Catching Some Z's

Nearly everyone in this business has heard the term "impedance" at one time or another. We speak pretty freely of high and low impedance microphones and microphone inputs, loudspeaker impedance, and even 75 ohm coax for our video signals, but the concepts of source and load impedances and how they relate is often misunderstood. This session we'll take a look at what impedance means, when it's important to match input and output impedance, when it's important not to, when you need to be concerned about it, and when you don't. It's hard to talk about impedance without giving some examples, so we'll be looking at microphones, speakers, and power amps, too.

Y Z (and what about X)?

Impedance is the resistance to the passage of an alternating current. It's abbreviated with the letter Z, and the practical unit of measure is the ohm, just like DC resistance. The abbreviation V for voltage is pretty obvious, as is R for resistance. Even I, the abbreviation for current makes sense when you recognize that French scientists made contributions to electrical theory early on, and the French word for current is intensitie. Mr. Volta was Italian and Mr. Ohm was German, but Z doesn't mean anything in any language other than mathematics.

The following is Internet folklore, and may actually be true, but it's interesting. Voltage, current, and resistance were initially studied using direct current (DC), which is what you get from a battery, but things got more complicated when the scientists started to study the behavior of devices under alternating currents (AC). They discovered that capacitors and inductors exhibited different "resistances" depending on the frequency of the alternating current. They called that characteristic "impedance" and split it into "real" and an "imaginary" parts - the real part being the resistance that's constant, and the imaginary part called reactance, which varies with frequency. The vector sum of the real and imaginary parts is known in mathematics as a complex number, with the generalized form: $Z = X + iY$, where i represents the imaginary part of the number. Impedance was the only thing in electricity that needed a complex number to represent it, so they adopted the letter Z out of the general equation as an abbreviation.

Sources and Loads

Ever notice, particularly in an older house, how the lights dim momentarily when the refrigerator or air conditioner switches on? If the wiring is old and thin enough, the lights stay a little dimmer all the time the refrigerator is running. On a much smaller scale, the same thing happens when you interconnect any two pieces of studio equipment. No, your house lights dim when you connect your DAT to your console's mix output, but if you were to measure the output level of the console with a very sensitive voltmeter before and after, you'd see that your connection caused a very small change.

The reason why the voltage change is insignificantly small is that nearly all modern audio equipment, with only a couple of exceptions, are designed with relatively low source (output) impedance and relatively high load (input) impedance. In order to understand why, let's look to one of the fundamental formulas of electricity, Ohm's Law. Ohm stated that the current flowing through a resistance is directly proportional to the voltage applied, and inversely proportional to the resistance. I know I told you this column was about impedance, but we're going to cheat for the moment and just talk about the steady-state part of impedance, resistance. We'll see later on why this is a reasonable approach. The common statement of Ohm's Law is fundamental formula,

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

Mismatching Impedances

A simple but effective model of an unbalanced output (we'll use unbalanced sources for simplicity, but the same thing works for balanced sources) is a voltage source with a resistor in series with it. This could represent the output of a mixer, a signal processor, or a recorder. An input can be modeled simply by a resistor between the input connector and ground. Undignified as it is to represent the expensive recorder that you've plugged into your mixer as a single resistor, it allows us to complete our simple circuit:

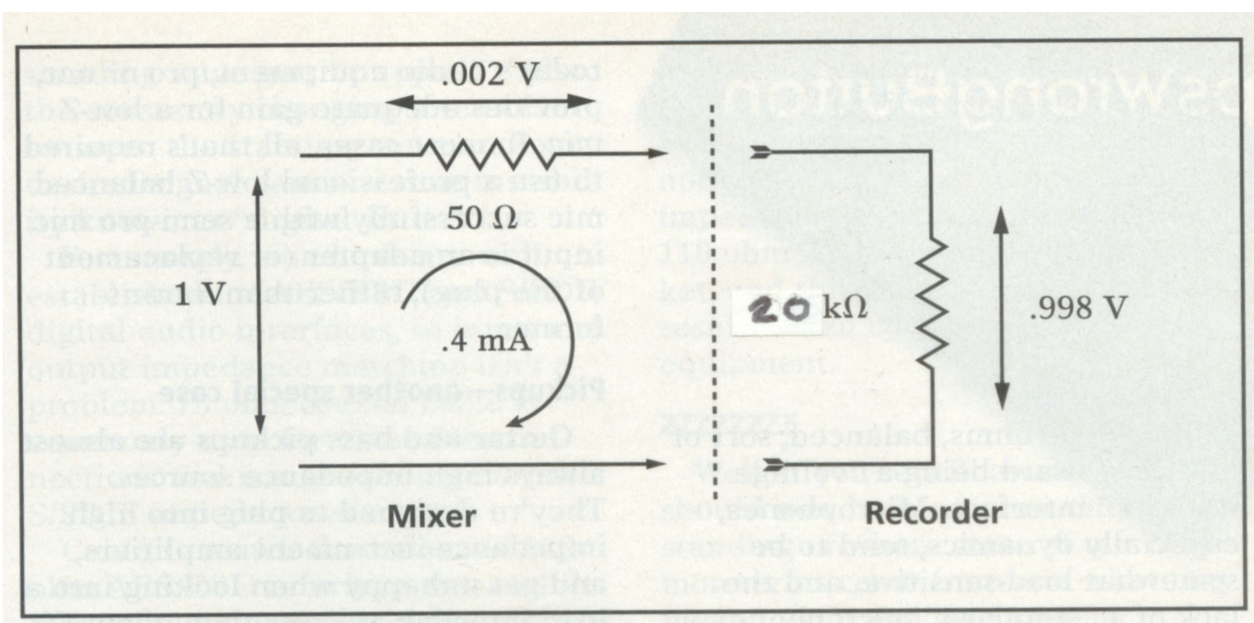

figure 1

Most modern equipment makes liberal use of operational amplifiers which, in the most common output applications, appears as a source impedance on the order of 50 ohms. When used as input amplifiers, most opamp input circuits come out in the ballpark of about 25Kohms (25,000 ohms). I've used those values in the diagram above. Notice that the same current flows through both the 50 ohm source and the 25Kohm load. Applying Ohm's Law, we see that this current is $\frac{1V}{(50+25000)\Omega}$ or about 0.00040 amperes (0.04 milliamperes) - not very much current, but here we're just pushing electrons around, not loudspeaker voice coils, so it doesn't have to do much work.

Now, juggling the terms of Ohm's Law, we see that that current causes a voltage of 0.998 volts to appear across our 25Kohm load, while the remaining .002 volts appears across our 50 ohm source. We've divided the voltage between the source and the load, but we managed to get nearly all of the voltage out of the mixer and into the recorder where it will do us some good.

Now, for illustrative purposes, let's do something not so smart and substitute a set of headphones for the recorder. Typically, headphones have a load impedance of 50 to 100 ohms, so let's substitute 100 for 25K and run the numbers again. Now, for the same input voltage of 1 volt, we have a current of 6.7 ma, quite a bit more than in our previous example. In addition, the voltage divider situation is here considerably different. In the first example, the 50 ohm source impedance, and hence the voltage lost across it, was insignificant compared to the load impedance. Now that our load impedance is much closer in value to the source impedance, look at what happens when we crank the numbers: We lose .33 volts across our source (which only leaves the mixer in the form of heat), and have only .66 volts across our headphones. Chances are this won't be very loud, so let's turn it up to 11.

A typical "+4 output level" console can put out nearly 10 volts before it runs out of headroom, so there's room to crank it up. All our numbers get multiplied by 10 and we'd probably now have enough level to drive our headphones except for one thing - most opamps typically used in modern audio circuitry are unable to provide 67 ma of output current, so we'll run out of steam and trade distortion for our desired output level.

So here's the lesson: With equipment that's designed for voltage transfer, you don't want to match source and load impedances. You want the source impedance to be low and the load impedance to be high. A good rule of thumb is about 50:1 ratio minimum. Since most equipment today is designed with a much higher ratio than that, you can easily "mult" an output to several inputs without overloading your source. Typically you might split a tape track output to more than one mixer input so you can set different equalization and effects in different parts of the song, and this discussion illustrates that it's not an electrical problem to do so.

Matching Impedances

One instance where it's important to match source and load impedances is in connecting loudspeakers to power amplifiers. Since a loudspeaker is a mechanical device and needs to do some hard work pushing air molecules around, we need to transfer electrical power, which is defined as voltage multiplied by current. A power amplifier has its limits for both the current and voltage it can produce, but the limits are much higher than our opamp mixer output. Connecting a speaker that's lower than the rated output impedance of the amplifier will tend to draw excessive current, possibly damaging the amplifier. Connecting one that's higher than the rated output impedance won't draw the full current when the amplifier is putting out it's maximum voltage, so you won't get all the power that you paid for to the speaker.

Most solid state power amplifiers today have source impedances somewhere around 5 ohms, and you'll typically find power ratings stated something like "100 watts at 8 ohms, 150 watts at 4 ohms", which indicates that it'll stay within ratings down to 4 ohms, but you won't quite get twice the power with a 4 ohm load as you will with an 8 ohm load.

Impedances (as resistances) add in series, but in parallel it's more complex. The formula for resistors in parallel is: $R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + etc}$

Since loudspeakers are typically built as 4, 8 or 16 ohm units, you can generally match things up. You want to make sure, though, that in your enthusiasm for adding more speakers, you don't load your 8 ohm amplifier down with 2 ohms.

There's another special flavor of impedance associated with power amplifiers that's generally not of concern with other pieces of equipment. This is the impedance that the speaker sees when looking back into the amplifier's output, and, because of feedback circuitry used in power amplifiers, is not the same as the source impedance. Typically, the impedance looking back into the amplifier is extremely low, well under one ohm, and it effectively damps extraneous motion of the speaker cone due to it's mechanical momentum. This "backwards" impedance is often called the amplifier's damping factor, and in general, the lower it is, the more accurately the motion of the speaker cone will represent the signal that's going into the amplifier, with minimum ringing and overshoot.

Microphones

Dynamic and ribbon microphone elements have an impedance of just a couple of ohms. Although there's no real need to increase a source's impedance, the output voltage from the guts of a mic is so low that it needs to be amplified before it can even be safely sent down a cable. Virtually all dynamic mics have a transformer inside the case to increase the output voltage, and in the process the impedance is also increased. The voltage ratio of a transformer is equal to the ratio of the number of turns of wire on the input side to the output side. The impedance ratio is equal to the square of the turns ratio. If a transformer increases the microphone element's signal by 10 times, it will increase the source impedance by 100 times (10 squared). So if the basic element has an impedance of 1.5 ohms, our transformer would step it up to 150 ohms, typical of most modern Low-Z dynamic mics.

A condenser microphone element needs some circuitry in order to produce a useful signal, and this always includes some amplification. The output level and impedance of a condenser mic is determined by the electronics, though a transformer is frequently employed to provide a balanced output. Typically a condenser mic has an output impedance about the same as a Low-Z dynamic, though its signal level is usually somewhat higher.

The rise of home recording (wire and disk) in the 1940's and the associated demand for low cost microphones brought us the first common truly high impedance mics. Piezoelectric crystal and (later) ceramic microphone elements are built from materials that are very poor electrical conductors, hence they have an extremely high source impedance. On the other hand, they have fairly high output level. Electronics manufacturers liked this because their amplifiers didn't require input transformers and they could usually save a tube since less amplification is required.

The fidelity of these piezo mics was pretty poor, but good enough for the times. Today about their only applications are for speech (paging and communications) and for amplifying blues harmonica, plugged the piezo mic directly into a guitar amplifier.

Demand for higher quality microphones in the home brought us the high impedance dynamic mic. Instead of using a transformer with a 10:1 turns ratio, simply changing the ratio to around 300:1 brought the output level and impedance up to about that of a piezo mic but retaining most of the quality of the dynamic element.

A couple of things happened in the '70's that changed the way we build microphones and microphone input circuits. First, we discovered that most low impedance microphones sound better when working into a load impedance of about 1200 ohms than they do when working into a matched load of the 150 ohms typical of professional mic preamps of the time. Today nearly all console and preamp microphone inputs are around 1000 to 2000 ohms, balanced, sort of half way toward being a "voltage transfer" interface. Microphones, especially dynamics, tend to be somewhat load-sensitive, and the lack of a "standard" microphone input impedance leads to contradicting opinions of the sound of a particular mic or mic preamp. Unless several combinations are tried, it's not clear if one is hearing the difference between preamps or the way a different preamps affect the sound of a particular mic.

Another thing happening around that time was the introduction of "semi-professional" studio equipment. Electronically balanced low impedance microphone input circuits hadn't yet been perfected, and good transformers are expensive, so the semi-pro manufacturers brought us a new flavor of mic input. These mic inputs (common on both mixing consoles and integrated multitrack recorder/mixers) were unbalanced, almost always using 1/4” phone jacks, but with an input impedance somewhat higher than what’s appropriate for professional Low-Z mics. The hitch was that many were designed around the lower cost High-Z dynamic mics popular at the time and didn’t have quite enough gain to work well with the lower output Low-Z mics.

The solution was to add an input transformer, though at the user’s expense. Since most semi-pro users had a tight budget, inexpensive plug-in transformers of questionable quality were common in the personal studios of the day. Fortunately, most of today’s audio equipment, pro or not, provides adequate gain for a Low-Z mic. In most cases, all that’s required to use a professional Low-Z, balanced mic successfully with a semi-pro mic input is an adapter (or replacement of the plug) rather than a transformer.

Pickups - another special case

Guitar and bass pickups are almost always high impedance sources. They’re designed to plug into high impedance instrument amplifiers, and get unhappy when looking into a load impedance lower than about 50 Kohms. A tube input stage typically has an impedance of 1 to 10 megohms, one of the differences that contributes to the “tube sound”.

Connecting a pickup to a low impedance input (for example, a microphone input) will cause most of its signal to be dropped across its own high source impedance (recall our example with the headphones connected to the mixer line level output). This will reduce the signal level available at the plug and cause the pickup to sound dull.

The common studio tool to use, when we want to record the pure pickup sound, is a direct box. This is nothing more than an impedance converter. A passive direct box consists of a transformer, occasionally with a few components added to control ringing or shape the frequency response to emulate a speaker cabinet. Transformer direct boxes typically have input impedances between 50K and 100Kohms, and output impedances to match balanced low impedance microphone inputs. Active direct boxes have a solid state or tube input stage typically providing an input impedance well above 1 megohm for truly minimal loading of the pickup.

There’s no reason why guitar pickups have to be high impedance sources, it’s just that they’ve always done it that way. The electric guitar industry is much larger than the recording industry, so they call the shots. Chet Atkins used some low impedance pickups for direct recording back in the ‘50’s, and there was a Les Paul Professional Recording model guitar which had low impedance pickups and was equipped with an XLR connector. It wasn’t well accepted, however, because you couldn’t plug it into just any amp, and it wasn’t compatible with common stomp boxes.

So what about this “complex” stuff?

So far, we’ve talked about impedances as if they were simple resistors. We can get away with this much of the time because, compared to resistance, the other components of impedance are insignificant at audio frequencies. In the audio field, we can usually ignore the inductance of cables (though it’s important to the Telephone Company running 10 miles of wire), but we can’t always ignore the effect of capacitance. The conductors and shield of a cable form a capacitor that’s connected in parallel with the load resistance. Cable capacitance is generally specified in picofarads per foot, with around 33pF/ft being typical. The longer the cable, the bigger the capacitor, and the higher the frequency, the lower the “AC resistance”, which we call reactance.

The formula for capacitive reactance is $X_c = \frac{1}{2\pi fC}$ A 150 foot cable with a capacitance of 33 pF/foot at 20 kHz looks like $\frac{1}{2 \times \pi \times 20{,}000 \times \left[150 \times \left(33 \times 10^{-12}\right)\right]}$ or about 1600 ohms. When hung across our typical 150 ohm microphone source impedance, this will cause a loss of about 1 dB at 20 kHz. A look at the formula shows that the reactance goes up as frequency goes down, so there will be even less loss at lower frequencies. Not perfect, but not too bad, as if a gentle low-pass filter was connected across our microphone. Mic cables of this length or greater are common in remote recording and large PA situations, though today’s trend toward perfection is leading us to putting mic preamps right at the stage and driving long cables with a more robust amplified, very low impedance signal.

Cable capacitance becomes very significant when we have a high impedance source, such as an instrument pickup or Hi-Z microphone. Remember our guitar pickup that doesn’t like working into a load impedance lower than 50 Kohms? If the source and load impedances are equal, we’ll drop half our voltage across the source and the other half across the load. That’s a 6 dB loss. Rearranging the terms of the capacitive reactance formula to solve for capacitance, we have $C = \frac{1}{2\pi f X_c}$
Accepting that 7 kHz is about the highest frequency you can expect to get out of even the most screeching guitar, we can calculate that a capacitive load of $\frac{1}{2 \times \pi \times 7{,}000 \times 50{,}000}$ or 455 pF is all we want to accept. At 33 pF per foot, that’s about 14 feet of cable. Its no wonder your guitar doesn’t sound very good with a 50 foot cable.

Impedance and Digital Audio

In the world below 20 kHz, we need to be concerned with the impedances of our sources and loads, but we don’t worry too much about what kind of wire we use to interconnect them. If the speaker wire is heavy enough to carry the current, and if the mic cable is sufficiently well shielded so that it doesn't pick up hum, that's generally good enough. Now that we find ourselves sending digital data from one unit to the next, a signal that's a radio frequency (RF) around 6 megahertz. At these frequencies, the impedance of the cable itself becomes significant.

The electrical wavelength of a 1 kHz signal in a perfect conductor is about 186 miles, considerably longer than any cable in our studio is likely to be. (note: the acoustical wavelength that might be familiar to you from studying delays and echoes is a bit less than 1 foot. The difference is that sound travels through the air at about 1100 feet per second, and electricity travels at the speed of light, 186,000 miles per second) At 6 MHz, however, the wavelength through a piece of coaxial cable is on the order of 120 feet (real world cable slows things down a bit).

Like audio, if the cable length is short compared to the wavelength of the signal we're passing through it, it doesn't make much difference what kind of cable you use. If we consider cable shorter than about 1/100 of a wavelength to be short enough to ignore, almost any practical piece of cable is long enough to matter when interconnecting 6 MHz signals. If the source, the load, and the cable impedance isn't accurately matched, reflections of the signal will occur along the cable. The these reflections (they're called "standing waves") can have several detrimental effects ranging from a small loss of power to a total loss of power (when the cable length is exactly a half wavelength and the standing wave gets "trapped"). Also, the constantly changing interaction between the standing wave and our desired signal causes a time instability known as "digital jitter".

Fortunately, standards are well established for AES/EBU and S/PDIF digital audio interfaces so input and output impedance matching isn't a problem. 75 ohm coaxial cable is commonly used for video interconnections and is a good match for the S/PDIF impedance standard. Cable to match the balanced 110 ohm AES/EBU interface was a while in coming, though. For about the first ten years of digital audio, people used microphone cable (since the XLR is the standard connector for AES/EBU) for interconnections, and as resolution got better, we began to notice the effects of improper impedance matching. There is now 110 ohm cable available on the market, and this should be used for best results when connecting AES/EBU equipment.

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Well, if you're still awake, you should now have a better understanding of where some of our common terms come from, and what they mean to you and your system.