

Loudspeakers and Power Amplifiers

I am not going to enter the debate about which amplifier or wire sounds best. In the context of loudspeakers and rooms, any real or imagined influences they have are of a much lower order than anything discussed in this book. However, there are a few factors that do have significant effects on sound quality, and in the interests of completeness we will discuss them here. These are hard electrical engineering issues, but they routinely get elevated to different planes of thought. The reason for talking a little about them here is because, as a result of them, frequency responses of loudspeakers get altered, and sometimes this can be heard.

16.1 Consequences of Loudspeaker Impedance Variations

Impedance: 8 ohms. This is the kind of specification one sees for loudspeakers. It is an invented number. For a few, very, very few loudspeakers it is a good approximation, but for the vast majority it is a dreadful description of reality. [Figure 16.1a](#) shows a typical impedance that

varies substantially with frequency and that crosses the rated impedance at a few places only. The variations are normally of no concern.

Most power amplifiers are designed to be constant-voltage sources so, unless an unfortunate interaction between amplifier and loudspeaker provokes limiting or protection, all is well. Sadly there have been some notable examples of high-end loudspeakers having impedances that dipped very low: to an ohm or less. This is a problem of incompetent loudspeaker design. However, sensing a market, amplifier designers responded with monster “arc-welder” devices that can drive these problem loudspeakers, but it is overkill for most circumstances. It was amusing at the time to read that these incompletely designed loudspeakers “revealed” differences between power amplifiers, as if it were a virtue. They were the *cause* of the differences.

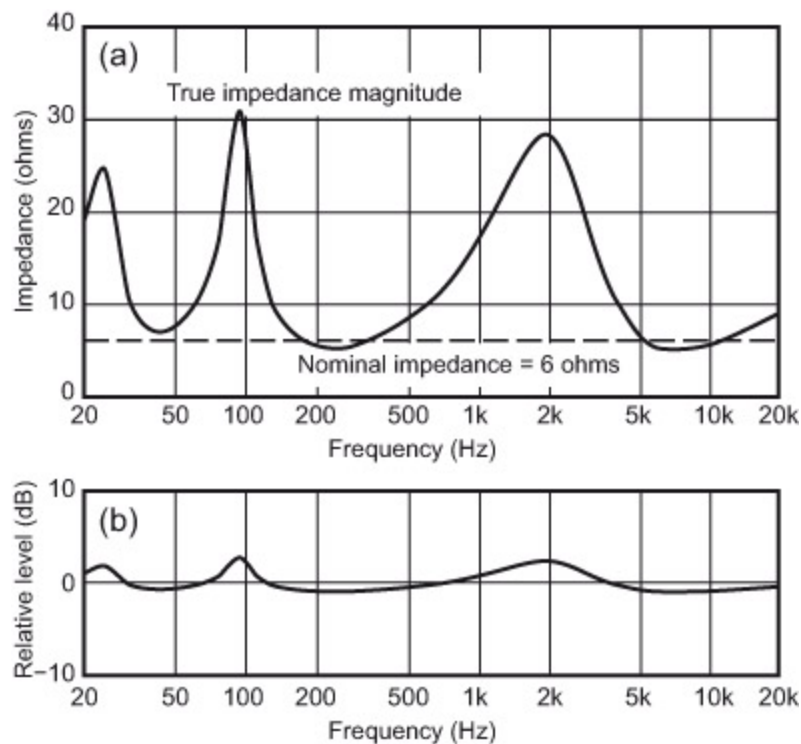


Figure 16.1 (a) [an impedance curve for a loudspeaker compared to the nominal impedance rating chosen by the manufacturer for it.](#) (b) [the change in frequency response of this loudspeaker caused by driving it with a tube amplifier having a large output impedance. Note that the shape of the frequency-response error is the same as the loudspeaker impedance curve.](#)

But there is a situation in which simple variations in impedance become an issue. Going straight to the problem, [Figure 16.1b](#) shows the kind of change in loudspeaker frequency response that can be caused by variable impedance—it is easily audible. The culprit? In this case a tube power amplifier with a large output impedance. The explanation is in [Figure 16.2a](#) and [b](#). The output impedance of the power amplifier and the resistance of the loudspeaker wire are components in a voltage divider circuit. When combined with the frequency-dependent impedance of the loudspeaker it means that the “flat” frequency response voltage at location “A” inside the power amplifier acquires a shape following that of the impedance curve at location “B.” Because this is the voltage driving the loudspeaker, the overall performance of the loudspeaker, that is, all of its frequency response curves, are modified by this amount. Different loudspeakers have different impedance curves; some are strikingly variable, others change little.

The amount of the change in frequency response depends on the total voltage drop across the combined amplifier output impedance and wire resistance, meaning that minimizing both of these is desirable. For solid-state power amplifiers output impedances tend to be very small: typically 0.01–0.04 ohms. Those for tube power amplifiers are much higher: typically 0.7–3.3 ohms, but occasionally even higher, which is inexcusable. These numbers come from a survey of *Stereophile* magazine amplifier reviews over several years—thank you, John Atkinson, for doing useful measurements.

To reviewers these are moderately discomfiting numbers, because the inevitable conclusion is that tube power amplifiers, as a population, cannot allow loudspeakers to perform as they were designed. Different reviewers handle it in different ways. Some ignore it; others have danced around the issue concluding that it is just one more uncertainty in sound reproduction. Rarely is it acknowledged to be what it is.

Loudspeakers can be designed to exhibit almost constant impedance, although it is rarely done. Such loudspeakers can perform with remarkable consistency in spite of significant losses in the upstream signal path. Rarely, though, is impedance ever discussed as a virtue or a problem. One well-known high-end loudspeaker specified that it should be used with wire

having resistance less than 0.2 ohms. This conscientious advice is admirable, but it means that the restriction is violated as soon as any tube amplifier is connected, no matter what wire is used. It is sobering to think that 10 ft (3 m) of the much despised lamp cord has 0.148 ohms resistance—much less than typical tube amplifiers (See [Table 16.1](#)).

Minimizing wire resistance is easy: use large wire, having low gauge numbers (see [Table 16.1](#))—or, better yet, use less wire. If there is a risk of radio-frequency signal pickup, it is important to know that unshielded wires act as antennas. A great deal of mystique has evolved around loudspeaker wires, attempting to elevate this simple device to impossible heights of importance. Notions that they behave as transmission lines persist, but Greiner (1980) offers persuasive arguments that this is unrealistic. There are other beliefs, some of which are impossible (e.g., directional wires), or irrelevant (e.g., skin effect, which is significant only at frequencies much above the audio frequency band).

Table 16.1 [Resistances per unit length of two-conductor stranded copper wire, stated for both wires in the circuit—so just measure how long the two-conductor wire is, and multiply by these numbers. For reference, common lamp cord is typically 18 gauge. If you do not see a gauge rating for a loudspeaker wire, be very suspicious. Some exotic cables use small wire for seriously mistaken reasons.](#)

AWG wire gauge	Resistance per ft (ohms) BOTH conductors	Resistance per m (ohms) BOTH conductors
10	0.0020	0.0067
12	0.0032	0.0106
14	0.0052	0.0169
16	0.0082	0.0268
18	0.0148	0.0483

At prices that can exceed \$20,000 for a pair of 8-foot (2.4 m) loudspeaker wires, one expects a lot. Enough said. Wire is a good product for the industry: totally reliable, inexpensive to manufacture, highly profitable and,

if you like what you hear, an excellent investment, so long as you did not pay more than you needed to—“aye, there’s the rub.”

16.2 The Damping Factor Deception

One of the universal compliments attached to audio products, including wires, is that it results in “tighter bass.” In the case of loudspeaker wire, it seems as though there might be some truth to it because of its role in the loudspeaker/amplifier interface and damping. Damping unwanted motion of a loudspeaker diaphragm is undoubtedly a good thing.

In 1975, I wrote an article for *AudioScene Canada* called “Damping, Damping Factor and Damn Nonsense.” I still like the title because is a succinct statement of reality. The point of the article is summarized in [Figure 16.2c](#). The internal impedance of the power amplifier is used to calculate something called the damping factor (DF) of the amplifier ($DF = 8$ divided by the output impedance); the number 8 was chosen because it is the nominal load (resistive) used to measure the power output capability of amplifiers. The logical inclination is to think that larger is better. Solid state amplifiers have damping factors ranging from about 200 to 800, using the impedances quoted earlier in this section. Tube amplifiers in my survey ran from 2.4 to 11.4 because of their high output impedances.

[Figure 16.2c](#) shows the complete circuit involved in the electrical damping of loudspeakers—it does not mysteriously stop at the loudspeaker terminals. Current must flow through components and devices inside the enclosure. After flowing through the wire, it typically passes through an inductor, part of the low-pass filter ahead of the woofer in a passive system. Then, inside the woofer there is the voice coil. The inductor resistance is commonly around 0.5 ohm, and the voice coil resistance can have different values but is commonly around 6 ohms. So, let us examine all of the resistances in the circuit to arrive at the following progression of damping factor changes:

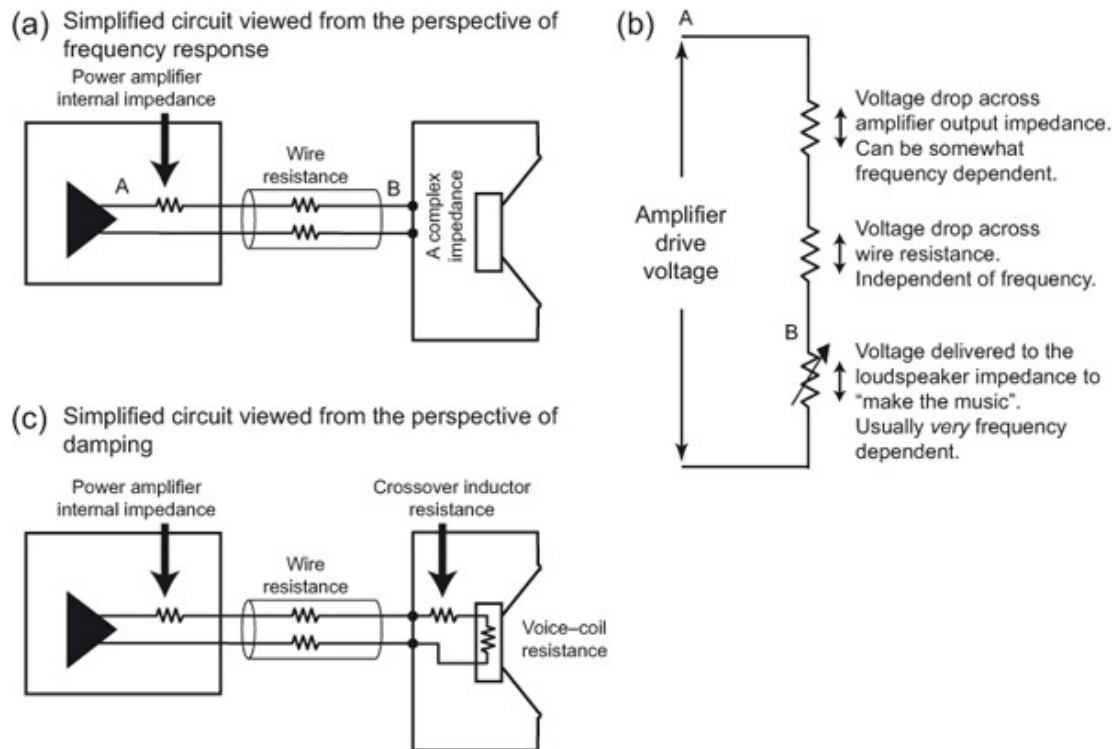


Figure 16.2 *Schematic diagrams showing (a) and (b) the electrical circuit explaining how amplifier and wire impedances cause variations in loudspeaker frequency response, and (b) how they affect loudspeaker damping.*

Amplifier internal impedance: 0.01 ohm	DF = 800
Add wire resistance: 10 ft of 10-gauge	
Both conductors: 0.02 ohm	DF = 266
Add crossover inductor resistance:	
0.5 ohm (typical)	DF = 15
Add voice-coil resistance: 6 ohms (typical)	DF = 1.2

Obviously the resistances inside the loudspeaker are the dominant factors. Even eliminating the inductor and driving the woofer directly changes things only slightly. The article (Toole, 1975) shows oscilloscope photographs of tone bursts of various frequencies and durations while the damping factor of the amplifier was varied from 0.5 to 200. At damping factors above about 20 (internal impedance less than 0.4 ohms), no change was visible in any of the transient signals, and changes in frequency response were very much less

than 1 dB, and then only over a narrow frequency range. On music no change in sound quality could be discerned, including attentive listening for “tightness.” Because 0.4 ohms is at least a factor of 10 higher than internal impedances found in typical solid state amplifiers, it means that, from the perspective of damping the transient behavior of loudspeakers, the wire resistance can be allowed to creep up substantially. However, as shown earlier, doing so can change the frequency response of the loudspeaker and that, we know, *is* audible.

In summary, with tube amplifiers, the internal impedance is already so high that damage is done to the frequency responses of loudspeakers having normal impedance variations. Added losses in wire simply make the situation worse. Listeners do not hear the loudspeaker that the manufacturer created.

With solid-state amplifiers internal impedances are negligibly low, so wire resistance must be controlled in order to minimize corrupting the frequency response of loudspeakers. How low? It depends on the *variations* in the impedance of the loudspeakers being used, and how low those impedances are—wire resistance represents a higher percentage of low impedances. For example: a loudspeaker ranging from 3 ohms to 20 ohms (not unusual for consumer loudspeakers and a moderately demanding situation) would experience about 0.6 dB variations in a system with 0.2-ohm wire resistance. [Section 4.6.2](#) shows that this is slightly higher than the detection threshold for low-Q spectral variations in quiet anechoic listening. Twelve-gauge wire would allow for a run of $0.2 / 0.0032 = 63$ ft (19 m). Obviously this is not very restrictive.

Loudspeakers having nearly constant impedance (a few exist) can tolerate large wire losses, sacrificing only efficiency up to the resistance at which damping is affected. If compelled to do better than this suggestion, more copper, shorter runs, or higher-impedance loudspeakers are the solutions.

[16.3 Loudspeaker Sensitivity Ratings and Power Amplifiers](#)

Years ago, loudspeaker sensitivity was rated as the sound level at a distance of 1 m for an input of 1 watt. Power input is $\text{voltage}^2 / \text{resistance}$. Because loudspeakers do not have the same impedance at all frequencies, a sensitivity rating would apply only at a single, or at most a few, frequencies. [Figure 16.3](#) shows the impedance curve for a loudspeaker, specified by the manufacturer as an 8-ohm unit. It is 8 ohms at four frequencies, but looking at the curve it is generally hovering at a level slightly above 4 ohms, dropping to a minimum of 3 ohms. A more realistic rating would have been 5 ohms. But that is an “odd” number in the industry, and such numbers, however true, tend to be avoided. The 3-ohm minimum is important because many receivers and some stand-alone power amplifiers are unhappy driving these low impedances as they lack the current capacity to deliver the required power into the load.

The figure shows the actual power delivered at a constant input voltage of 2.83 V, and it ranges from a high of 2.7 W at the impedance minimum, to a low of 0.4 W at the highest impedance point. Obviously, rating sensitivity according to power input does not work well. The domination of solid-state amplifiers really provided the solution. These amplifiers are essentially constant-voltage sources, with power rated according to what they can deliver into an 8-ohm resistor. If the load impedance drops to 4 ohms, the power will double; at 2 ohms the power quadruples, and so on, until the amplifier can deliver no more current or exceeds some other limitation. At this point one can see an opportunity to “work the system” by dropping the impedance of the loudspeaker, thereby extracting more power from the amplifier, and elevating the sensitivity rating. Being the louder loudspeaker in a simple A vs. B comparison is not a bad thing at the point of sale. However, if there is truth in advertising, the customer will know to seek out a power amplifier that is content to drive a relatively low impedance.

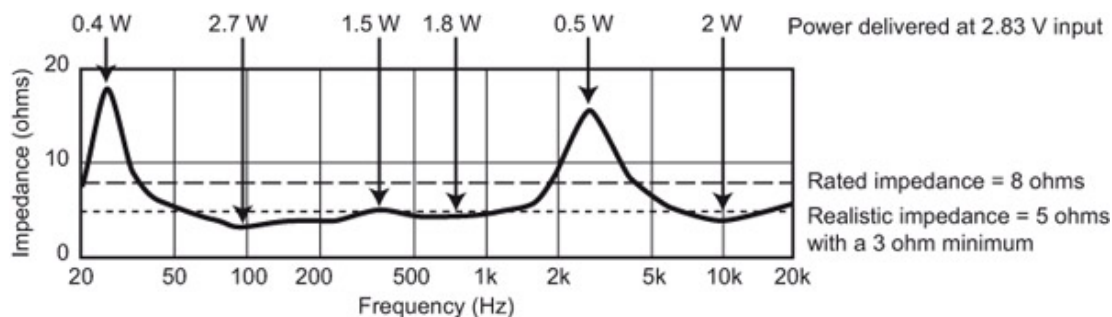


Figure 16.3 *A typical loudspeaker impedance curve, showing the rated impedance of the product and, at several frequencies, the input power for 2.83 V.*

Amplifiers that are optimized to meet a specification sheet deliver their rated power into 8 ohms, but may fail to deliver double power into 4 ohms. This is a major differentiating factor among power amplifiers. Those big, heavy monoblocks with massive heat sinks are the ones that are able to drive huge currents into very low impedances, and they tend to double their output into halved impedances.

Returning to the theme of sensitivity ratings, the present circumstances allow us simply to define an input voltage, not an input power. The selected standard voltage is 2.83 V, the voltage that delivers one watt into 8 ohms. All of the measurements shown in this book were made with loudspeakers driven with 2.83 V. Measurements were made at 2 m, a distance that safely represents the far field for small loudspeakers, although it is borderline for very large ones (see [Section 10.5](#)). The SPL is adjusted to show what it would have been at 1 m, which is the standardized distance (in this case 6 dB higher than the sound pressure level measured at 2 m). Not all manufacturers are accurate in their sensitivity ratings. However, as shown in [Figure 16.3](#), at only four frequencies is the input power 1 watt—those where the curve crosses the 8-ohm line. That is why SPL @ 1 W @ 1 m is a specification relegated to history.

[16.4 The Audibility of Clipping](#)

How much amplifier power is necessary? Enough, is the correct answer. If the loudspeaker load is well behaved, well-designed inexpensive amplifiers can work just fine. Powered loudspeakers have a big advantage: the power amplifiers needed to drive individual transducers can be much less ostentatious devices because the details of the load they drive are known and well defined. It is the uncertainty of the load that forces us to buy amplifiers that are able to drive anything we connect to them. There is more to this tale than is revealed here. Benjamin (1994) and Howard (2007) add much more perspective.

If the amplifier does not have sufficient power to deliver a rewarding sound level it will likely be driven into clipping—the tops of waveforms are chopped off. If the amplifier is well behaved, this will result in clean clipping. At the 1987 AES Convention in London, there was a public test of the audibility of amplifier clipping. Although the results were never published, the result was that about 6 dB of clean clipping was rarely audible. I participated in the test and was surprised by the result. Voishvillo (2006, 2007) removed 50% of the waveform amplitude before it became an audible problem. This amount of clipping generates about 20% THD (total harmonic distortion). Interestingly, in comparison he found that this was less annoying than 3% of zero-crossing distortion. If the clipping is not clean or symmetrical, many forms of audible misbehavior can occur, something more likely to occur in low-cost amplifiers, especially those with inadequate power supplies.

Obviously, all such misbehavior should be avoided, but when attempting to deliver very high sound levels to listeners at a distance from the loudspeakers, the power requirements may rise more rapidly than is commonly thought. Examine the right-hand scale in [Figure 4.3](#) for the relationship to sound level, and [Figure 14.3](#) for the relationship to distance from the loudspeaker—remembering that each 3 dB increment is a doubling of power. In the real world it is likely that a lot of people are listening to clipped audio during loud passages.