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Amps and Speakers, Living Together

By Pat Brown

The role of impedance, resistance and reactance in an audio system

Click here for Audio power trip Part 1

My column last month (LSI February 2003 issue) provided a look at some of the basic fundamentals of power generation and consumption. All of the examples used were not specific to audio. Greater insight into audio can be gained by looking outside of the traditional ways that we understand these concepts and learning from things that we experience everyday. This issue, we will continue in the same form as we explore the complex impedance and its role in power delivery systems.

In mechanical systems (which include loudspeakers), the frictional component of the load is accompanied by the very real but less tangible (at least intellectually) effects of mass and inertia. A body at rest wants to stay at rest, so the mass of an object must be overcome by the applied force to get it into motion. Once the body is in motion, it wants to stay in motion. Some of the applied energy has been stored in the load, and serves to lessen the amount of applied power that is required to keep the mass in motion. The mass of the load produces a reactance - an opposition to the applied force that is frequency-dependent.

Isaac Newton gets much of the credit for quantifying these effects. The electrical equivalent of this mechanical characteristic is called inductance - a characteristic that all loudspeakers possess, and one that the amplifier has to deal with. When the total impedance of a load has both resistive and reactive components, we say that the load has a complex impedance.

REFLECTED POWER

Reactive elements affect the flow of power from one system to another. To further understand the complex impedance, let's take a trip to Home Depot and consider a mechanical system not unlike a loudspeaker. Grab a shopping cart and head down the aisle. Shopping carts don't have much mass, so they are pretty easy to handle when they are empty. Let's visit the construction department and load a half-dozen bags of ready-mix concrete into the cart. The added weight has made the cart much harder to push, so we dig in and extend a lot of effort to get it going. But once it's in motion, we can let up on the applied pressure.

The shopping cart is now a mass in motion that wants to stay in motion. Its momentum carries it forward - which is a bad thing for the unwary consumer that wanders across your path. The mass reactance of the cart stored some of your early effort to get the cart going, and is now being reflected (returned to the source), making it easier for you to keep the cart in motion. The stored energy (which you supplied) must now be overcome to stop the cart.

Like a moving mass opposes changes in velocity, an electrical inductance opposes changes in the current flowing through it. This opposition is called inductive reactance. And because loudspeakers are electro- mechanical devices, they exhibit this characteristic both mechanically and electrically.

How can one counteract the momentum of the cart? Does a "mechanical opposite" exist? If we connected a big spring between the cart and a rigid object (stay with me), the spring would expand as the cart moved farther from the object. This force would oppose the momentum of the cart, and could cancel it completely if its value were carefully selected.

Energy stored in a compressed spring, like momentum, is reflected back to the source - a concept that is sometimes learned the hard way if we are the source! "Springy" mechanical loads have compliance. The electrical equivalent is capacitance and the effect is capacitive reactance - another characteristic that loudspeakers possess. If the tension of spring and the momentum of the cart exactly compensate each other, only the resistance remains. The system (or circuit) is said to be in resonance.

INDUCTIVE AND REACTIVE

Just as mechanical loads have friction, momentum and compliance, electrical loads have resistance, inductance and capacitance. Acoustical loads (like the air) have the same properties. The "catch all" term for the total opposition to current flow into a load is impedance. In many circuits, the inductive and reactive components may be insignificant and can be neglected. This is the case for most interfaces in a sound reinforcement system, at least at audio frequencies.

In loudspeakers, reactance abounds and must be considered. Because all three are present we say that the loudspeaker has a complex impedance. A concise mathematical expression for impedance is shown in **Figure 1**.

$$Z = \sqrt{R_{AC}^{2} + \left(X_L - X_C^{2}\right)}$$

Impedance — Resistance — Inductive Reactance — Capacitive Reactance

Figure 1: This equation shows that the reactances are in opposition to each other.

The unit for impedance, resistance and reactance is the ohm. The equation tells us that the reactances are in opposition to each other. At some frequencies one will dominate the other. It is also possible for them to cancel each other, leaving only the resistance.

The equation also shows that impedance is a pretty complex quantity. Because reactance is frequencydependent, the impedance will have to be expressed on a graph.

The shopping cart experience is exactly what happens when we drive a real-world loudspeaker with an amplifier. The loudspeaker is a mass/spring system that will both reflect and consume the power that flows into it. At some frequencies the mass effects will dominate (the load is inductive), at others the spring effects will dominate (the load is capacitive), and at others these two effects will cancel and the load will be purely resistive. It's becoming easy to see why we can't accurately describe the impedance of a loudspeaker with a single number rating.

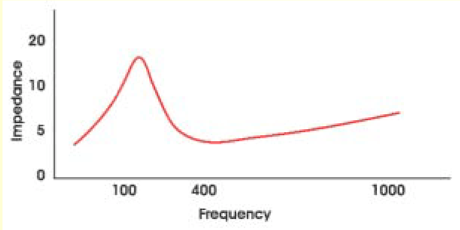

Figure 2: Impedance is a complex function of frequency.

The impedance is a complex function of frequency (**Figure 2**). Manufacturers usually state the nominal impedance on the spec sheet, such as 8 ohms. In reality, there won't be many frequencies at which the impedance is 8 ohms, a source of great confusion to those that have just obtained their first impedance meter and set out to measure every loudspeaker in the shop.

The DC resistance of the voice coil wire is the lowest value that the impedance can be, so it is of special interest when determining the maximum power flow into the loudspeaker. Look for the lowest point on the impedance curve when determining how many loudspeakers you can hook to an amplifier.

LOADING THE AMPLIFIER

In last month's column, we saw that a power source can be rated in available power. This is simply a measure of how much power is available, whether from an automobile, a jet engine or you on an exercise bike. Available power can be stated in watts or horsepower. When a time metric is included, it can be expressed in watthours, calories, or BTU (British Thermal Units). Think of available power as how much power a source can supply on a continual basis. Next, we must consider how much power we can get from the source - something that is determined by the load.

Physics, like audio (and life) has many ironies. We don't need knowledge of the load characteristics to state the available power from a source, but we do need detailed information about the load to determine how much power we can get. It is also becoming apparent that putting a power rating on an amplifier is no easy task. Every loudspeaker's impedance curve is different, so which one do we test the amplifier with? One way to do it is to use a purely resistive load - no reactive component. This levels the playing field when comparing amplifiers.

But in the real world of loudspeakers and transformers, there may be significant reflected power back to the amplifier (remember the shopping cart?). Can the amplifier handle reactive loads? If it can't, then it will likely fail in the real world of complex load impedances. Don't read more into an amplifier specification than what is there. Specs are great to get the "big picture," but they seldom tell the complete story.

POWER TRANSFER

The best way to understand power transfer from the amplifier to the loudspeaker is to put reactance on the "back burner" for a while and simplify the complex impedance to a pure resistance. This is not the real-world, but it's the next step in understanding what happens in the real world. Using resistance-only allows us to temporarily ignore the effects of stored and reflected power.

All of the generated power from the amplifier will simply heat the load resistor, and none of it will bounce back and slap the amplifier in the face (which is not an uncommon occurrence in sound systems, as evidenced by the smell of burnt resistors and semiconductors accompanied by smoke pouring out of the rack).

The power transfer between a source to a load is determined by the impedance ratio between the two, which is simply the load impedance divided by the source impedance. Since we are temporarily ignoring reactance, this becomes a ratio of the load resistance to the resistance in the amplifier's output circuit.

There is also resistance in the wiring, but we will also neglect it for the present (magic wire). The load resistance is the opposition to current flowing from the source, resulting in power conversion into heat. For a loudspeaker, the direct current resistance of a voice coil can be found with an ohmmeter. In most cases it's a low number - less than 8 ohms. This accounts for one part of the impedance ratio that determines the power transfer from the amplifier to the loudspeaker.

The other part is the source impedance of the amplifier. All sources have internal impedance - an opposition to the flow of current that is inside the device. The amplifier's internal wiring, circuit board traces, and transistors all have inherent resistances (all conductors of electricity do) and the electrons must fight through this internal opposition as well as the opposition of the load as they travel around the circuit. The source/load impedance ratio determines whether the generated power gets dissipated inside the amplifier, in the interconnecting wiring, or in the load.

In fact, all of these elements will dissipate power, but the idea, obviously, is to get it to the load. Since power is voltage times current, you need both to get an appreciable amount of power flow. If the load resistance is too high, less current flows (there's more opposition) and power flow is reduced. If the load resistance is too low, lots of current flows but the voltage (pressure) is reduced, so again power flow is reduced. The maximum power transfer takes place when there is a balance between these two extremes, known as the impedancematched interface (or just matched interface for short).

This condition exists when the source and load resistances are equal. Impedance matching has been around as long as time and space - nature does it all the time. It has been used to interface electrical devices for about 150 years.

CONSTANT VOLTAGE INTERFACE

Don't stop reading at this point! If you do, you might walk away with the idea that impedance matching is the proper way to hook an amplifier to a loudspeaker. Actually, it's a terrible way to do it, for several reasons.

First, in the matched interface, half of the available voltage from the source is dropped across the output impedance of the source, and only half of it gets developed across the load. While the matched interface has good power transfer characteristics, it doesn't have good voltage transfer characteristics. The way to get more of the amplifier's voltage to develop across the load (loudspeaker) is to make the load impedance higher than the source impedance.

It's kind of like sticking your thumb in the end of a garden hose - the pressure goes up as the flow is reduced, as evidenced by your red thumb. But because increasing the load resistance produces more opposition to current flowing from the amplifier (or water through the garden hose), the power transfer actually goes down. We are sacrificing power transfer to get better voltage transfer. This seems counterproductive, but this configuration can still produce plenty of power into the load - just not as much as is potentially available.

Are you ready for another irony? If you make the load resistance at least ten times higher than the source resistance, the voltage across the load is no longer affected by the load resistance's value. Going back to the water hose, if you stick your thumb into the end so tightly that the flow stops, you have realized the maximum pressure available from the source. From then on, you can't get any more pressure, even though you add more opposition. You have constructed a constantpressure interface.

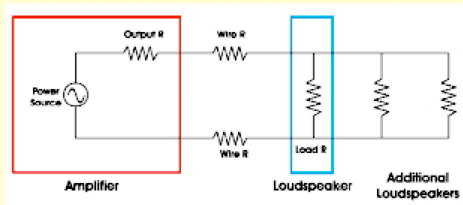

Figure 3: The amplifier/loudspeaker interface.

The analogous electrical interface is the constant-voltage interface. This mode of operation is nearly universal in audio (I always hate to say always). Output impedances are low relative to the input impedance that they are connected to. See **Figure 3** for a schematic representation of the amplifier/ loudspeaker interface.

TRADING OFF POWER TRANSFER

Why would we deliberately reduce the power transfer between the amplifier and loudspeaker by using the constant-voltage interface? Why not impedance-match and get maximum power transfer? There are several really good reasons.

The first is that the constant-voltage interface facilitates the connection of additional loudspeakers in parallel with the first. If impedance matching were used, and one loudspeaker were connected across the amplifier, the connection of a second one in parallel (or series) with the first one would reduce the power flow to the first loudspeaker. So, every time another loudspeaker is connected, the loudness of the existing ones would change (what a mess!). The constant voltage interface maintains the same voltage (and power flow) to the existing loudspeakers connected to the amplifier as additional ones are hooked-up.

Now don't get carried away - if you connect too many you will upset the conditions that made this a constant voltage interface to start with. But it is usually possible to connect one, two, or even three loudspeakers onto a power amplifier and still maintain the constant- voltage condition. We just have to make sure that the parallel combination of all of the loudspeakers doesn't get low enough to make the amplifier's voltage drop. This is why amplifier manufacturers specify the minimum impedance that the amplifier can safely drive. As each additional loudspeaker is connected in parallel with the first, the total impedance seen by the amplifier is reduced, so the current flow goes up.

This may seem counterintuitive, but think of a bucket of water with two holes in it instead of one. More water will flow out of the bucket in a given span of time. Adding more holes will allow even more flow. When you hook-up additional loudspeakers to an amplifier, you're putting more holes in the bucket! If load impedance seen by the amplifier gets too low there's a lot of fallout. The amplifier's voltage might drop, its current producing abilities may wane, and the otherwise relatively small amount of resistance in the interconnecting wires and plugs can start to become a factor. If operated this way over time, the amplifier may actually shut down or burn up.

We now have one more piece of the puzzle for discussing meaningful ways to understand and specify power transfer in audio circuits. Next month we will discuss some characteristics of audio signals that determine how much power they are likely generate into the complex impedance of the loudspeaker.

*Pat Brown, with his wife Brenda, heads up Syn-Aud- Con, leading audio training sessions around the world. For more info, go to **www.synaudcon.com**.*

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