Audio power amplifier measurements, Part 2

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Introduction

This article is a continuation of “Audio power amplifier measurements,” which first appeared in the July 2001 issue of *Analog Applications Journal* (see Reference 1) and which contains guidelines for measuring the following three parameters:

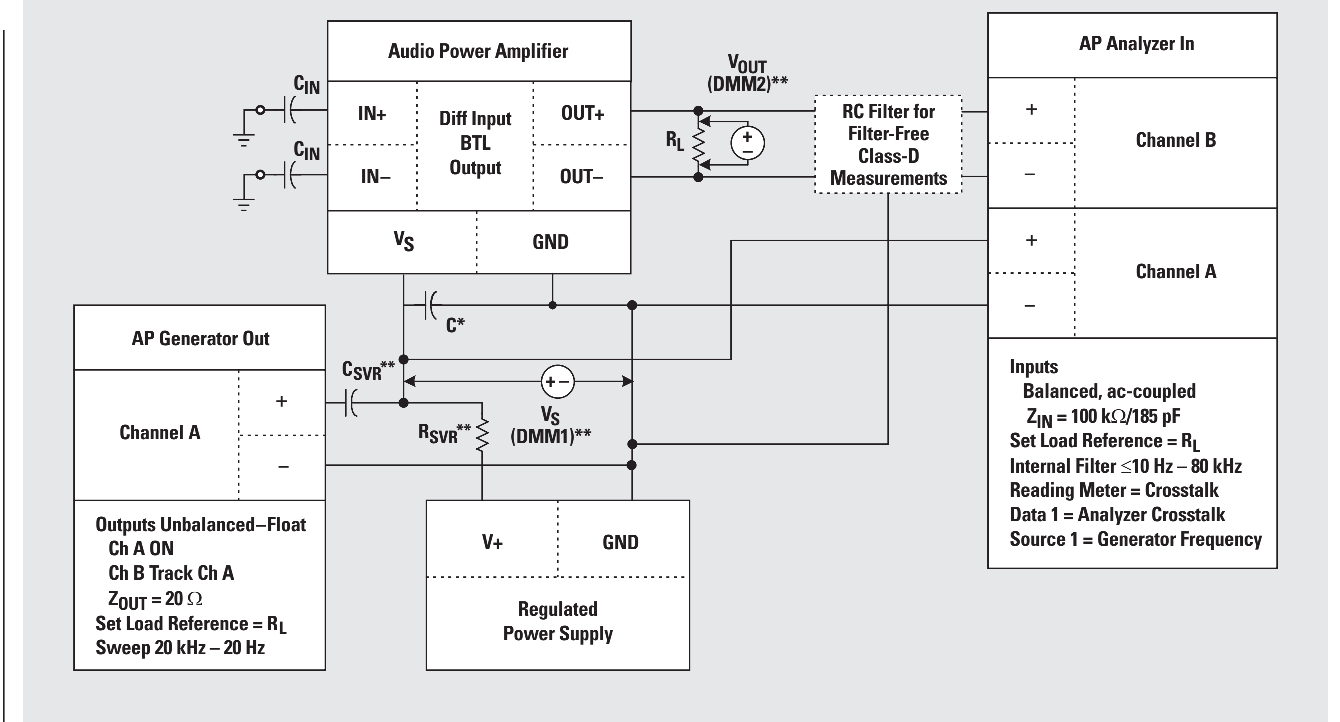
- power supply rejection ratio (PSRR),
- supply ripple voltage rejection ratio (k_{SVR}), and
- efficiency.

All measurements were made by using TI Plug-n-Play APA evaluation modules (EVMs) for the TPA2001D1 filter-free class-D and the TPA731 class-AB mono devices. Note that the graphs in the data sheets reflect typical specifications and were measured on test boards specifically designed to allow accuracy and ease of measurement. Board space, layout, and components were not constrained by size/cost requirements. The measurements in this article, however, were taken by using circuits on EVMs that reflect real-world layout constraints. The measurements of a particular audio circuit may vary from the typical specifications. A large variance is usually indicative of a PCB layout or measurement system issue. Reference 2 provides more details about the measurements in this article.

Supply rejection

Two types of supply rejection specifications exist: power-supply rejection ratio (PSRR) and supply ripple voltage rejection ratio (k_{SVR}). The only difference between them is that PSRR is a dc specification and k_{SVR} is an ac specification that measures the ability of the APA to reject ac-ripple voltage on the power supply bus. All power supply decoupling capacitors are removed from class-AB circuits, and class-D circuits have a small 0.1-µF decoupling capacitor, C, placed close to the APA power pins to provide a reverse path for recovery switching currents. It is recommended that the designer use equal decoupling capacitance values when comparing devices from different manufacturers to

Figure 1. PSRR and k_{SVR} measurement circuit



* The 0.1-µF capacitor, C, is required for class-D operation.

** The PSRR measurement uses the DMMs only since it is a dc value. k_{SVR} measurements use either the analyzer, oscilloscope, or DMMs since they are ac values. R_{SVR} and C_{SVR} are used for k_{SVR} measurements only.

get a valid comparison of the performance, since a higher capacitance equates to a better k_{SVR}.

PSRR is the ratio of the change in the output voltage, $V_{OUT(dc)}$, to a change in the power supply voltage, V_S, expressed in dB as shown in Equation 1.

$$\mathrm{PSRR} = 20\log\left(\frac{\Delta V_{OUT(dc)}}{\Delta V_S}\right) \tag{1}$$

For example, the output voltage of an audio power amplifier that has a PSRR equal to –70 dB would change by 31.6 µV if the supply voltage changed by 0.1 V.

k_{SVR} is the ratio of the output ripple voltage, $V_{OUT(ac)}$, to a change in the supply ripple voltage, V_S, expressed in dB as shown in Equation 2.

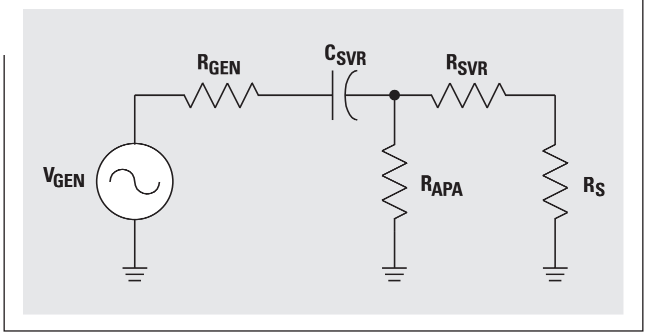
$$k_{SVR} = 20\log\left(\frac{V_{OUT(ac)}}{V_S}\right) \tag{2}$$

This parameter is normally listed as a typical value in the data sheet tables at a specified frequency and temperature of 1 kHz and 25°C, respectively. A graph is provided in the data sheet of the typical values of k_{SVR} over the audio bandwidth because it is a frequency-dependent term.

The PSRR and k_{SVR} measurement circuit is shown in Figure 1. All inputs are ac-coupled to ground. The PSRR measurement requires only the two DMMs. The power supply voltage, V_S, is initially set, then read from the meter on the power supply. When the power supply meter does not have the desired resolution, DMM1 is used to measure V_S. DMM2 then measures V_{OUT} across the load. V_S is then stepped up or down by a specific amount, and the corresponding value of V_{OUT} is measured. The differences of the two measurements are then substituted into Equation 1, and the PSRR is calculated for that specific change in supply voltage. PSRR is specified as a typical value that is valid for a given supply voltage range at 25°C.

The k_{SVR} measurement requires the signal generator, analyzer, a DMM, and the k_{SVR} filter components R_{SVR} and C_{SVR}. The RC measurement filter[1, 2] is used when the analyzer cannot accurately process the square wave output of the filter-free class-D APAs. DMM1 is used to measure V_S at the APA power pin. The generator injects a small sine wave signal onto the power bus, and the audio analyzer measures this ac voltage at the APA power pin and at the output. Here the analyzer, an Audio Precision System–II, is configured for a crosstalk measurement[1, 2]; it sweeps the ac voltage at constant amplitude over the audio band, measuring and presenting a graph of the data points in dB.

Figure 2. k_{SVR} filter circuit



The k_{SVR} filter circuit is shown in Figure 2. The dc power supply output impedance, R_S, is very low (milliohms); and the impedance of the APA to ground, R_{APA}, as seen by the power supply or signal generator, is very high (hundreds of ohms). The value of R_{SVR} is added to the circuit to increase the equivalent impedance of the power supply and is chosen to be approximately equal to the ac signal source generator output impedance, R_{GEN}. A voltage divider is formed between R_{SVR} and R_{GEN} that provides a reasonable amplitude ac signal at the APA power pin.

C_{SVR} is added to ac-couple the signal generator to the APA. The filter cutoff frequency, f_C, should be set 3 dB below the lowest frequency of the audio band, f_{MIN}, which in this case is 20 Hz. Equation 3 provides the value for f_C, which is ~14 Hz.

$$f_C = \frac{f_{MIN}}{\sqrt{2}} \tag{3}$$

The equivalent resistance is then calculated with Equation 4, where R_{APA} is the supply voltage divided by the quiescent current of the device (V_S/I_Q).

$$R_{EQ} = R_{GEN} + R_{APA} \parallel (R_{SVR} + R_S) \approx R_{GEN} + R_{SVR} \tag{4}$$

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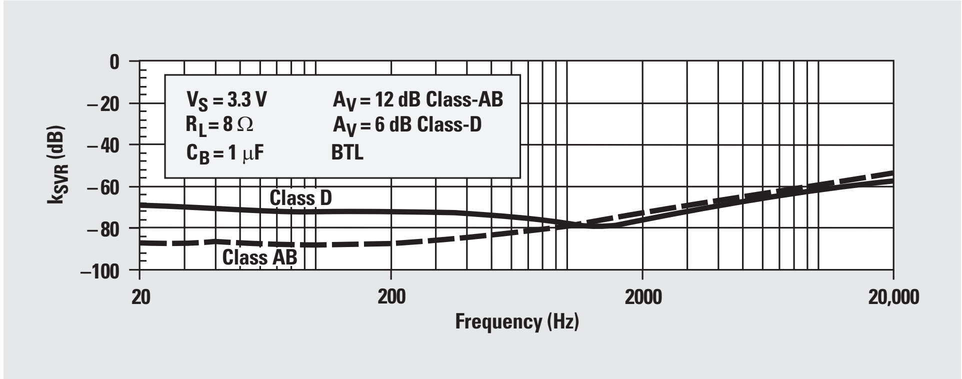
Figure 3. k_{SVR} of the TPA2001D1 and the TPA731



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The value for C_{SVR} is then calculated with Equation 5.

$$C_{SVR} = \frac{1}{2\pi \times f_C \times R_{EQ}} \qquad (5)$$

The capacitor will most likely be electrolytic due to the value required. It will have some reactance that will vary with frequency as shown by Equation 6.

$$X_{C_{SVR}} = \frac{1}{2\pi \times f_C \times C_{SVR}} \qquad (6)$$

At 20 Hz the impedance will be quite high—approximately the value of R_{GEN} and R_{SVR}; and at 20 kHz the value will be in the milliohms.

The actual values for the measurement circuit were $R_{GEN} = 20\ \Omega$, $R_S \approx 0$, $R_{APA} = 5\ V/6\ mA = 833\ \Omega$, $C_{SVR} = 330\ \mu F$, $R_{SVR} = 20\ \Omega$, and $f_C = 12$ Hz. This yields a capacitive reactance of 24 Ω at 20 Hz, and 24 mΩ at 20 kHz. The value of the ac signal must be adjusted at low frequencies so that the desired voltage is applied to the APA power pin. The value of the dc voltage from the power supply must also be adjusted, since I_Q will create a small voltage drop across R_{SVR}.

Those devices with BYPASS pins will have improved k_{SVR} as the capacitance on the pin is increased. Those operated SE have lower k_{SVR}, particularly at the extreme low and high ranges of the audio band. This is primarily due to the resonance of the output ac coupling capacitor.

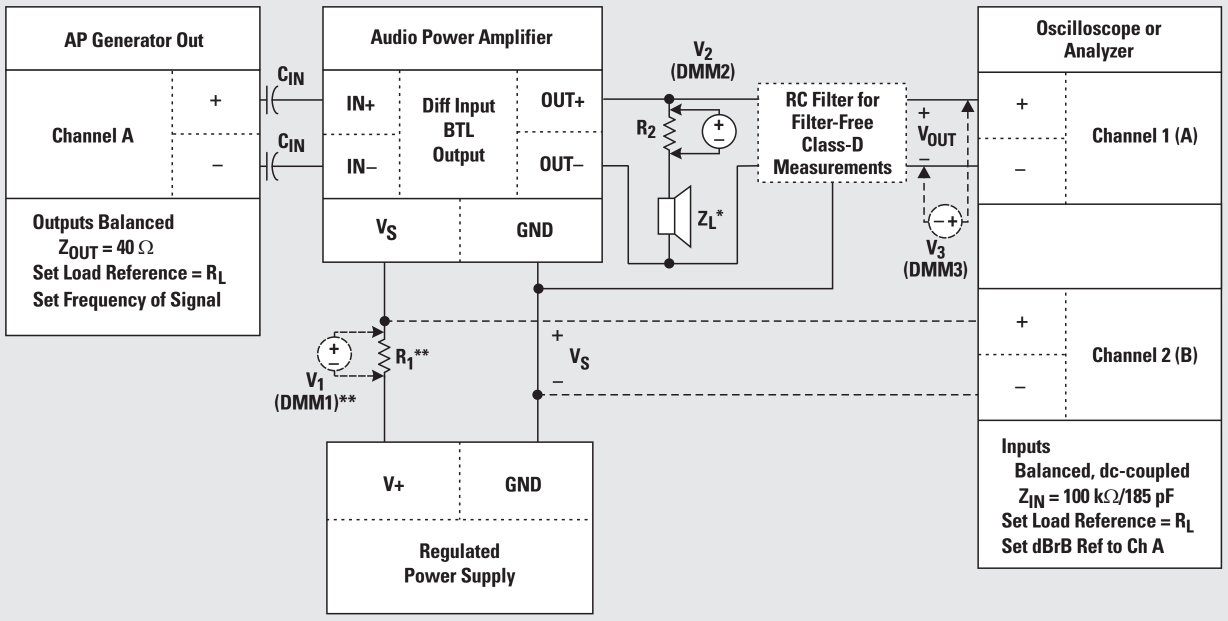
The k_{SVR} graphs of the TPA2001D1 and the TPA731 are shown in Figure 3. Both of these devices are differential input and BTL output. The TPA731 was measured with the inputs floating. Newer devices are typically measured with the inputs ac-grounded.

Efficiency measurements

Efficiency is the measure of the amount of power that is delivered to a load for a given input power provided by the supply. A class-AB APA acts like a variable resistor network between the power supply and the load, with the output transistors operating in the linear region. They dissipate quite a bit of power because of this mode of operation and are therefore inefficient. The output stage in class-D amplifiers acts as a switch that has a small resistance when operated in the saturation region, which provides a much higher efficiency.

A circuit for measuring the efficiency of a class-AB or class-D system is shown in Figure 4. The simplest setup occurs when the power supply voltage and current meters are accurate and have the resolution required. When the

Figure 4. Efficiency circuit, BTL



* Load Z_L is a speaker for class-D APAs and is a purely resistive load for class-AB APAs.

** DMM1 and Channel 2 of the AP/oscilloscope (or a third DMM) are used to measure the average power supply current and voltage when power supply meters are not accurate. Resistor R_1 can be removed when power supply meters are used.

supply current meter is not sufficient, R_1 is placed in the circuit. It should be a small value (0.1 Ω) and able to handle the power dissipated. The average voltage, V_1, across R_1 provides the average supply current ($I_S = V_1/R_1$) that is used to calculate the average power provided by the supply.

The true rms DMMs and the audio analyzer provide an rms value of both the voltage and the current, which, when multiplied together, provide the average power. When used, the power supply meters provide the average value of the supply voltage and current. The oscilloscope can measure the average or rms values of the power supply and output voltage. Some oscilloscopes even have current probes that can be used to measure the current through a wire, in which case R_1 is not needed.

The load measurement is different for class-AB and class-D APAs. Two elements are shown: one is the actual load, Z_L, and the other is resistor R_2. The Class-AB load is a non-inductive power resistor, $Z_L = R_L$. R_2 is not required for class-AB efficiency measurements since the load is purely resistive.

The filter-free class-D load is a speaker, so the impedance will vary with frequency. A speaker is used because it has the inductance that helps provide the high class-D efficiency. A purely resistive load is not a true indicator of the operating environment of the filter-free class-D, and will not provide accurate efficiency numbers. The power must be calculated independently of the speaker impedance since it varies with frequency. The small power resistor, R_2, provides a means of measuring the current that is used in the efficiency calculation ($I_{OUT} \approx V_2/R_2$).

Equation 7 provides the efficiency of the class-AB APA, and Equation 8 provides the efficiency of the class-D APA. The input power of both equations is just the average voltage applied to the power pin of the APA, multiplied by the average value of the power supply current. Average value is used for the power supply measurements, since the voltage and current have dc and ac components and are nonsinusoidal. The output power is also an average that results from the multiplication of two rms terms.

The RC measurement filter is used for making filter-free class-D output measurements when the analyzer or DMM cannot accurately process the switching waveform.[1, 2] The filter resistance must be large enough to minimize current flow through the filter; while the capacitance must be sized to achieve the desired cutoff frequency, which should be just above the audio band. If the filter resistor is not large enough, the filter current must be accounted for in the efficiency equation. The recommended values of R_{FILT} and C_{FILT} are 1 kΩ and 5.6 nF, respectively. This provides a filter cutoff frequency of ~28 kHz. This filter is not used with traditional class-D devices since they already have LC filters in the output circuit.

The efficiency was measured with a 3.3-V supply; the results are shown in Figure 5. Figure 5 provides the measured efficiency from the power supply meter and a Fluke 87III DMM measuring the voltage across the load.

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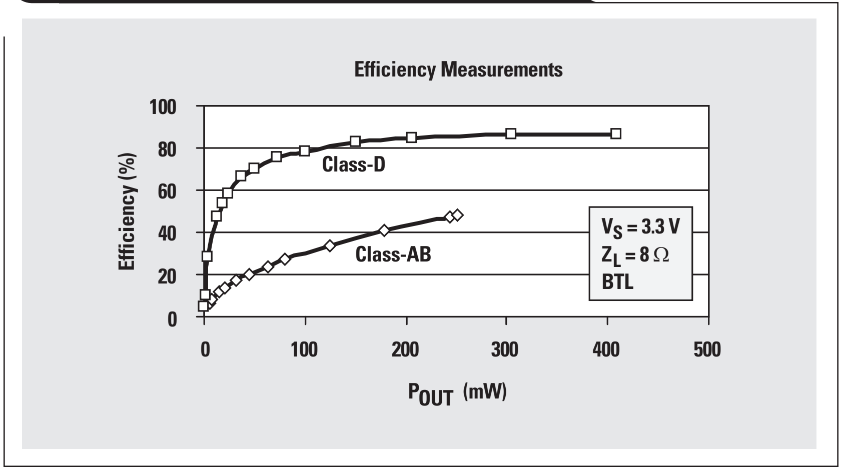
$$\eta_{Class-AB} = \frac{P_{OUT}}{P_S} = \frac{\left(\dfrac{V_{OUT(RMS)}^2}{R_L}\right)}{V_{S(AV)} \times I_{S(AV)}} \qquad (7)$$

$$\eta_{Class-D} = \frac{P_{OUT}}{P_S} = \frac{V_{OUT(RMS)} \times I_{OUT(RMS)}}{V_{S(AV)} \times I_{S(AV)}} = \frac{V_{OUT(RMS)} \times \left(\dfrac{V_{R_2(RMS)}}{R_2}\right)}{V_{S(AV)} \times I_{S(AV)}} \qquad (8)$$

Figure 5. Efficiency of the TPA731 class-AB APA and the TPA2001D1 class-D APA



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The DMM class-AB data was in close agreement with measurements made with the AP-II Analyzer or a TDS 754 oscilloscope. The class-D DMM and AP data were similar, but the oscilloscope measured 5–10% higher due to its averaging, which introduced a somewhat large margin of error, particularly at high power output. The DMM reading is more reliable, since it filters out the high-frequency harmonics of the switching waveform to provide a more stable, low-frequency value. Tables of measurement values for both amplifiers are available in Reference 2.

Power dissipated versus power to the load

The efficiency measurements provide the information required to calculate the amount of power dissipated, P_D, in the amplifier. P_D provides some insight into the supply currents and power that will be required. P_D is calculated by using Equation 9 and the measured values of supply and output power from the efficiency measurements. It is assumed that the power dissipated in the RC filter, used for the filter-free class-D APA measurements, is negligible; therefore it is not included in the calculation. When it is significant, it must be included as part of P_{OUT}.

$$P_D = P_S - P_{OUT} \tag{9}$$

Figure 6 shows graphs of dissipated power versus the output power calculated with Equation 9. The data was measured up to the maximum output power, which occurs just prior to clipping, and can easily be discerned from a graph of THD+N versus output power.^{2} The designer can choose the percent distortion (level of clipping) that is acceptable for a system and test the device through that power level.

Crest factor and output power

The crest factor (CF) is the ratio of the peak output to the average output. It is typically graphed in terms of output power and is in units of dB. For example, the crest factor of a sine wave is 3 dB. Sine waves are used in the characterization of APA performance but do not give a clear idea of what the performance will be with music. The CF of music may vary between 6 dB and 24 dB and directly impacts the amount of heat dissipated in the device—the higher the crest factor, the lower the heat dissipated and the higher the ambient operating temperature may be. The P_D data discussed in the previous two paragraphs can be used to determine the CF of the device.

Equation 10 may be used to calculate CF. Since a sine wave was used for the measurements, the crest factor is 3 dB, and the average output power, $P_{OUT(AV)}$, is known. The peak output power, $P_{OUT(PK)}$, is calculated by manipulating Equation 10 into Equation 11, where $P_{OUT(PK)}$ and $P_{OUT(AV)}$ are expressed in watts and CF is expressed in dB.

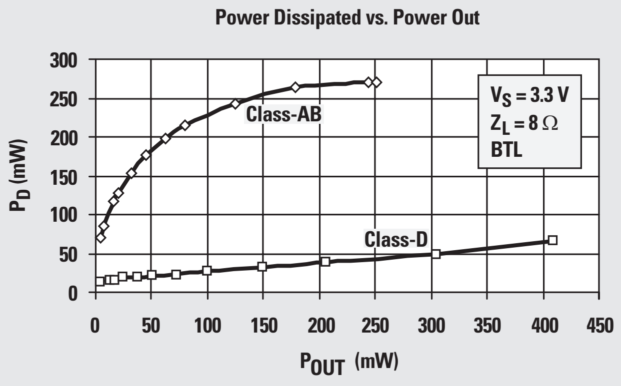
$$\mathrm{CF(dB)} = 10\log\left(\frac{P_{OUT(PK)}}{P_{OUT(AV)}}\right) \tag{10}$$

$$P_{OUT(AV)} = \frac{P_{OUT(PK)}}{10^{\left(\frac{CF}{10}\right)}} \tag{11}$$

For example, the maximum peak output power is 500 mW for the TPA731. This is calculated by using 250 mW as $P_{OUT(AV)}$ and a CF of 3 dB for the output sinusoid. The peak will not change throughout the calculations, as it is the maximum output power possible and is independent of the output waveform. The CF is then increased in 3-dB steps up to 18 dB, and the corresponding $P_{OUT(AV)}$ is calculated for each step. The P_D in the device is measured for each value of $P_{OUT(AV)}$ with the efficiency measurement circuit.

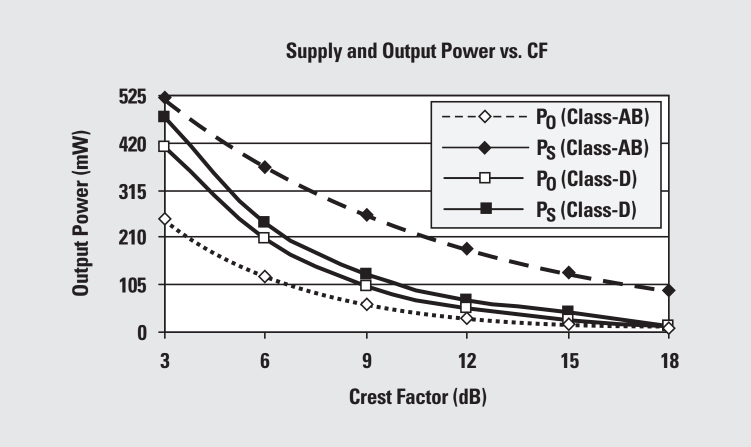
The efficiency data and CF calculations can help the designer approximate the power that must be provided by

Figure 6. Power dissipated vs. output power



the power supply. Figure 7 shows the graph of P_S and P_{OUT} versus crest factor. The graph allows easy comparison of the devices, and it is clear that the class-D APA provides more P_{OUT} with less power from the supply than the class-AB APA. The difference between P_S and P_{OUT} is the dissipated power, P_D.

Figure 7. Supply and output power vs. CF



Measurement pitfalls

The following is a list of common pitfalls, or mistakes, that can be encountered and will produce measurement errors.

- The signal generator should be balanced for differential inputs, unbalanced for SE inputs.
- Wires should be twisted together to minimize magnetic coupling into loops and ground loops.
- Use the RC measurement filter for the filter-free class-D outputs when using an analyzer or oscilloscope. The capacitor should be connected to either the power supply or the APA power ground.
- The leads of filter components should be kept short.
- The DMM must be “true rms” to get accurate measurements.
- The wires from the power supply and from the APA to the load should be at least 18 AWG for 2-W APAs.[2]

Supply rejection ratio measurements

- A 0.1-µF decoupling capacitor is required for class-D operation. All other capacitors should be removed. All decoupling capacitors should be removed for class-AB measurements.

Efficiency measurement

- The filter-free class-D RC measurement filter should have a high resistance for R_{FILT}, with a value of 1 kΩ recommended in conjunction with a 5.6-nF capacitor. The current through the filter must be considered when R_{FILT} is small.
- Check to make sure that the DMMs used at the load are set to measure ac volts and to measure dc volts at the power supply.

References

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Document Title **TI Lit. #**

1. Richard Palmer, “Audio power amplifier measurements,” *Analog Applications Journal* (July 2001), pp. 40-46. . . . . .slyt135
2. “Guidelines for Measuring Audio Power Amplifier Performance,” Application Report . . .sloa068

Related Web sites

www.ti.com/sc/docs/products/analog/tpa731.html
www.ti.com/sc/docs/products/analog/tpa2001d1.html

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