

Audio power amplifier measurements

By Richard Palmer

Application Specialist, Audio Amplifiers

Introduction

Characterization is an important step when a part is released to production. The data sheet is the medium through which the manufacturer relates this information to the customer. It is of paramount importance that the information on the data sheet be relevant and clear. It is sometimes beneficial for the customer to re-create these characterization measurements in order to evaluate a device in his system.

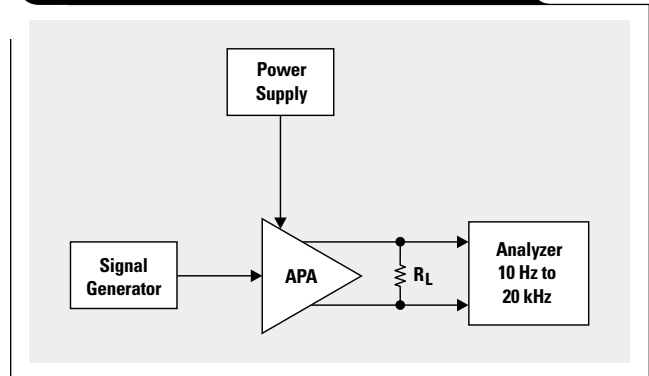
The primary goal of audio characterization measurement is to determine the performance of a device in the audible spectrum—20 Hz to 20 kHz. Although most people do not hear frequencies below 50 Hz nor above 15 kHz, the broader spectrum is an industry standard and allows more accurate comparison of devices. A method for measuring standard data sheet information is presented for several key parameters: total harmonic distortion plus noise (THD+N) versus output power (P_O) and frequency; gain and phase versus frequency; and crosstalk and noise versus frequency.

Basic measurement system

This article provides the guidelines for measuring the parameters of Texas Instruments audio power amplifiers (APAs). The measurements were made using off-the-shelf evaluation modules (EVMs) that are compatible with the TI Plug-n-Play platform. EVMs for the TPA2001D1 and TPA731 were used for all but the crosstalk measurement, which requires a stereo device. TPA2001D2 and TPA0212 EVMs were used for the crosstalk measurements.

Figure 1 shows the block diagram of a basic measurement system for class-AB amplifiers. These amplifiers are relatively easy to measure since they are linear—the output is a linear representation of the input. The input signal of the APA is provided by a low-output-impedance source. A sine wave is normally used as the input signal since it

Figure 1. Class-AB basic audio system measurement



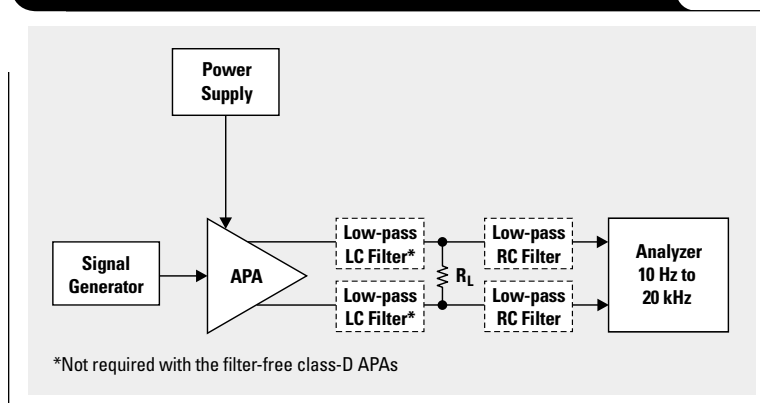
ideally has only the fundamental frequency (no harmonics are present). An analyzer is then connected to the APA output to measure the sine-wave output. The analyzer must measure from 20 Hz to 20 kHz. A regulated dc power supply is used to reduce the noise and distortion injected into the APA.

A block diagram of a class-D APA measurement system is shown in Figure 2. The system is the same as the class-AB system, except for the addition of the LC and RC low-pass filters. These filters reduce the level of the high-frequency output signal of the pulse-width-modulated class-D APA prior to the analyzer inputs. The rail-to-rail square-wave signal exceeds the common-mode voltage of the analyzer, making accurate distortion measurements impossible without some sort of filter.

The RC filter is required to measure any of the filter-free class-D APAs, which use an improved modulation scheme that greatly reduces the quiescent current and the need for the expensive, bulky LC filters used with the more contemporary class-D devices. These filters are mutually exclusive—when one is present, the other is not required.

More information about the selection of the RC filter is provided later in this article. See Reference 1 for more information about the class-D LC filter.

Figure 2. Class-D basic audio system measurement



Interfacing with the APA inputs and outputs

The APA inputs are either differential (Diff) or single-ended (SE), and the outputs are configured for either a bridge-tied load (BTL) (otherwise known as an H-bridge circuit) or a single-ended (SE) load. There are four possible configurations of these inputs and outputs for the APA:

- Diff input and BTL output (Diff/BTL)
- Diff input and SE output (Diff/SE)
- SE input and BTL output (SE/BTL)
- SE input and SE output (SE/SE)

Differential inputs have two pins per channel that amplify the difference in voltage between them. They reduce noise and distortion in the APA. BTL outputs have two pins that provide voltages 180° out of phase. The load is connected between these pins. This type of output is normally used when the APA and speaker are in the same enclosure. It has the benefits of quadrupling the output power to the load and eliminating a dc output coupling capacitor.

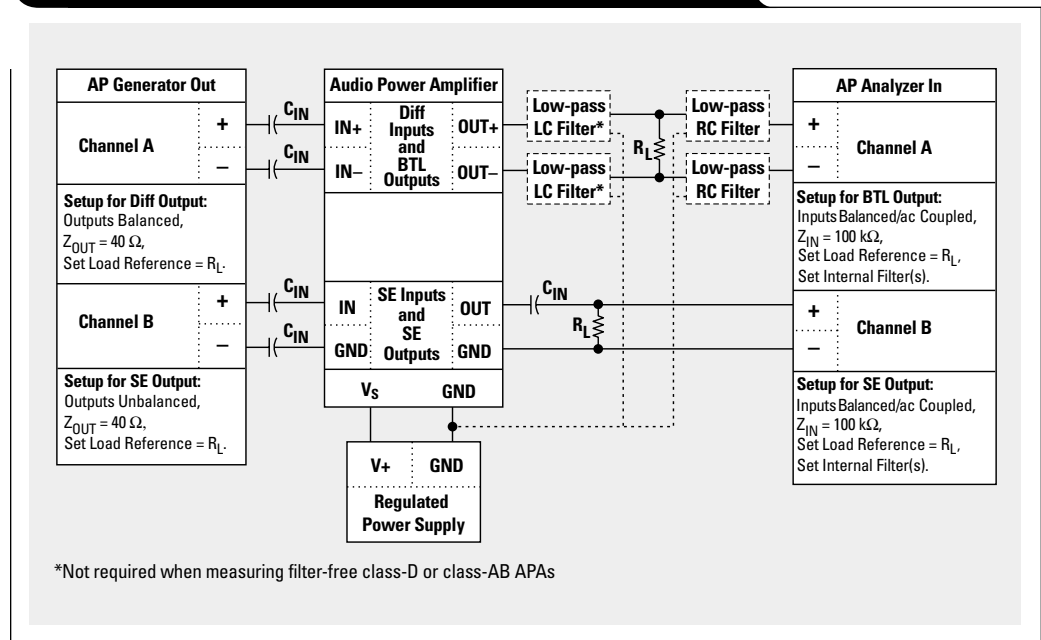
The SE inputs normally have one pin per channel and are used for line amplifiers (speakers) when a differential signal is unavailable from the source. SE inputs are commonly used with amplifiers that have SE outputs, such as headphone amplifiers. SE outputs have one pin that is tied directly to one end of the load; the other end of the load is tied to ground. This output configuration is normally used when the APA and speaker are in separate enclosures. A dc coupling capacitor is often required with this type of output.

There are class-AB devices for each configuration. Good examples include the TPA711 with SE inputs and either BTL or SE outputs, and the TPA0212 that can be configured into any of the four combinations. Most class-AB headphone amplifiers have SE outputs and normally have SE inputs. There are a few exceptions, like the TPA6112A2, which are Diff/SE. The class-D devices operate with differential inputs and BTL outputs.

An audio measurement circuit for class-AB or class-D is shown in Figure 3. The RC filters are included for simplicity but are not required for class-AB measurements. The circuit shows an audio precision (AP) measurement system that includes an analog signal generator with sweep capability and an analog analyzer optimized for audio signals. To emphasize the different input/output configurations, channel A (Ch A) is set up for differential inputs and BTL outputs, and channel B (Ch B) is set up for SE inputs and outputs. The remaining combinations (Diff/SE or SE/BTL) can be set up by referencing the appropriate input or output configuration in Figure 3. The BTL and SE settings for the AP generator and analyzer are shown below the appropriate channel. The input ac coupling capacitors, C_{IN} , are included on the device evaluation modules.

Twisted-pair wire should be used on all connections. The twisted pair reduces the loop area between the conductors, protecting against magnetic, or inductive, coupling. Shielding protects against electric, or capacitive, coupling and is used when the system environment is noisy or to reduce radiation from the APA circuit to other nearby circuits.

Figure 3. Class-AB or class-D audio system measurement



The signal source should have balanced outputs for APAs with differential inputs. The balanced output really means the outputs have the same impedance. The analyzer should have balanced inputs, particularly when APAs with BTL outputs are measured. The cable shielding (when used) should be terminated at the end where the impedance is high for Diff/BTL-type connections.² This will occur at the APA and analyzer inputs. The single point connection prevents return currents from flowing through the shield between connections that are at slightly different voltage potentials, thus minimizing ground loops.

When APAs with SE inputs are measured, the signal source should have unbalanced outputs to prevent any voltage drop from occurring due to ground-current flow. The analyzer should have balanced inputs to reduce the common-mode noise. The signal and ground wires of the twisted pair should be connected at both ends to allow return currents to flow. When the generator is grounded and cable shielding is used, the latter should be connected at both ends to provide an additional return current path, reducing the noise in the twisted-pair wire.² See Reference 2 for more details concerning grounding and cable connections.

RC low-pass measurement filter

The RC filter is designed to reduce the square-wave output of the filter-free class-D output so as not to interfere with the measurements. It is required by the analyzer inputs, which do not have the common-mode capability to handle the fast-switching class-D output waveform. The high frequency of the square wave is not a factor in the audio measurements because it is well above the audible frequency range, and the speaker cannot respond at such a fast rate.

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When the RC filter is used, it is connected as shown in Figure 4. C_{Filter} is grounded to the APA to form a path for return current and to minimize ground loops. The input resistance and capacitance of the analyzer are substituted for R_{IN} and C_{IN} . The equivalent circuit is shown in Figure 5. The equation for this circuit is

$$\frac{V_{OUT}}{V_{IN}} = \frac{\left(\frac{R_{IN}}{R_{IN} + R_{Filter}}\right)}{1 + j\left(\frac{\omega}{\omega_O}\right)}, \tag{1}$$

where $\omega_O = R_{EQ}C_{EQ}$, $R_{EQ} = R_{Filter} \parallel R_{IN}$, and $C_{EQ} = (C_{Filter} + C_{IN})$. The filter frequency should be set above the bandwidth of the highest measurement frequency, yet low enough to filter out most of the switching frequency so the AP analyzer can measure it.

$$f = 10^{\frac{20 \times \log(f_{max}) + 3 \text{ dB}}{20}} \tag{2}$$

Equation 2 provides the cutoff frequency of the RC filter 3 dB above the highest-frequency component, f_{max} , of the

spectrum being measured. The value chosen for R_{Filter} must then be large enough to avoid attenuating the output voltage, yet small enough to minimize the attenuation of the analyzer-input voltage through the voltage divider formed by R_{IN} and R_{Filter} . These are conflicting criteria, and a balance must be sought. Once R_{Filter} is selected, C_{Filter} is calculated:

$$C_{Filter} = \frac{1}{2\pi \times f \times R_{Filter}}, \tag{3}$$

where f is the cutoff frequency of the filter. The values used for the measurements in the following discussion were $R_{Filter} = 100 \Omega$ and $C_{Filter} = 47 \text{ nF}$. Some current will flow through the RC filter to ground, but it is generally not a consideration for these measurements.

THD+N versus power and frequency

The THD+N measurement combines the effects of white noise, distortion, and other undesirable signals into one measurement and relates it (usually as a percentage) directly to the fundamental frequency. Ideally only the fundamental frequency is present at the output, which in practice is never the case. Nonlinearity of the amplifier, internal noise sources, external noise sources, and layout and grounding issues are some of the contributors that distort the original input signal. The distortion shows up at the output as harmonics of the fundamental frequency.

The bandwidth is usually limited with filters in the analyzer to reduce the noise; yet this also reduces the relevant harmonics of the higher-frequency signals, and a tradeoff is made. A filter cutoff frequency of 80 kHz is used for class-AB APAs to allow measurement of the third harmonic. The filter cutoff frequency is set to 22 kHz for class-D APAs to remove the switching waveform from the measurements.

The AP measurement circuit is shown in Figure 6 for a mono-channel, BTL output APA. The measurements for the TPA2001D1 and TPA731 output power sweep are shown in Figure 7, and an output frequency sweep is shown in Figure 8. The maximum input voltage for producing maximum output power can be found by increasing the input until the output clips, then reducing it until it is just below clipping. Another method is to calculate the maximum peak-to-peak input voltage:

$$V_{IN(PP)} = \frac{2\sqrt{2 \times P_{O(max)} \times R_L}}{A_V}, \tag{4}$$

where $P_{O(max)}$ is the maximum-rated RMS output power, R_L is the load resistance, and A_V is the voltage gain of the APA.

Figure 4. RC filter for filter-free class-D

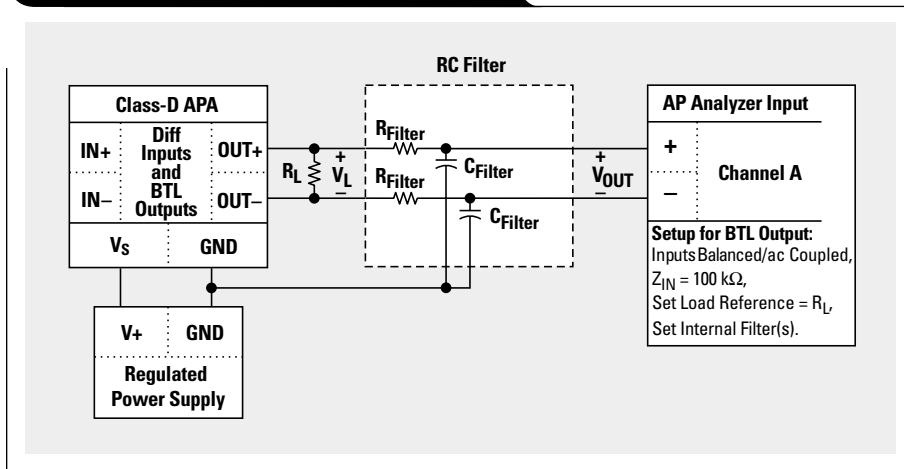


Figure 5. Equivalent filter circuit

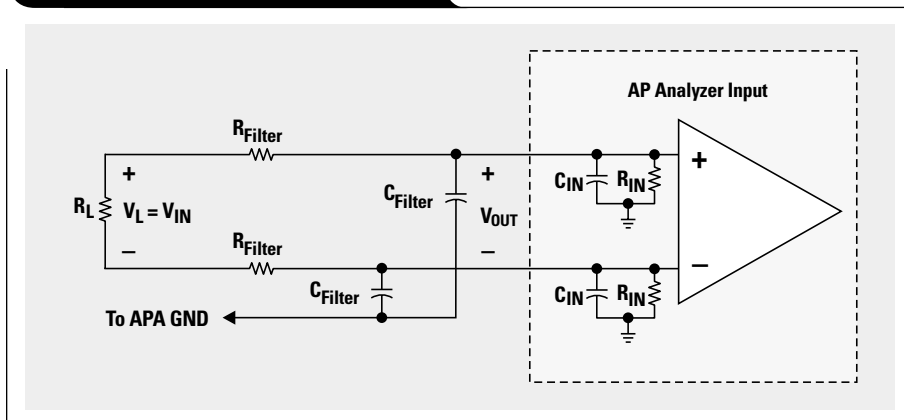
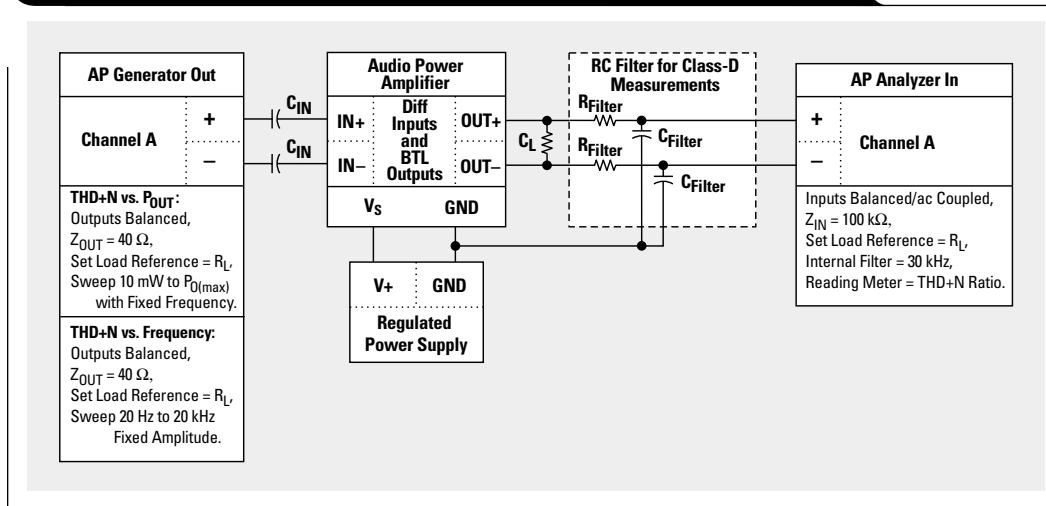


Figure 6. THD+N measurement circuit for a mono-channel BTL APA



When the THD+N versus output power is measured, the analog generator sweeps the input voltage from low to high at a fixed frequency. The output signal harmonics are then measured at specified voltage steps, and the output power is calculated for a given load-impedance value that is provided to the audio analyzer. This value is then divided by the amplitude of the fundamental frequency and graphed as a percentage of the fundamental. Figure 7 shows a typical THD+N-versus-power curve. The higher distortion at low values of P_{OUT} is due to the decrease in signal-to-noise ratio as the harmonics decrease in amplitude below the noise floor.³ The sudden increase at the upper level of P_{OUT} is due to clipping of the output signal.

When the THD+N versus frequency is measured, the analog generator sweeps the frequency from 20 kHz to 20 Hz at a fixed voltage. The harmonics of the output are measured at specified frequency steps. Each step is divided by the amplitude of the fundamental frequency and graphed as a percentage of the fundamental. This graph provides a fundamental check when compared to the THD+N versus power—they should match at one specific frequency and power. The increase at low frequencies is primarily due to the 1/f noise. If the THD+N measured at low frequencies is considerably higher than the data sheet value, the APA input ac coupling capacitance may need to be reduced to limit the noise bandwidth.

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Figure 7. TPA2001D1 and TPA731 output power sweep

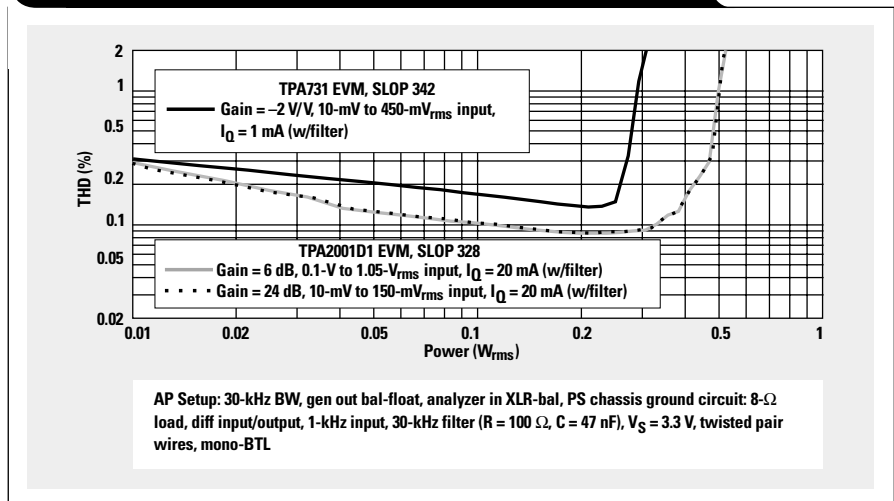


Figure 8. TPA2001D1 and TPA731 output frequency sweep

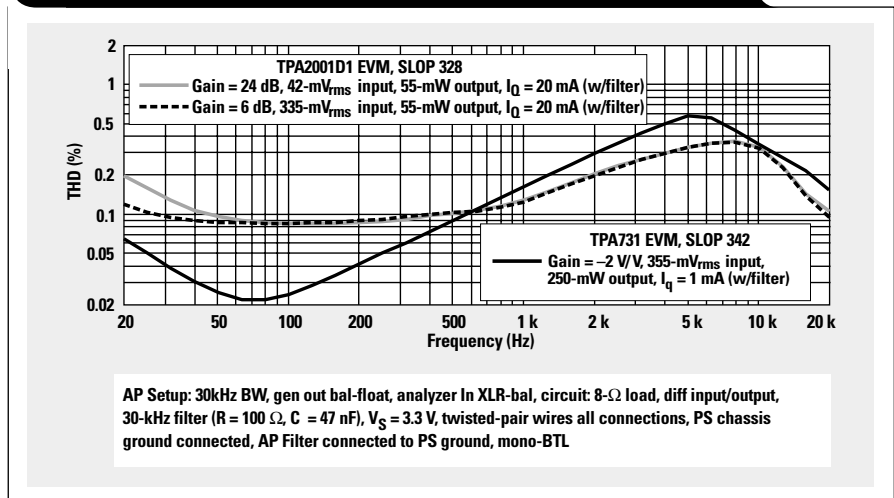
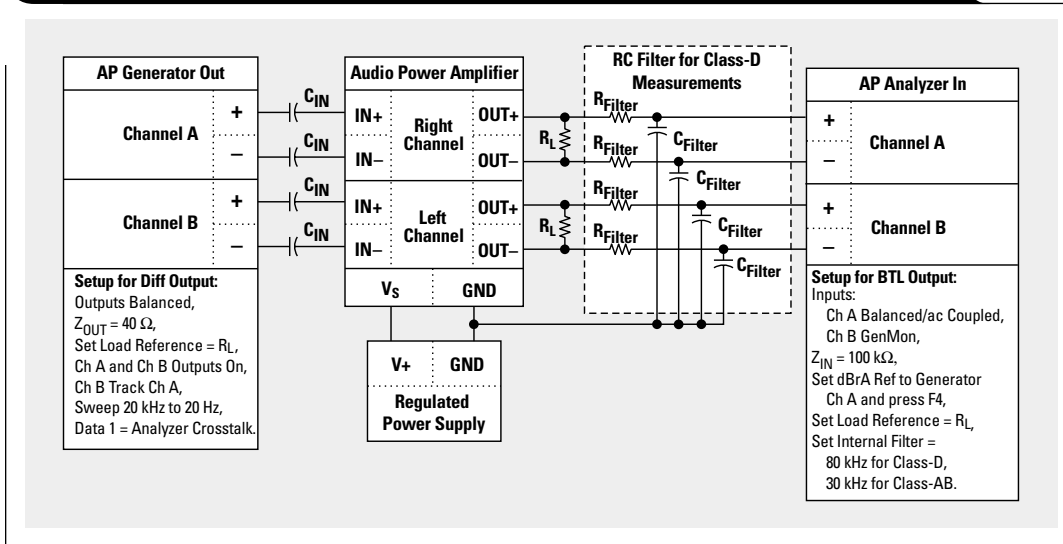


Figure 9. Gain and phase measurement circuit for a mono-channel BTL APA



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The high-frequency increase is due to device nonlinearities. The rolloff at high frequencies is due to the attenuation of harmonics, as the band-limiting filter in the analyzer was set to 30 kHz. This is normally a characteristic of the class-D measurements due to the filters used to reduce the switching frequency. The graph would continue in a straight line if there were no filter present, as is typically the case with class-AB amplifiers. Output filters are not typically used with class-AB measurements.

The load resistance must be set properly to get the right output power, and the shielded cable must be grounded properly or the THD will increase dramatically at high power. If there is unusually high distortion at lower power, check the ground connections and be sure to use twisted-pair, shielded wires. Also check that the generator outputs

are set correctly for SE or Diff APA inputs. These measurements will vary with C_{BYPASS} for devices that have a BYPASS pin, with THD increasing as C_{BYPASS} decreases.

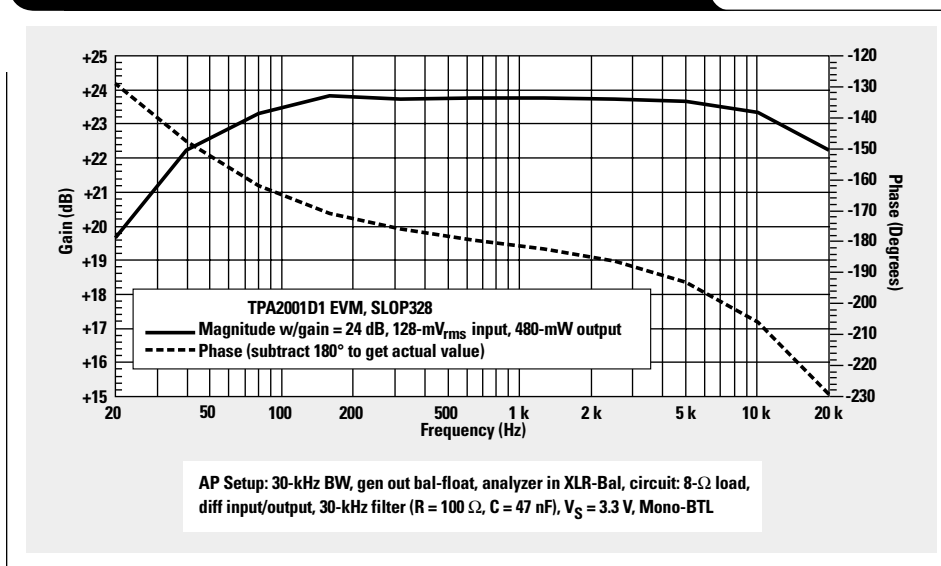
Gain and phase

The AP measurement circuit is shown in Figure 9 for a mono-channel BTL APA. Measurements for the TPA731 and TPA2001D1 are shown in Figures 10 and 11. The gain and phase can also be measured at a single point with an oscilloscope by using Equation 5 for the gain and Equation 6 for the phase, where Δt is the interval time between voltages and f is the frequency of the input signal:

$$A_V(\text{dB}) = 20 \times \log \left(\frac{V_{OUT}}{V_{IN}} \right) \tag{5}$$

$$\theta = \Delta t \times f \times 360^\circ \tag{6}$$

Figure 10. Gain-phase measurement for a TPA2001D1



Both channels must be turned on at the generator panel in the software, and Ch B must be set to track Ch A. The analyzer Ch B is set to GenMon, which means it takes its input directly from the generator output internal to the AP and uses it as the input-phase reference. The reference dBrA value should be set equal to the channel being swept, which in this case is Ch A. It may be necessary to subtract 180° from the measurement to get the actual value. The APA input high-pass filters and the RC filter introduce some attenuation and phase shift at the measurement endpoints, as seen in the figures.

Crosstalk

Crosstalk is the measurement of the signal coupling between channels of a stereo device. The input to one channel is swept at a constant amplitude, and the outputs of both channels are then measured at specific frequencies using band-pass filters to limit the noise at that particular frequency. The value of the channel being measured is compared to the channel with the signal applied, and the log ratio is graphed versus frequency.

The crosstalk measurement circuit is shown in Figure 12 for an APA with Diff inputs and BTL outputs. This particular setup is referred to as right-to-left (R-L) channel. A graph of the crosstalk is shown in Figure 13 for the TPA2001D2 and the TPA0212.

Figure 11. Gain-phase measurement for a TPA731

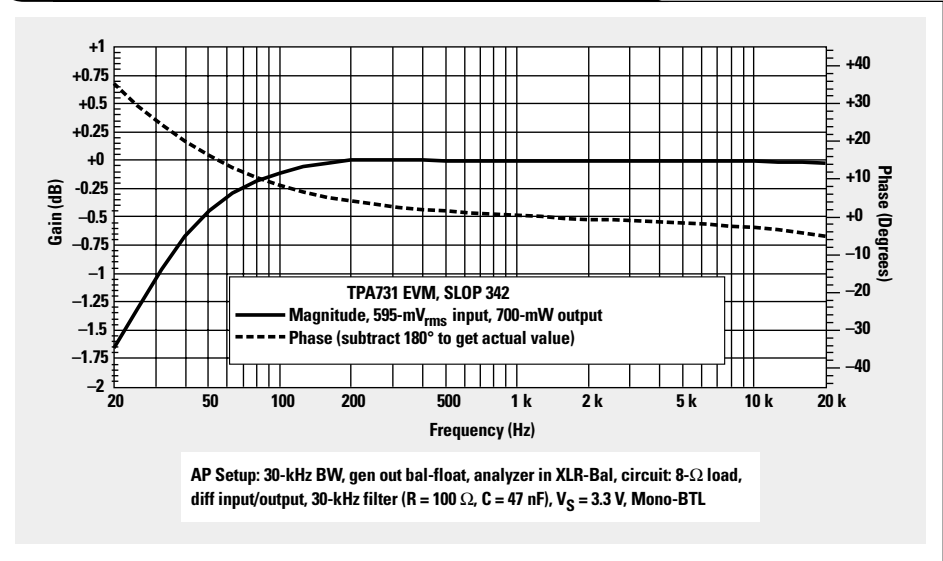
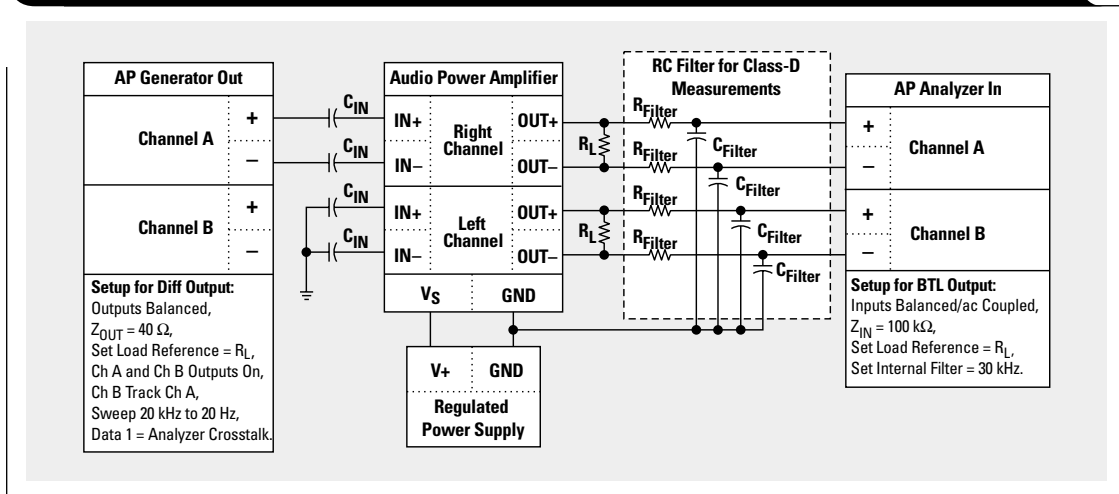


Figure 12. Crosstalk measurement system for an APA with Diff inputs and BTL outputs



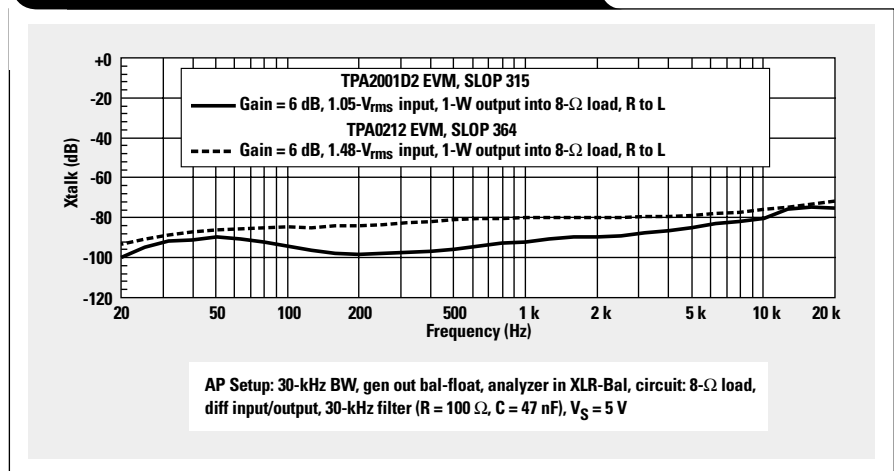
It can be measured point-to-point by using Equation 7, which is correct for the graph in Figure 13:

$$\text{Crosstalk} = 20 \times \log \left(\frac{V_{\text{Ch B}}^{\text{OUT}}}{V_{\text{Ch A}}^{\text{OUT}}} \right) \quad (7)$$

Both channels of the AP must be turned on at the generator panel in the software, and Ch B set to track Ch A. The input is swept over the audio frequency range at a constant amplitude—normally the maximum output power. The internal filter of the analyzer can be set to 30 kHz to limit noise but is otherwise not required. The output cables of the two channels should be

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Figure 13. TPA2001D2 and TPA0212 crosstalk



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twisted together to minimize the loop between them, and the inputs of the channel being measured should be ac grounded. The setup is reversed to graph the L-R channel crosstalk. Normally the two channels will be different due to impedance variations between the channels.

Output noise voltage

The output noise voltage is an integrated value that is measured over the audio frequency spectrum. The measurement circuit is shown in Figure 14 for an APA with Diff inputs and BTL outputs. A graph depicting the Diff/BTL output noise voltage of the TPA2001D1 and the TPA731 is shown in Figure 15. All of the inputs of the APA are ac coupled to ground. The AP generator outputs are not used in this measurement and should be turned off. The analyzer is active, with the reading meter function set to amplitude. The AP bandwidth should be limited to the audio frequency spectrum. The data is set to measure the analyzer amplitude; and the sweep source is the generator frequency, which is swept across the frequency spectrum from 20 kHz to 20 Hz. The output is in V_{RMS} and must be divided by the gain to get the input-referred noise voltage.

Conclusion

A method for measuring audio power amplifier characteristics with an audio analyzer has been presented. All measurements were taken with off-the-shelf TI APA evaluation modules. These values correspond closely to the data sheet values, which were measured by using characterization boards that are optimized for measuring the device. This shows that reasonable measurements can be made quickly and efficiently with audio circuits by using basic test equipment and pre-fabricated evaluation modules that save time and money spent on layout during initial evaluation of a device.

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References

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Figure 14. Measurement system for an APA with Diff inputs and BTL outputs

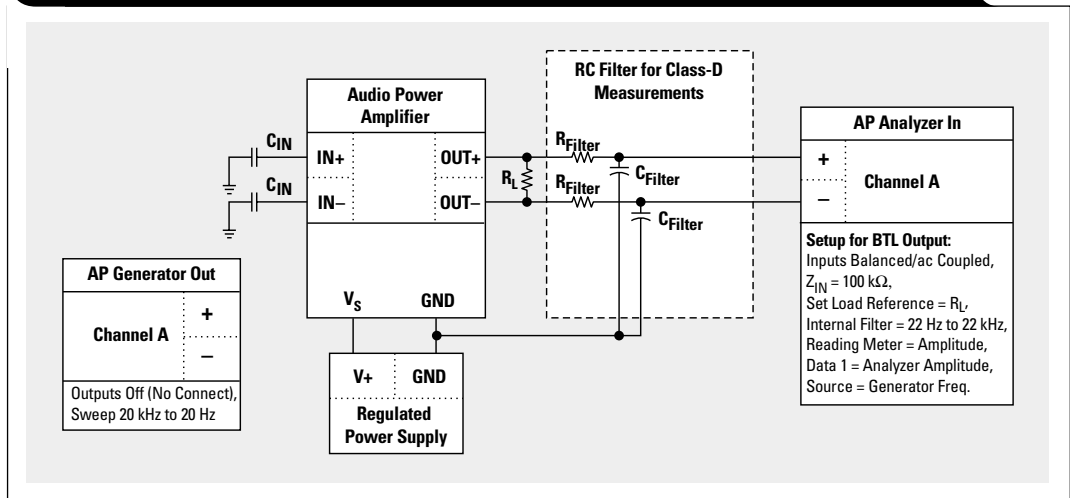
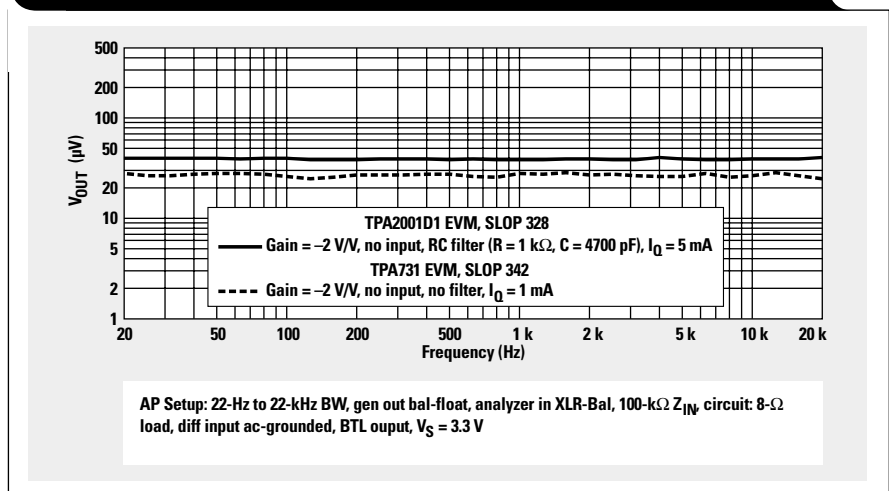


Figure 15. TPA2001D1 and TPA731 Diff/BTL output noise voltage



litnumber and replace "litnumber" with the TI Lit. # for the materials listed below.

Document Title **TI Lit. #**

1. Michael D. Score, "Reducing and Eliminating the Class-D Output Filter," Application Report . . .sloa023
2. Henry W. Ott, *Noise Reduction Techniques in Electronic Systems* (Wiley Interscience, 1976). —
3. Bob Metzler, *Audio Measurement Handbook* (Audio Precision, 1993). —

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