Amplifier Output Impedance; The Amplifier - Loudspeaker Interaction

One of the most commonly misconstrued topics on audio amplifiers is output impedance and what it means for your loudspeakers. Many articles touch on one aspect of the subject without considering others. Some have misinformation altogether. This article should give a good understanding on how amplifier output impedance affects the interaction between the amplifier and loudspeaker.

The best way to think of the output terminals of an audio amplifier is an AC voltage generator or source. AC meaning alternating current, where the signal current (the waves that make up music in this case) varies sinusoidal with time. When current varies with time, so too does the voltage through a resistive load. AC Voltage, Voltage AC, or VAC are just nomenclatures for the same thing and all can be used interchangeably.

It is also important to keep in mind that the standard of measuring AC voltage is in RMS. In engineering, values of AC voltage and current are assumed to be RMS unless otherwise specified such as peak-to-peak, or peak. A quality digital multi-meter on the AC function will measure RMS values as well. The significance of RMS is beyond the scope of this discussion, but in simple terms, AC voltage or current measured in RMS allows the electrical power delivered to an external load from an AC source to be directly compared to the electrical power delivered to an external load from a DC or direct current source.

For the rest of this discussion we will use the Engineering standard that

- Current in Amps (AC or DC) = I
- Voltage (AC or DC) = V
- Resistance in Ohms = R

Along with the AC voltage model, the output of an amplifier has output impedance, or more simply resistance, in series with the output voltage generator. This is due to the internal construction of the amplifier. This alone is not very exciting, but how this impedance interacts with a loudspeaker load is.

Amplifier Output Model

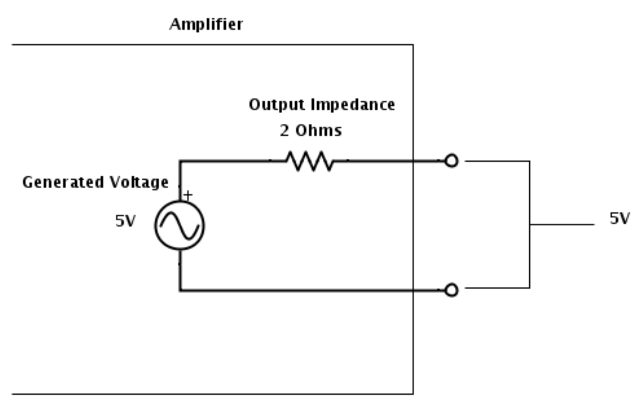

Figure 1

Figure 1 above shows the electrical model of the amplifier output. In this case, the amplifier is developing a 5V signal. The output impedance is 2 ohms. Ohm’s law states that the voltage drop across a resistor is proportional to the voltage and the current.

Ohm's Law:
V = IR

Since there is no external load applied across the output of the amplifier, there is no current flow. The circuit is said to be incomplete or "open." Applying Ohm's law, we can first find the current and prove that it is zero.

I = V / R = 5V / (2-ohms + infinity-ohms) = 0A

In the denominator due to the open circuit, we have an infinite resistance term. Any number divided by infinity is equal to 0.

Using Ohm's law again we can find the voltage dropped across the 2-ohm output impedance.
0A x 2-ohms = 0V. The voltage drop across the amplifier's output impedance is 0V since there is no current. Therefore, at the output terminal, we would measure with a multi-meter the full 5V developed by the amplifier.

Now let's add a 16-ohm loudspeaker load across the output.

16-ohm Load

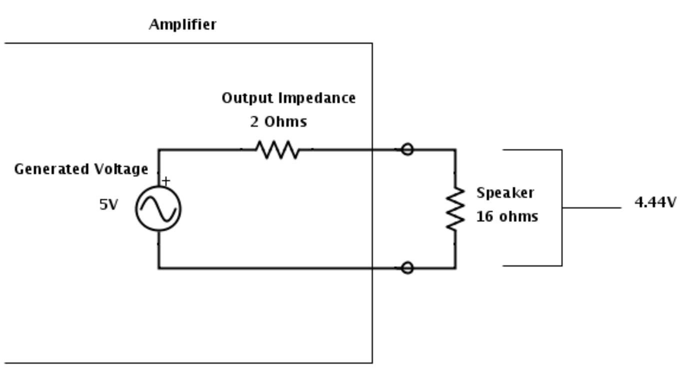

Figure 2

The output of the amplifier is no longer open as there is now a completed loop for current to flow. Using Ohm's law, we can determine the current. V/R = I
5/(2 + 16) = 0.278 Amps. Since the loop is closed and we have current flow, Ohm's law tells us that the output impedance of our amplifier will now consume some voltage due to the current. This means that only a percentage of our 5V generated will reach our speaker! The voltage across the speaker is simply (0.278A x 16) = 4.44V! We have lost 11% of our 5V potential across the amplifier's own output impedance!

What if the speaker load was 8-ohms?

8-ohm Load

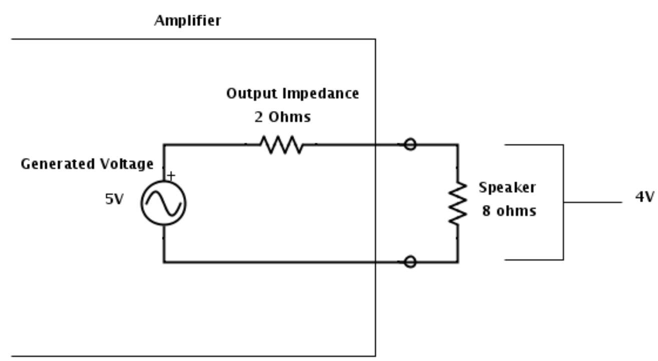

Figure 3

The loop current would be 5/(2 + 8) = 0.5A. The current has increased since the total load seen by the amplifier has decreased. The voltage across the speaker load is now
(0.5A x 8) = 4V. We have now lost 20% of our 5 volts!

How about a 2-ohm load?

2-ohm Load

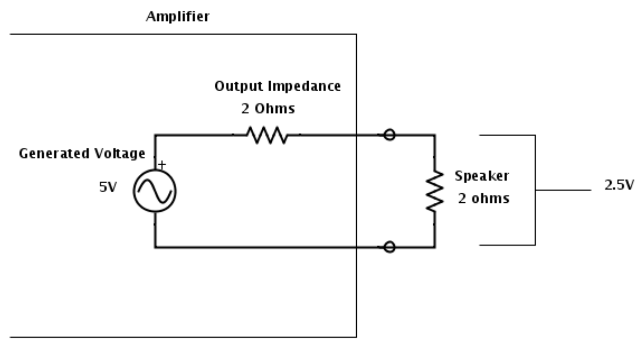

Figure 4

Our speaker would see 2.5V, only 50% of the 5V available! This makes sense intuitively since both the output impedance and the speaker load must consume the total 5V available and their resistances are equal.

A Real World Loudspeaker

So far we have been using the terms resistance and impedance interchangeably but there is a difference. The term impedance implies that the value, in ohms, varies with frequency. A resistance, such as a resistor, is fixed in value across frequency.

Amplifier output impedance, although called impedance, is usually relatively fixed across frequency and only undergoes minor fluctuations. It is analogous to a resistor in most cases. This terminology is confusing I know but stick with it.

A loudspeaker on the other hand is almost always highly reactive, meaning its impedance varies wildly with signal frequency. A typical 8-ohm moving cone transducer can have impedance as low as 4-ohms at bass frequencies and an impedance as high as 70-ohms or more at high frequencies! The 8-ohm rating is simply an average for the usable range of the driver, hence why speakers are listed as an 8-ohm impedance, not an 8-ohm resistance.

(Note there are some speaker types with very flat impedance characteristics. These speaker types are considered to be easier to drive by an amplifier)

From the examples above, it should be clear that the voltage developed across the speaker will vary with the impedance! This will cause the speaker to produce some frequencies louder than others since the load voltage fluctuates and thus power delivered to the load also fluctuates.

Using a loudspeaker that has a 4-ohm minimum and a 70-ohm maximum and the same 5V 2-ohm output impedance amplifier from before: Vmin = 3.33V and Vmax = 4.86V. This is a 46% change in the voltage across the speaker due to its changing impedance!

Lowering the Output Impedance

Now let’s do the same example with an amplifier still developing 5V but has an output impedance of 1ohm: Vmin = 4V Vmax = 4.93V. Now the percent change in voltage across the speaker is only 23%.

This change in voltage due to varying loads (in this case the loudspeaker) is known as regulation. The better the regulation, the smaller the change in voltage delivered to a load due to impedance fluctuation of the load itself. Lowering the output impedance of the source improves load regulation. Thus, the apparent volume of the speaker will remain more constant across all frequencies. This is very important for high fidelity sound reproduction.

An ideal amplifier would have an output impedance of 0-ohms, but we live in a world bound by the laws of physics. However, some amplifiers can get very close.

Speaker Control

A second, and perhaps less obvious reason, for designing an amplifier with low output impedance is speaker control and dampening. However, speaker control is possibly the most important factor in determining how a speaker will sound with a given amplifier.

Have you ever tried connecting the two terminals on a small DC electric motor with a piece of wire? What happens if you then try to spin the shaft? From childhood tinkering or physics class in school, you may have noticed that it becomes much more difficult to spin than if you leave the terminals open.

Just as an electric motor will consume power by turning electric energy into rotational energy, rotational energy (as an input on the shaft of the motor) will be converted to electrical energy. Motors not only consume power but they are generators too. Adding the short between the two terminals of the motor makes it difficult to spin since the energy produced has nowhere to go. Therefore, the motor attempts to cancel out what you just did to it by making it harder to spin the shaft. The faster you spin the shaft, the more rotational resistance felt. In an ideal world with zero losses, it would be impossible to spin the shaft since every bit of energy produced would be spent trying to undo the rotational movement you just made. However, motors have losses due to the resistance of the armature windings and magnetic field losses.

Well, a loudspeaker is no different than an electric motor. In fact, it is just a linear motor that converts electricity into linear motion rather than rotational. The lower the amplifier output impedance is, the closer we come to the short circuit motor analogy. This short consumes any external forces imposed upon the cone of a speaker and the linear motion is resisted.

If you have a loose woofer lying around you can do a quick test to prove this. Tap on the cone gently with your ear hovering just above the speaker. You should hear a deep low note. Now short the terminals together with a piece of wire and tap. The low note is gone and the speaker sounds very "restricted." Even this tiny amount of movement from the tapping has been canceled out. This should also give you an idea on how sensitive a speaker motor is!

This property is known as control or dampening of the loudspeaker. An amplifier that exhibits low output impedance has better control over the motion of the cone since the speaker is better forced to move to the voltage signal from the amplifier and is less affected by external forces.

External forces are mainly composed of the cone's momentum, the suspension or springiness of the cone that returns it back to its natural resting state, and acoustic loading from air pressure. All of these effects get magnified at higher excursions where the cone travels more distance.

For example, if a woofer cone is driven outward hard, it has some momentum and loading that will make it move nonlinearly to the amplifier signal. If we just consider momentum, the cone would want to continue moving in the same direction even if the amplifier attempts to drive it in the other direction. This is especially true with low bass frequencies, which require lots of cone movement. An amplifier with lower output impedance is said to have tighter bass and better faster bass control. The linear overshoot and nonlinearities due to cone mass, suspension, and acoustic loading is minimized.

Reducing The Effects of Speaker Generated Voltages

Since there are internal losses in an amplifier (output impedance) and in a speaker, there will always be some amount non-linearity in the speaker movement compared to the amplifier signal. As with the electric motor example, we can still turn the shaft even with a short circuit.

Due to this fact, and the fact that any motor is also a generator, the cone overshoot will produce power and therefore a voltage. However, this generator is now the speaker not the amplifier. The load that the speaker sees is everything connected to it. This includes the crossover and other speakers (in a multi-way speaker system), and the amplifier's output impedance.

Loudspeaker Voltage Generation Model

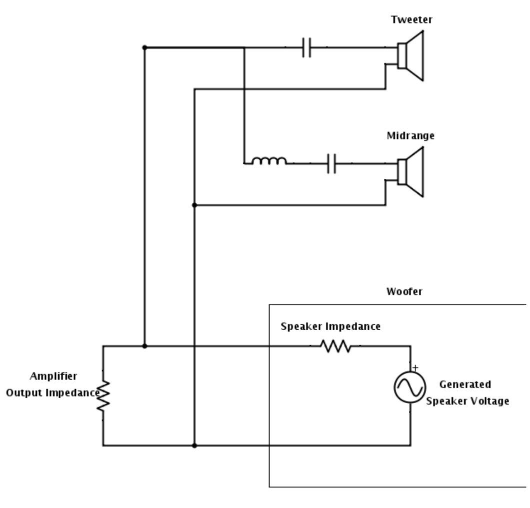

Figure 5

From figure 5 above, we can see this new voltage generation model due to woofer overshoot in a multi-way speaker system. Analogous with the signal generation of an amplifier, the voltage produced by the loudspeaker is in series with the loudspeaker's internal impedance. The speaker is now driving the output impedance of the amplifier paralleled with the crossovers and other drivers of a multi-way speaker system.

Now let's say that an 8-ohm woofer produces a 5V signal due to cone overshoot and the amplifier output impedance is 2-ohms as before (see Figure 6). Using Ohm's law, the voltage dropped across the output impedance of the amplifier is 1V.

In reality this would be less than 1V due to the parallel connections of the other speakers. Their parallel impedance would reduce the total effective impedance seen by the speaker. However, for the sake of analysis, we will assume that the other crossovers and speakers have an infinite impedance but are still connected as illustrated. Therefore, we only need to consider the amplifier's output impedance for our calculations.

This 1V produced across the amplifier's output impedance is also developed across all of the other connected speakers! Therefore, any voltage overshoot produced by the speaker is reflected into all of the other drivers. The amount of which is determined by the amplifier's output impedance, 1V in this case. This means that the other drivers in a multi-way speaker system may move and reproduce the overshoot nonlinearities in response to external cone movement in any of the other drivers!

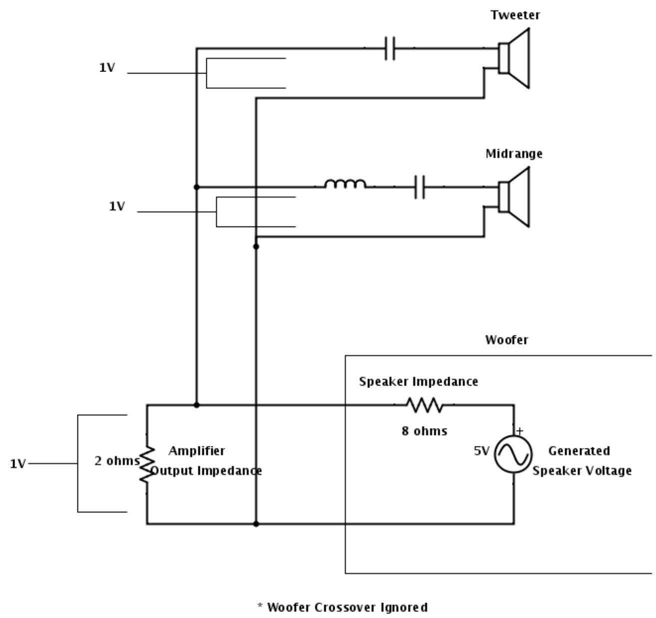

Figure 6

If we reduce the amplifiers output impedance to 1-ohm above, the voltage developed across the amplifier's output impedance is equal to 0.556V. This is almost half from the previous case! This means the voltage reflected into the other drivers is also now 0.556V. The other drivers in a multi-way system will respond less to the same amount of woofer overshoot as before!

Lowering the output impedance will lead to a cleaner sounding multi-way loudspeaker with less blurring and a more precise feel. This is caused by a decrease in reflected overshoot and noise into the other drivers. It can be said then that the lower the output impedance of an amplifier, the better it is at shunting any developed speaker motor voltage to ground, reducing the effect of this voltage on the other drivers in a multi-way system.

Conclusion

From this discussion we have looked into three factors that support the conclusion that an amplifier with low output impedance is a more ideal amplifier.

1. Lower output impedance improves voltage regulation into the varying impedance of a loudspeaker.

2. Lower output impedance forces the speaker to move quicker and better follow the power delivered by the amplifier. The speaker is better controlled and fidelity is increased,

3. Lower output impedance reduces the voltage reflected back into the other drivers in a multi-way speaker system when the other drivers inevitably produce small signal voltages due to overshoot and nonlinearities.

From this we can conclude that the performance and sound of any speaker system is dependent on the amplifier as well. A speaker system compared against two identical amplifiers, only having a difference in their output impedance, will sound dramatically different.

It may seem like that an amplifier with the lowest output impedance is the best amplifier. However, it is essential to keep in mind that there are many other factors in determining the quality of an amplifier. Pursuit of low output impedance at the expense of other parameters is not good design. The best audio amplifiers strike a balance between all of these parameters.

Maximizing one parameter will inevitably destroy others. Any product in the marketplace must strike this balance, or at least, the designers must be aware and make a conscious decision on which parameters to consider. An extremely low output impedance amplifier doesn't mean it sounds good.

Additionally, the resistance from the speaker cable can be lumped into the output impedance of the amplifier. Long runs of poor quality speaker cable can "spoil" an amplifier design that boasts low output impedance. Shorter cables are always better.