Attenuators for Measurement

In this article, our author discusses external attenuators and compares the impact different attenuators' thermal noise will have on measurements of distortion. At low test voltages, the added thermal noise of the attenuator is of primary concern. At high test voltages, the heat dissipation in the external attenuator is of primary concern. For this reason, it can be handy to have multiple attenuators of similar attenuation but with different impedances on hand.

By
Jonathan Novick
(United States)

External attenuators are an effective and cost effective way to measure signals above the maximum input voltage of an audio analyzer. However, commercial off-the-shelf attenuators are usually not a good choice in this application as they are typically designed for low-voltage use only. There are several trade-offs to consider when designing attenuators for higher voltages, including topology, power handling and voltage ratings, resistor choices, and added measurement noise.

Attenuation values are typically given as a ratio expressed in decibels (dB). **Table 1** represents the ratio of the input voltage to the output voltage, which can be determined using Equation 1:

$$Attenuation = -20Log\left(\frac{V_{output}}{V_{input}}\right)$$

Attenuator Topology

Attenuators can be constructed using many topologies, each offering different attributes to suit different needs. For audio noise measurements, an attenuator with a low output impedance is desirable. This makes the L-pad and U-pad topologies ideal choices for power amplifier measurements. These attenuators are asymmetrical in nature. In other words, they have a specific input and output direction. Symmetric topologies, such as T-pads and Pi-pads and their variants are primarily used in RF communications, where impedance matching and bi-direction signal flow are of greater importance than handling high voltages and minimizing added noise.

An L-pad is a simple resistive divider network consisting of a series resistor attached between the signal source and the audio analyzer and a shunt resistor across the audio analyzer input. The output voltage of an attenuator can be calculated using Ohm's law:

$$\text{L-pad output voltage} = Vin \times \frac{Rshunt}{Rshunt + Rseries}$$

The U-pad is simply two identical L-pads placed back-to-back in a mirrored configuration; each side attenuating one side of the balanced signal (see **Figure 1**). The two shunt resistors of a U-pad can be combined into a single resistor but keeping them separate provides a ground reference that can be useful to control common mode issues with floating test systems. The ground point also enables the U-pad to be used in both balanced and unbalanced configurations. The U-pad resistor values are shown here as half the L-pad values. This is so the same calculations used here can be applied to either case.

Attenuation	6 dB	10 dB	12 dB	18 dB	20 dB	24 dB	30 dB	40 dB
Voltage Ratio	2:1	3.2:1	4:1	8:1	10:1	16:1	32:1	100:1

Table 1: Attenuation and voltage ratios

The Test Load as an Attenuator

Power amplifiers are often tested with resistive loads. These loads can also be configured as L-pads or U-pads using multiple resistors. This is the recommended way to attenuate an amplifier output for measurement.

An 8-Ω load can be made with eight 1 Ω resistors in series. Each node between the resistors provides a differing attenuation value. The center node (between the fourth and the fifth resistors) provides 6 dB attenuation. The node between the sixth and the seventh resistors provides 12 dB attenuation and the node between the seventh and the eighth resistors is attenuated 18 dB. Amplifiers with push-pull outputs should be tested using a U-pad with each side having eight 0.5 Ω resistors. The total resistance is 8 Ω and there is still access to 6 dB, 12 dB, and 18 dB attenuation points (see **Figure 2**).

Testing Without a Load

Testing amplifiers without a load requires more careful consideration of the attenuator's design. Most commercially available attenuators have an impedance of just a few hundred ohms and are comprised of 1/8 W or 1/4 W resistors. At high voltages, the power rating of these resistors could be exceeded, causing them to overheat. The heat dissipation can be reduced by using higher resistance values. However, higher resistance values add excess noise that may impact measurement accuracy. The remainder of this article discusses the design of higher impedance attenuators.

Choosing a Resistor Type

There is no such thing as a perfect resistor. There are many trade-offs to be considered for both electrical and physical properties as well as cost.

Thermal (Johnson) noise is the voltage noise produced by a resistor that is proportional to the square root of the resistance value. The higher the resistance, the higher the noise voltage. The RMS level of this noise is defined as:

$$V = \sqrt{4 \times R \times k \times T \times BW}$$

where, R = Resistance value
k = Boltzman's constant, 1.38×10^{-23}
T = Operating temperature in degrees Kelvin
BW = Bandwidth in Hertz (Hz)

Current noise, sometimes referred to as $1/f$ noise, is caused by the electron flow through the resistive material and varies with the voltage across the resistor. Carbon-film, thick-film and carbon-composition resistors have a higher noise index than other types and should be avoided for measurement purposes.

The temperature coefficient indicates the sensitivity of a resistor's value to temperature changes. Heating differences between the series and shunt resistors in an L-pad can produce changes in attenuation that can throw off measurements. This can be mitigated by using resistors with lower temperature coefficients (≤50 ppm), using higher wattage resistors in the series element, or constructing the series element from multiple resistors. Small surface-mount resistors with low thermal mass can exhibit nontrivial changes in temperature within a single cycle of a low-frequency signal and are not recommended unless used in large arrays to minimize heating.

Inductance in attenuators should generally be minimized. Wire-wound resistors can handle tremendous heat loads, but they also exhibit higher inductance than other resistor types. The actual inductance is a function of the construction method but vary from 0.1 to 400 µH depending on wattage and value. The maximum acceptable inductance should be considered for the specific device being tested.

Magnetic susceptibility occurs because wire wound resistors can both emit and pick up magnet fields. If used, they should be placed away from sensitive circuits or strong magnetic sources such as power transformers.

Power ratings are an indication of how hot resistors can operate without failing. However, operating the resistor well below its maximum rated power insures the operating temperature stays closer to the ambient temperature.

Cost and availability can vary significantly with resistor type. Metal-foil resistors approach

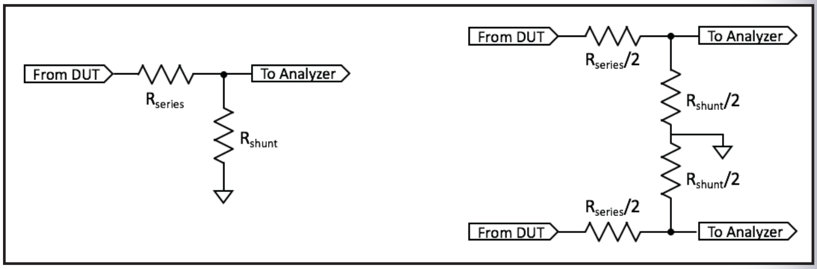

Figure 1: The U-pad is simply two identical L-pads placed back-to-back in a mirrored configuration—each side attenuating one side of the balanced signal.

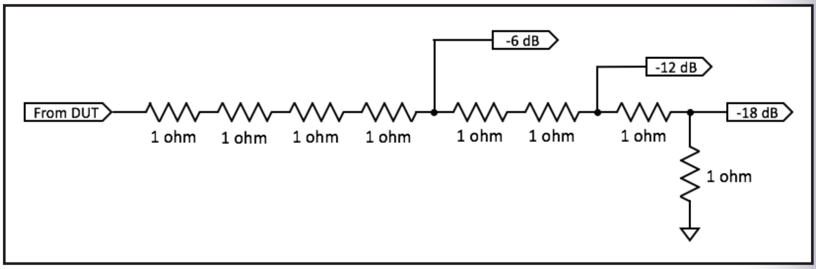

Figure 2: Amplifiers with push-pull outputs should be tested using a U-pad with each side having eight 0.5 Ω resistors. The total resistance is still 8 Ω and there is still access to 6 dB, 12 dB, and 18 dB attenuation points.

	Resistor Choices		Actual Attenuation	Thevenin Resistance	Thermal Noise
	Series	Shunt			
Case 1	100 Ω	11 Ω	-20.08 dB	9.1 Ω	0.057 µV/-145 dBv
Case 2	1,000 Ω	110 Ω	-20.08 dB	99 Ω	0.18 µV/-135 dBv
Case 3	5,000 Ω	560 Ω	-19.94 dB	504 Ω	0.41 µV/-128 dBv
Case 4	10,000 Ω	1,100 Ω	-20.08 dB	991 Ω	0.57 µV/-125 dBv
Case 5	20,000 Ω	2,200 Ω	-20.08 dB	1,982 Ω	0.81 µV/-122 dBv
Case 6	47,000 Ω	5,100 Ω	-20.19 dB	4,601 Ω	1.23 µV/-118 dBv

Table 2: L-pad resistor combinations for 20 dB

the performance of an ideal resistor in many ways. However, they can cost up to 100 times more than other resistor types. Availability can also be a problem. Leaded thin-film resistors offer an inexpensive, readily available compromise for constructing attenuators. Thin-film resistors rated at 0.6 W, 1% tolerance and a 50 ppm/°C temperature coefficient cost approximately 15 to 30 cents each in individual quantities. These can be wired in series and parallel combinations to handle higher power dissipation at a reasonable cost.

Impact of Noise on a Measurement

The thermal noise from an attenuator can impact the readings of certain measurements. This will be most evident in noise-related measurements such as signal-to-noise ratio (SNR) or total harmonic distortion + noise (THD+N), particularly at lower signal levels.

The thermal noise of an L-pad is determined as a function of its Thevenin equivalent resistance. Assuming the amplifier under test has a negligible output impedance, the Thevenin equivalent circuit is simply the parallel combination of the series and shunt resistors of the attenuator. **Table 2** shows some common resistor combinations that can produce ~20 dB attenuation as well as the thermal noise produced by that combination over a 20 kHz bandwidth at 27°C.

The significance of this thermal noise depends on the needed measurement accuracy, the signal level of the test and the residual noise and distortion of the product being tested. Suppose the desired measurement is distortion. This is defined by the equation for THD+N:

$$\text{THD+N (in dB)} = 20\ \text{Log}\left(\frac{\text{residual noise and distortion}}{\text{total signal}}\right)$$

Putting This to Work

The following two examples demonstrate the types of trade-offs needed when designing an attenuator. I used AverLAB, the new audio analyzer from Avermetrics, to measure high-powered amplifiers. To keep AverLAB small, its maximum input was limited to 15.5 Vrms (balanced) and 7.7 Vrms (unbalanced). Without an attenuator, it can test up to 30 W into an 8 Ω load at the balanced inputs or 7.5 W at the unbalanced inputs. For larger amplifiers, 20 dB of external attenuation increases those limits to 3000 W for balanced and 750 W for unbalanced connections. AverLAB has provisions to offset measurements for external attenuation which makes making these measurements easy.

Measuring a 200 W Amplifier

This hypothetical amplifier is rated at 200 W into 8 Ω with a THD+N of -100 dB (0.001%). The amplifier output is 40 V at the rated power and solving Equation 4 shows that there is 400 µV of residual noise and distortion. A 20 dB L-pad will reduce the output signal to 4 V, which is well within AverLAB's input range, and will also reduce the residual to just 40 µV. The analyzer will still show a THD+N reading of -100 dB unless the attenuator has added too much noise of its own. The question is how much of this added attenuator noise can be tolerated.

If the maximum acceptable measurement error due to added noise is 0.1 dB, the distortion reading must be ≤-99.9 dB. Equation 2 is solved for -99.9 dB to show the total residual seen by the analyzer cannot exceed 40.46 µV. Given that the amplifier is producing 40 µV of this residual, the RMS allowable noise from the attenuator can be determined. Since noise sources are uncorrelated

	Resistor Choices		Dissipation at 40 V		Dissipation at 141 V	
	Series	Shunt	Series	Shunt	Series	Shunt
Case 1	100 Ω	10 Ω	13.22 W	1.322 W	165 W	16.5 W
Case 2	1,000 Ω	110 Ω	1.30 W	0.143 W	16.2 W	1.8 W
Case 3	5,000 Ω	560 Ω	0.259 W	0.029 W	3.23 W	0.36 W
Case 4	10,000 Ω	1,100 Ω	0.130 W	0.014 W	1.62 W	0.18 W
Case 5	20,000 Ω	2,200 Ω	0.065 W	0.007 W	0.81 W	0.09 W
Case 6	47,000 Ω	5,100 Ω	0.028 W	0.003 W	0.35 W	0.04 W

Table 3: L-pad power dissipation at 40 V and 141 V

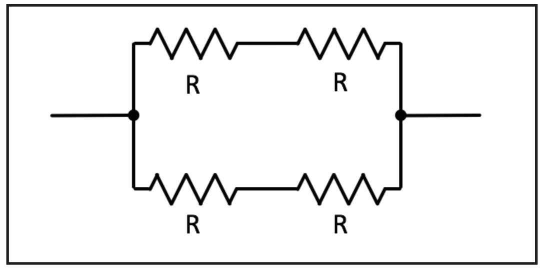

Figure 3: Any resistor of value R may also be constructed from multiple elements to further reduce heating.

RMS summation, the equation:

$$\text{Total noise}^2 = \text{amplifier residual}^2 + \text{attenuator noise}^2$$

is used to determine the allowable attenuator noise. This shows that the maximum allowable attenuator noise for 0.1 dB accuracy is 6.1 µV. Any of the attenuators shown in Table 2 are thus sufficient to measure the amplifier. However, this is only true for measurements at 40 V.

Amplifiers are often tested by sweeping from a low amplitude to maximum power. An audio analyzer would normally auto-range its input as the signal level changed to ensure maximum measurement accuracy. However, a fixed external attenuator cannot be similarly switched in and out as needed during an automated level sweep. Therefore, the noise of the attenuator must be considered at the lowest level being tested.

At 1 W (2.83 V into 8 Ω) from the amplifier, the analyzer sees only 0.283 V with the 20 dB attenuator in place. The same equations as above are used again to find that allowable attenuator noise for 0.1 dB accuracy is now just 0.43 µV. Table 2 shows that Case 3 offers the highest impedance resistor combination that would satisfy that accuracy target.

Measuring a 1,500 Watt Amplifier

The previous example was only for a 200 W amplifier, such as those found in home sound systems. Professional live-sound amplifiers frequently have outputs in the kilowatt range. A 1500 W amplifier produces approximately 141 V into an 8 Ω load. A 20-dB attenuator would reduce this voltage to ~14 Vs (within AverLAB's balanced input range) but heat dissipation within the attenuator becomes a significant factor to consider. **Table 3** shows the same resistor combinations as Table 1 along with the power dissipated by each resistor at both 200 W and 1,500 W.

It is easy to see that significant power can be dissipated in an attenuator at 141 V. Case 6 is the only attenuator that could be made using 0.6 W

More Helpful Information

The following calculations are helpful in the design and use of external attenuators:

- Equations for design: Determine the ideal resistor values based on test level and desired accuracy
- Equations for use: Determine the measurement accuracy based on actual resistor values, test level and distortion reading

These equations are simply variations of equations shown earlier solved for different variables. These can be conveniently entered into a spreadsheet as a handy reference. Such a spreadsheet is available for download at www.avermetrics.com.

Project Files

To download a spreadsheet with all the equations to calculate the attenuators, visit www.audioxpress.com/page/audioXpress-Supplementary-Material.html

Variable	Equations for Design
Vn_{DUT}	$Vn_{DUT} = Level \times 10^{Dist/20}$
Vn_{Att}	$Vn_{Att} = Vn_{DUT} \times 10^{Atten/20}$
Vn_{meas}	$Vn_{meas} = Vn_{Att} \times 10^{Acc/20}$
Vn_{Atten}	$Vn_{Atten} = \sqrt{Vn_{meas}^2 - Vn_{Att}^2}$
R_{Thev}	$R_{Thev} = Vn_{Atten}^2 / \left(4 \times Temp \times BW \times 1.38E^{-23}\right)$
R_{series}	$R_{series} = R_{Thev} / 10^{Atten/20}$
R_{shunt}	$R_{shunt} = R_{Thev} / \left(1 - 10^{Atten/20}\right)$
P_{series}	$P_{series} = \left(\frac{Level}{R_{series} + R_{shunt}}\right)^2 \times R_{series}$
P_{shunt}	$P_{shunt} = \left(\frac{Level}{R_{series} + R_{shunt}}\right)^2 \times R_{shunt}$
	Equations for Use
$Atten_{Actual}$	$Atten_{Actual} = 20 \times Log\left(R_{shActual} / R_{shActual} + R_{seActual}\right)$
$R_{ThevActual}$	$R_{Thev\,Actual} = \left(\frac{1}{1/R_{seActual} + 1/R_{shActual}}\right)$
Vn_{Actual}	$Vn_{Actual} = \sqrt{4 \times Temp \times BW \times 1.38E^{-23} \times R_{ThevActual}}$
Vn_{Meas}	$Vn_{Meas} = LevelActual \times 10^{Dist_{Meas}/20}$
$Vn_{DUTActual}$	$Vn_{DUTActual} = \sqrt{Vn_{Meas}^2 - Vn_{Actual}^2}$
$Dist_{Actual}$	$Dist_{Actual} = 20 \times Log^{\left(Vn_{DUTActual} / Level_{Actual}\right)}$
Acc_{Actual}	$Acc_{Actual} = Dist_{Meas} - Dist_{Actual}$

Variable	Description	Units
Level	The output level of the device under test (DUT)	volts (V)
Distortion	The rated distortion level of the DUT	decibels (dB)
Temperature	Temperature in degrees Kelvin	K
Bandwidth	Bandwidth of measurement	Hertz (Hz)
Vn_{DUT}	The residual noise and distortion of the DUT at Level and Distortion	volts (V)
Attenuation	The value of the external attenuation	decibels (dB)
k	Voltage divider ratio of a given attenuator	k:1
Vn_{post}	Value of N_{DUT} following the external attenuator	volts (V)
Accuracy	Tolerable measurement of accuracy	decibels (dB)
Vn_{meas}	Residual seen by the analyzer at limit of accuracy specification	volts (V)
Vn_{Atten}	Noise contribution of the attenuator at limit of accuracy	volts (V)
R_{Thev}	Highest Thevenin equivalent resistance for an L-pad attenuator that will meet the accuracy specification at the rated distortion and level (at 27°C and 20 kHz BW)	ohms (Ω)
R_{series}	Highest value of a series resistor for an L-pad that meets accuracy specification	ohms (Ω)
R_{shunt}	Highest value of a shunt resistor for an L-pad that meets accuracy specification	ohms (Ω)
P_{series}	Power dissipated in the series resistor at Level	ohms (Ω)
P_{shunt}	Power dissipated in the shunt resistor at Level	ohms (Ω)
$R_{shActual}$	Chosen shunt resistor	ohms (Ω)
$R_{seActual}$	Chosen series resistor	ohms (Ω)
$Atten_{Actual}$	Precise attenuation given the chosen resistors	decibels (dB)
$R_{ThevActual}$	Thevenin equivalent resistance of the actual attenuator	ohms (Ω)
Vn_{Actual}	Noise produced by the actual attenuator	volts (V)
$Dist_{Meas}$	Measured distortion reported by the audio analyzer	decibels (dB)
Vn_{Meas}	Residual noise and distortion measured by the analyzer	volts (V)
$Level_{Actual}$	Signal level seen by the audio analyzer	volts (V)
$Vn_{DUTActuual}$	Residual noise from DUT (without attenuator noise)	volts (V)
$Dist_{Actual}$	Actual distortion of the DUT	decibels (dB
Acc_{Actual}	Accuracy of the measured distortion based on the test level and attenuator used	decibels (dB)

resistors. However, Table 2 shows that the noise will be 1.23 μV.

At full power, the analyzer will be seeing a 14.1 V signal and the amplifier's residual would be 0.14 μV for a distortion of -100 dB. The 1.23 μV of additional noise from the attenuator would not cause the reading to change significantly. In fact, it would take 21.6 μV of noise to change the measurement by 0.1 dB. However, at 1 W, it takes only 0.43 μV of noise to change the measurement by 0.1 dB. With 1.23 μV of attenuator noise the new THD+N reading would be -99.25 dB, a difference of 0.75 dB.

The series resistor in Case 3 could be built using multiple 0.6 W resistors to handle the heat load. For instance, eight 10 kΩ resistors could be wired as four series-pairs in parallel to produce the 5000 Ω series resistance. This brings the dissipation in each resistor to ~0.4 W. However, at 0.4 W, these resistors will see almost a 70°C temperature rise, which may not be tolerable.

The resistor combination in Case 4 changes the measurement reading by less than a 0.2 dB and Case 5 would cause less than a 0.4 dB. These other solutions make it easier to handle the heat load in the attenuator.

The shunt resistor dominates the noise produced by the L-pad. In Case 3, the temperature of a 0.6 W thin-film shunt resistor will rise almost 60°C whereas in Case 4 it will rise less than 20°C. Any resistor of value R may also be constructed from multiple elements to further reduce heating (see **Figure 3**).

Conclusions

This article discusses the impact an attenuator's thermal noise will have on distortion measurements. At low test voltages, the added thermal noise of the attenuator is of primary concern. At high test voltages, the heat dissipation in the external attenuator is of primary concern. For this reason, it would be handy to have multiple attenuators of similar attenuation but with different impedances on hand. The use of 0.6 W 1% thin-film resistors makes this a very practical and cost-effective solution.

About the Author

Jonathan Novick is an electrical engineer with more than 25 years of test and measurement experience, the last 15 exclusively in audio. He most recently served as VP of Sales and Marketing for Avermetrics, LLC. Prior to that he was a Director of Sales for Audio Precision and a Senior Product Manager at Agilent Technologies (now Keysight). He is also a former vice president and governor of the Audio Engineering Society. Jonathan co-chairs the R3WG2 audio standards committee of the Consumer Technology Associations and contributes on other working groups as well.