheostat measured. This resistance equals the internal impedance of the amplifier.

It may sometimes happen with an amplifier of very high damping factor that you cannot get down to one-half the no-load voltage with the rheostats available. In that case the internal impedance can be calculated from the following formula, using voltage readings taken at the lowest resistance setting of the rheostat.

$$Z_a = \frac{RE_o}{E_R} - R.$$

Z_a is the internal impedance of the amplifier, E_o is the no-load output voltage, E_R is the voltage across the load resistance R. For example: if the open-circuit voltage at the 8-ohm tap is 2.0 volts and when the load resistance is lowered to 1.3 ohms (as far as you can go with your rheostat), the output voltage is 1.4 volts, and the internal impedance is

$$Z_a = \frac{1.3 \times 2.0}{1.4} - 1.3 = 1.85 - 1.3 = 0.55 \text{ ohms.}$$

These measurements should be made at several different audio frequencies until the entire audio range is covered. A good plan is to check at 1,000, 100, 50, 30, 20, 5,000, 10,000, 15,000 cycles. If the results are about equal or change smoothly you have a good picture of the amplifier's internal impedance characteristics. If irregular results are obtained, further checking is in order.

The internal impedance curves of two very different amplifiers are shown in Fig. 3. The lower curve (amplifier A) is that of the Brook 12A amplifier. This is a triode output amplifier (push-pull 2A3's), with a high-quality output transformer and with inverse feedback. The upper curve (amplifier B) is that of a home-built beam-power-tube amplifier with a lower quality output transformer and (as we now realize) a poorly designed feedback system. However, it is typical of many published designs and of amplifiers used in home music systems.

This type of curve results when the feedback is not uniform over the entire audio range. If the frequency response of the amplifier is not quite flat without feedback, then feedback may help flatten the response, but the internal impedance of the amplifier will rise at each end of the curve. Using the feedback loop around the final stage to adjust frequency response or using it in tone control circuits can cause a lot of trouble in the matter of damping factor. Amplifier B may sound satisfactory with a narrow range speaker

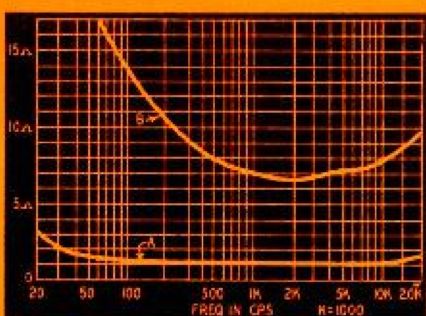


Fig. 3—Amplifier impedance curves. Details given in the text.

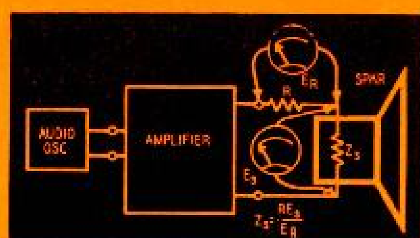


Fig. 4—Circuit for measuring the impedance of a loudspeaker.

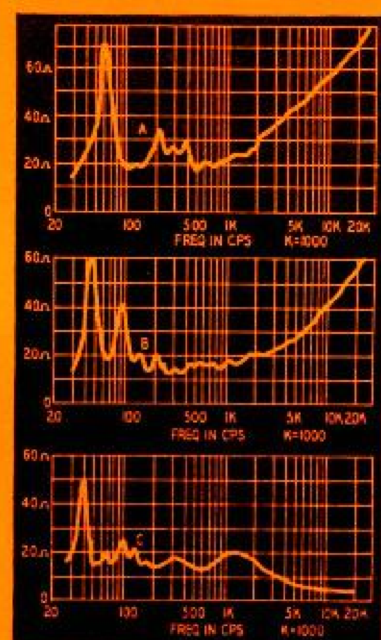


Fig. 5—Typical speaker impedance curves. See text for details.

system but the superiority of amplifier A with a wide range system is obvious.

To measure the impedance of a loudspeaker (or other nonresistive load) the oscillator, amplifier, speaker and a 10-watt resistor are connected as shown in Fig. 4. The resistor should have about twice the rated impedance of the speaker under test. The resistor value should be known accurately. The plan is to measure the voltage across the speaker and to compare it with the voltage across the resistor over the audio-frequency range. Since the resistor and speaker are in series the current through both is the same and the impedance of the speaker can be calculated from the following formula:

$$Z_S = R \frac{E_S}{E_R}$$

where Z_S is the speaker impedance, R is the resistor in ohms, E_S is the voltage across the speaker, and E_R is the voltage across the resistor. The oscillator is first set at 1,000 cycles and the amplifier output is adjusted so that conveniently measureable voltages are obtained across both the resistor and the speaker. It is a good point to have the sum of the two voltages less than the maximum of the meter scale in use so that you will not have to change the scale at any possible impedance.

If you have an insensitive voltmeter you may have to have the volume rather loud in order to get readings, but if the neighbors and the amplifier can stand it the results will be just as good. Voltage readings are taken across the standard resistor and across the speaker. It is a good plan to start at 1,000 cycles and to sweep continuously down the audio spectrum to 20 or 30 cycles. Since some speakers may have several closely adjacent peaks, a number of measurements should be made in these ranges to get an accurate picture of the impedance curve. One method is to leave the voltmeter across the speaker after each measurement and to note the significant peaks and valleys as the oscillator is tuned up and down. Readings are made at these peak points along with enough in-between measurements to draw a good curve.

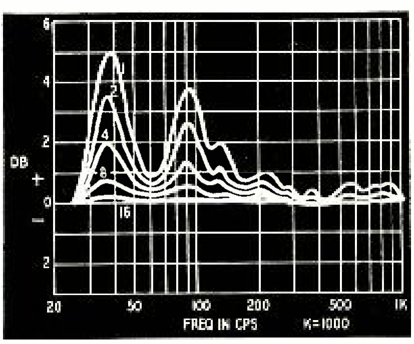


Fig. 6—The effect of amplifier damping factor on speaker response. See text.

After covering the bass range, the spectrum from 1,000 cycles up should be checked. A smoother curve is usually found in this range, but the technique of continuously sweeping the oscillator up and down the scale will reveal any peaks which exist. The voltage readings are then converted to impedance values.

Fig. 5 presents some typical speaker-impedance curves. Curve A is that of a single-cone 15-inch speaker in an open-back cabinet. Curve B is the same 15-inch speaker in a 7-cubic-foot bass-reflex corner cabinet. Curve C is a two-speaker system with dividing network at 800 cycles. Both speakers are horn-loaded. It is immediately apparent that though all these speakers are rated at 16 ohms, such a rating is only nominal, and much higher impedances are actually present at many frequencies. The high-impedance peaks in the bass range are produced whenever there is a tendency for the voice coil to resonate, either because of resonances in the speaker itself or in combination with the air loading in the cabinet. These peaks in the bass range tell us a good deal about the speaker system. The fairly smooth rise of impedance at the higher frequencies is due to the inductance of the voice coil. This inductance is really too high in the treble range but is needed in the bass. In dual-voice-coil speakers or two-speaker systems this impedance rise can be eliminated by designing each driver for its particular response range.

The high peak in curve A occurs at the resonant frequency of the speaker cone. Mounting the speaker in an open-back cabinet has done little to damp this resonance and seems to have added a couple of new ones at higher frequencies. In the reflex cabinet the air loading raises the frequency at which the cone resonates but reduces the amount of resonance and adds a lower frequency resonance of the reflex cabinet. These effects can be seen in the impedance curves which are very helpful in adjusting reflex baffles. The horn-loaded speakers show a more uniform impedance curve down to the bottom peak. This peak is at the cutoff frequency of the horn and the resonant frequency of the low-frequency driver. The driver has been selected to resonate at this point to hold up the low-frequency response where the horn falls off.

It might well be asked why the speaker impedance rises at these resonant points. It is helpful to look at it this way. The a.c. voltage from the amplifier sends current through the voice coil so that it vibrates in the magnetic field of the speaker. This vibration of the coil in the magnetic field causes it to generate an a.c. voltage of opposite sign to the driving voltage. When a resonant frequency is reached the mass of the voice coil and cone just balances the compliance of the cone and the air chamber, and the coil vibrates back and forth much more vigorously. The voltage generated by the voice coil increases, opposing the driving voltage and reducing the current. Thus the impedance of the unit rises. This is a desirable counterbalance because it is important to reduce the power input at these resonant points to avoid a loudness peak. However, if the amplifier has a high internal impedance, as the speaker impedance rises, the voltage across the speaker will also rise, thus increasing the tendency to resonate, and creating a peak.

As an example of this condition, Fig. 6 shows the frequency response as measured across the voice coil of a 15-inch speaker in a 7-cubic-foot bass reflex corner baffle when driven by amplifiers of different damping factors. These curves were determined by varying the internal impedance of a high-quality amplifier. The responses obtained can be calculated from the equation in Fig. 1, knowing the impedance curve of the speaker and the internal impedance of the amplifier. (Editor's Note—The equation is in voltage terms, not db.)

In all these cases the amplifier produced a flat frequency curve into a resistor load. The frequency deviations shown are simply the effects of the variations in speaker impedance with the variations in both frequency and the damping factor of the amplifier. Note that with damping factors of 8 or higher the effect on the response of even large changes in speaker impedance is negligible. With a damping factor of 4 the rise in frequency response is just noticeable. With factors of 2 or 1 the bass peaks are pronounced and may be noticeably boomy.

Another important angle is the damping effect of the amplifier on the natural speaker system resonances when the system is subjected to sudden bursts of tone or transient impulses. These shock impulses tend to throw the speaker into vibration at its resonant points unless the speaker is *critically* damped. Part of this damping is provided in the construction of the speaker itself; part is supplied by the air loading of the cabinet or horn and by the internal impedance of the amplifier. Damping is not greatly affected when the amplifier internal impedance drops to less than 1/8 or 1/10 of the voice coil resistance.

You will be on safe ground if your amplifier has a damping factor of at least 3 over the entire range of audibility.

Internal impedance measurements are therefore important tests for amplifier constructors. When coupled with speaker impedance measurements the information gained can be used to improve the over-all audio performance considerably.

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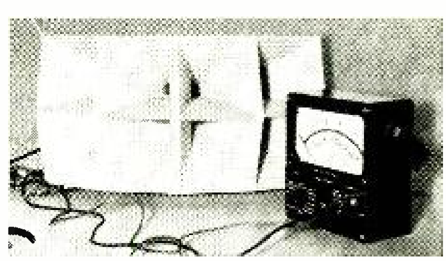

Measuring the impedance of a tweeter.