THE IMPEDANCE MEASURING FAQ

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1 INTRODUCTION

An oft-asked question is "What's a simple way I can measure the impedance of my loudspeaker or driver?" The answer to that depends upon a lot of things, like what equipment you might have at your disposal, how much work you want to put into the enterprise, and so on. I'll present one method here that can give reasonably accurate results with the bare minimum of test equipment needed.

2 WHAT IS IMPEDANCE?

Simply stated, it's the obstacle to current flow provided by an electrical circuit to the imposition of an AC electrical signal. It is like resistance in that sense, but different in that it is almost always (in these applications) frequency-dependent. That is, it's value is different at different frequencies, and it is "complex," meaning that, mathematically, it is a vector quantity, consisting of a resistive and a reactive part

The law governing the relationship between DC resistance, voltage and current, known as Ohm's law, is:

$$E = I\ R$$

where E is the impressed voltage in volts across the resistance R in ohms, resulting in a current I in amperes flowing through that resistance. Simple high school algebra allows us to rearrange this basic equation:

$$R = \frac{E}{I}$$

and

$$I = \frac{E}{R}$$

AC impedance, voltage and current follow the same basic rules:

$$E = I\ Z$$

where E is the impressed voltage magnitude in volts impressed across the impedance magnitude Z in ohms, resulting in a current magnitude of I in amperes flowing through that impedance. As above, we can rearrange our equations:

$$Z = \frac{E}{I}$$

and

$$I = \frac{E}{Z}$$

Now, I use the terms like "impedance magnitude" here. The AC impedance, as mentioned above, is a complex value: it is vector sum of the resistive (or real) and reactive (or imaginary[1]) components of the impedance. That vector sum is computed as (for example):

$$Z_{MAG} = \sqrt{R^2 + X^2}$$

where R is the resistive portion and X is the reactive portion.

Because of the energy storage properties of the reactive portion, the instantaneous current flowing through the impedance is not in step or in phase with the instantaneous voltage across it. Rather is precedes or follows the voltage by some amount dependent upon the ratio of reactance to the resistance, specifically:

$$\theta = \tan^{-1}\frac{X}{R}$$

where θ is the phase angle, usually expressed in degrees. It should be noted that in the grand scheme of

[1] In this context, real and imaginary have very specific mathematical meaning. An imaginary number is not one that exists only in one's imagination, rather it is a number that has the square root of negative one as one of its factors.

things, both the resistance R and the reactance X can take on any value, positive, negative or zero.

However, in the case of loudspeaker impedance, R will never be negative, and almost certainly never 0, while X can either be positive (inductive) or negative (capacitive) or 0. Looking at the equation for the impedance phase angle, this means that the phase angle of the impedance will always be inside the range of -90° to +90°. (Indeed, it is quite unusual to find the impedance phase to be outside the range of ±70°). The fact that the real or resistive portion of the impedance is always positive ensures that the impedance phase angle never exceeds these 90° limits[2].

Basically, all we need to do is then to put a voltage across the unknown impedance, measure the current going through it, plug the numbers into the following equation (from above):

$$Z = \frac{E}{I}$$

And out pops the impedance, Z.

In principle, this is absolutely correct, but in practice, it is more difficult. The main reason for this is the range of typical values for the impedance of most loudspeakers and drivers (from a few ohms to a few dozen ohms) combined with the sensitivity of most common measurement instruments.

Imagine putting a voltage of 10 volts across an 8Ω loudspeaker. Ohm's law says that the current going through that speaker will be:

$$I = \frac{E}{Z},$$

$$I = \frac{10\ Volts}{8\ \Omega},$$

$$I = 1.25\ Amps$$

While 1.25 amps is a convenient current to measure (it's large enough to ensure reasonable accuracy with many common meters), it is a *lot* of current to put through the voice coil. That poor speaker and the people near it will be subjected to a rather deafening level of sound. Additionally it does pose some risk of damage to some drivers.

3 MEASUREMENT SCHEMES

A common assumption is that one needs two meters: one to measure voltage placed across the impedance and one to measure current placed in series with the impedance. Then, by Ohms law:

$$Z = \frac{E}{I}$$

However, this poses some problems. As mentioned above, it requires a hefty amount of current to get enough of a reading to be dependable. Most commonly available meters that measure AC current at all well aren't very sensitive. There is also the issue of having to go through the calculation for each and every frequency being measured.

Another method that seems to have escaped many peoples' attention is the "impedometer." This is nothing more that a calibrated constant current source. When properly set up, no calculation is required and it is reasonably accurate over a wide range of impedance. Another advantage is that it requires less equipment than other methods. It is the impedometer method that we will discuss here.

4 TEST INSTRUMENTS

Very little is required for a properly working impedometer. We'll enumerate the requirements here.

4.1 AC sine wave generator

This can either a function generator (usually meaning an instrument that has the capability of sine, square, and triangle waves, and often has pulse output as well) or a Wein-bridge or twin-T audio oscillator. The major requirements are stable AC output, stable frequency, reasonably low distortion (less than 1%), flat frequency response over the audio bandwidth, and reasonable voltage output (10 volts or more into 1 kΩ is good).

There are a lot of new instruments that are acceptable, function generators by B&K, Tenma, Leader and others can be had, but often cost several hundred dollars new. Their performance is generally more than good enough, and they are versatile instruments for other purposes as well. Often they have frequency ranges far in excess of what's needed, like 0.02 Hz to 2 MHz, but that's okay, too.

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[2] For those with a more technical inclination, that means that the entire impedance is confined to the right of the imaginary axis in the complex s-plane. In order for the impedance phase angle to exceed the limits of ±90°, the real part of the impedance must be negative: that is, the speaker or driver must exhibit negative resistance. No loudspeaker can conceivable exhibit this behavior under even extreme conditions.

On the other hand, you can often find used equipment that is very serviceably as well as inexpensive. I have seen excellent units from the likes of Wavetek and Krohn-Hite for under $100. In working order, they have superb specifications and are ideal for this sort of use. Their distortion is not the lowest (because, like other function generators, they synthesize the sine wave from the triangle output), but, for impedance and frequency response measurements, they are superbly accurate for audio use.

One of the all-time best sine generators is the venerable HP 200 audio oscillator. I have seen them at swap meets and even at yard sales for as low as 5 dollars. The have good frequency response, good stability and high output voltage (25 volts into 600 ohms). There are several variants: the 200 AB and 200 CD are the most common and both are equally good. Look for examples from General Radio or GR as well. The GR1309 can often be had for $50 and can be tuned to have very low distortion, under 0.05%, while the 1309 will do 20-20 kHz without range sweeping and has high output voltage as well. Be prepared for a little tune-up work, like cleaning and lubing dial shafts, maybe replacing a tube and an electrolytic capacitor or two. Otherwise, these units last absolutely forever. I cannot recommend them too highly.

4.2 AC voltmeter

This can either be an analog or digital unit. Ideally, it must be capable of reading down to about 10 mV full scale with reasonable accuracy. It must also have flat frequency response over the audio range.

Unfortunately, the sensitivity requirement eliminates most "passive" VOMs (volt-ohm-milliammeters), including the ubiquitous and venerable Simpson 260 (which is truly unfortunate, because the 3 I have here of different vintages all have excellent frequency response to well beyond 50 kHz on the 2.5 volt AC scale, sigh).

Equally unfortunate is the fact that many hand-held DVMs (Digital Volt Meters) have poor high-frequency response, often showing significant errors as low as 500 Hz. Generally, most meters that advertise themselves as "true RMS" have adequate frequency response.

Again, turning to the used or surplus markets, there are treasures to be had. The Hewlett-Packard 400D has all the needed sensitivity (1 millivolt full scale), wide frequency response below 10 Hz to 1 MHZ), excellent linearity and are plentiful and easy to find. Again, I have seem them for as low as $25 in serviceable condition, and even arrived 30 seconds too late one day as I saw 20 of them being crushed at a local landfill! Again, they may need new capacitors here and there and occasional new tube, but little else is needed to keep them going. Most of the HP 400 series are equally useful. Look also for meters from GR, Ballantine, B&K and others. Heath made an AC millivoltmeter that was quite useful.

4.3 1 kΩ resistor

This need not be anything fancy. A noninductive carbon or metal film, 1/2 watt 5% resistor is really all that's needed. This will turn our oscillator into a current source.

4.4 4, 8, or 10 Ω precision non-inductive resistor

This is used to calibrate the impedometer. It can be any value that's close to the impedance you expect to measure. Just make sure that it's non-inductive (film resistors work here) and that you know its resistance accurately (a 1% or better tolerance is ideal). You'll only need a small resistor, 1/2 watt is probably fine.

4.5 Frequency counter

Not essential, but considering that the frequency dial calibration on many oscillators and function generators can be considerably off, it's a useful thing to have. Digital frequency counters can be had both on the new and used market for not a lot of money. Remember that the accuracy is directly proportional to the reciprocal of the needed accuracy: if you want 1/10 Hz accuracy, you'll have to wait 10 seconds to get there.

4.6 Oscilloscope

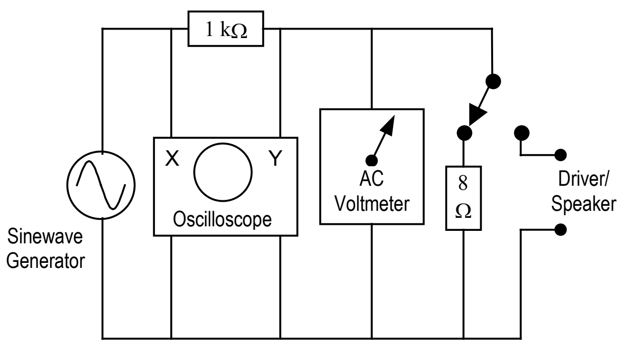
Not essential, but useful for several things: it can help you verify that nothing is being distorted. Connected as an X-Y scope, it can help you unambiguously find the exact resonant frequency and also enable you to (via a rather laborious procedure) estimate the phase angle of the impedance. If you're going to get a scope, get one that has X-Y capability with no less than 10 mV/cm on both axes. Scopes fitting the bill can be found for anywhere from $50 used to many tens of thousands of dollars. Look for an old HP 130, the best audio scope for the cheapest money around. There are some big-ass Tektronix 500 series that are huge and cheap, also look for 400 series, and scopes by Phillips and others.

4.7 Miscellaneous

If you're going to be doing this a lot, buy a metal box, some good 5-way binding posts and some high-quality switches, and make your life easier. Use good sized wire, because a 1/2 Ω of parasitic resistance in your test harness is a 1/2 Ω that *won't* be there when you connect your crossover.

5 MAKING AN IMPEDOMETER

The actual connection is very simple. Let's refer to the diagram below:



If you need more signal level, you can insert an amplifier between the oscillator and the 1 kΩ resistor.

Calibration is simple: connect the calibration resistor to the output (via the switch, if you've constructed it that way, or just hook the resistor where the speaker would be connected). Adjust the output of the oscillator and the gain of the meter until you get a reading in some convenient units that is the same as the resistance of the calibrator. For example, if the oscillator was putting out 1 volt into the 1 kΩ resistor, you'd probably find that the voltage across an 8Ω calibrator was almost exactly 8 millivolts. Fine, now you know that your impedomoter has a calibration factor or sensitivity of 1 mV/Ω. This is because we have calibrated our AC current source for 1 mA output. Remember Ohms law:

$$Z = \frac{E}{I}$$

so if I = 1 mA (0.001A), then, proportionally:

$$Z(Ohms) = E\left(millivolts\right)$$

You might want to adjust it for a higher level, like 10 mV/ohm. You see here why you might want an oscillator with a nice high output voltage, because you might want to measure the impedance at several different current levels. (I have a laboratory amplifier that's capable of more than 100 volts at 100 mA into a 1 kΩ load: this is very useful for measuring drivers at reasonably high current levels).

It's a good idea to check the calibration across the entire frequency range.

6 MEASURING IMPEDANCE

To actually measure the impedance, make sure your setup is calibrated, then disconnect your calibration resistor and connect your speaker. Dial the oscillator to the desired frequency and then read the impedance. It's that simple.

If your want to know the impedance across the whole frequency range, it's good to measure it at 1/3 octave intervals. This will be enough to plot an pretty accurate graph of the impedance curve. Here are the standard 1/3 octave frequencies:

20 Hz	200 Hz	2 kHz
25	250	2.5
31.5	315	3.15
40	400	4
50	500	5
63	630	6.3
80	800	8
100	1,000	10
126	1,260	12.6
159	1,590	15.9
		20 kHz

To find a resonance, look for a frequency where the impedance is at a maximum. In a typical loudspeaker system, or a bass-reflex enclosure system, you'll find several such maxima. Record them all.

Look for other "critical points" such as minima in impedance.

An oscilloscope can be useful here. Connect the X axis to the oscillator output (shown as 'X' in the above diagram) and the Y axis to the same place as the AC voltmeter ('Y'). Adjust the gain of the X axis so that the trace takes up nearly the whole width of the screen. The Y axis gain can be similarly adjusted, but you'll have to keep changing it as the impedance changes.

You'll notice that, over most of the range, the trace is an ellipse aligned along a line going from the lower left to the upper right (if it goes in the opposite direction look for a switch on the scope called "phase invert" and push it). The elliptical shape indicates that the impedance has both a reactive and a resistive component. In fact, you can measure the phase by measuring the relative "openness" of the ellipse, though we won't go into that here.

What *is* important is that at some frequencies, the ellipse closes up into a line. This indicates the impedance is purely resistive, and this will occur at the exact center of a resonance, and is a reliable way of finding the resonant frequency.

The trace can also tell you other things. If the ends of the ellipse are flattened or distorted, it's likely that you've exceeded the output voltage capability of your oscillator or amplifier. Sorry, only one way to fix it: turn it down and recalibrate your impedometer. If the traces shows a figure-8 shape, especially near and at resonance, you're likely looking at some non-linearity in the driver itself. Finally, if your trace looks fuzzy or has lots of little wiggles on it, you have an electrical interference problem that you'll have to cure.

7 CONCLUSION

The impedometer method provides a simple, inexpensive, reliable, repeatable and reasonably accurate way of measuring loudspeaker impedance, assuming you use reasonable instruments and take care to check and maintain calibration.

There are certainly more steam-lined methods, including new computer based applications that are fast, very detailed and accurate. Not everyone can afford such a solution, not everyone has the time, and not everyone needs that level of sophistication. The impedometer method is useful for occasional measurements, and the equipment needed is quite useful for an entire array of audio measurements.