PSRR: The Real Story about Closed- and Open-Loop Class-D Amplifiers

Understand why conventional power-supply rejection-ratio (PSRR) data for Class-D amplifiers is suspect, and an alternate way to look at the effects of supply ripple on audio-amplifier performance

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Abstract: *As open- and closed-loop Class-D amplifiers increasingly become the preferred choice of consumer-audio electronics designers, a different way of looking at the effects of power-supply ripple is needed to adequately capture the performance of the amplifier. Today's audio designers are increasingly focused on reducing system cost, shrinking form factors and delivering high-quality audio, all of which require high supply-noise rejection architectures. Unfortunately, the power-supply rejection ratio (PSRR) measurement does not accurately capture the performance of Class-D bridge-tied load (BTL) amplifiers.*

In this article, we discuss the traditional PSRR specification and measurement technique, and explain why it fails to adequately capture the supply-rejection capability of the amplifier. We then describe an alternate way to look at the effects of power supply ripple on the amplifier's audio performance.

Historically, power-supply rejection ratio (PSRR) has been an excellent measurement of an amplifier's ability to reject supply noise from its output. However, with the ever-increasing presence of Class-D amplifiers and the efficiency advantages they provide, it is no longer sufficient to rely only on PSRR as an indicator of power-supply noise rejection.

This is especially evident when comparing PSRR specs of open- and closed-loop digital-input I^2S amplifiers. Many times, the PSRR specs are identical, but when listening to the amplifiers with less-than-ideal power supplies, there is clearly a difference in audio performance. This article provides an overview of the traditional PSRR measurement, explains why it does not adequately capture the supply rejection performance in Class-D amplifiers in a bridge-tied load (BTL) configuration, and describes an alternate way to measure the effects of power supply noise in Class-D amplifiers.

Amplifier Classes and Configurations

To understand why the PSRR measurement no longer adequately captures the supply rejection performance, we need to look back in time to when Class-AB amplifiers dominated consumer audio electronics. Class-AB amplifiers were commonly configured in either a single-ended (SE) or BTL output configuration, as they are today. In fact, it was fairly common for SE Class-AB amplifiers to have split-rail supplies (i.e., +/- 12V) as power supplies were predominantly transformer-based and adding a second rail was not cost prohibitive.

The BTL configuration was more commonly used in audio systems that did not have a split-rail supply. Whether talking about SE or BTL configurations, Class-AB amplifiers inherently have good PSRR, given their fundamental architecture and output levels that are typically well below the supply-rail voltage.

For Class-AB amplifiers, the PSRR measurement provides a relatively good indication of the amplifier's ability to reject supply noise, and is especially accurate for the SE configuration (we'll expand more on this later). Fast forward a bit in time and we start to see Class-D amplifiers hitting the market. Their extremely efficient operation changed the market dynamics, enabling considerable innovation in industrial design, especially in smaller form factors. However, their architecture was fundamentally different than Class-AB amplifiers, and their output configuration of choice was almost exclusively BTL.

In the BTL configuration, the Class-D amplifier has two output stages, consisting of four FETS (also known as a full-bridge), while the SE Class-D amplifier has just a single output stage consisting of two FETS (also known as a half-bridge). The BTL output configuration has a number of advantages over SE configurations, including four times the output power for a given supply rail, better bass response, and superior turn on/off click and pop performance.

Some disadvantages of the BTL architecture are that you need twice the number of FET transistors. This means a larger silicon die size and associated cost, and double the reconstruction filter (LC filter) costs. While in today's market you can see both SE and BTL Class-D amplifiers, the majority are BTL.

In Class-D BTL configurations, the traditional PSRR measurement breaks down. To better understand why, look at how a Class-D amplifier operates and how PSRR is measured. Class-D amplifiers are switching amplifiers, with outputs that switch from rail-to-rail at very high frequencies, typically 250 kHz or greater. The audio signal is used to pulse-width modulate (PWM) the switching frequency (square wave). Then a reconstruction filter (LC filter) is used to extract the audio signal from the carrier frequency.

These switching architectures are incredibly efficient (same architecture found in switch-mode power suppliers), but are much more sensitive to supply noise than traditional Class-AB amplifiers. Think about it for a second … the amplifier's output is essentially the supply rail (pulse-width modulated), so any supply noise present is directly passed to the amplifier's outputs.

Now look at PSRR

Power-supply rejection ratio (PSRR) is a measure of how well an amplifier rejects power-supply noise, i.e., ripple. It is an important parameter when selecting audio amplifiers because an audio amplifier with poor PSRR often requires a more costly power supply and/or large decoupling capacitors. In the consumer market, power supply cost, size and weight are important design considerations, especially as form factors continue to shrink, prices rapidly erode, and portable designs become more and more common.

In the traditional PSRR measurement, the amplifier's supply voltage consists of a DC voltage plus an AC ripple signal (V_{ripple}). The audio inputs are AC grounded, so no audio signal is present during the measurement. All supply-voltage decoupling capacitance is removed, such that V_{ripple} does not get artificially attenuated (**Figure 1**). The output signal is then measured and PSRR is calculated using **Equation 1**:

$$PSRR(f) = 20 \log \frac{V_{out}(f)}{V_{ripple}(f)} \qquad \textbf{Eq. (1)}$$

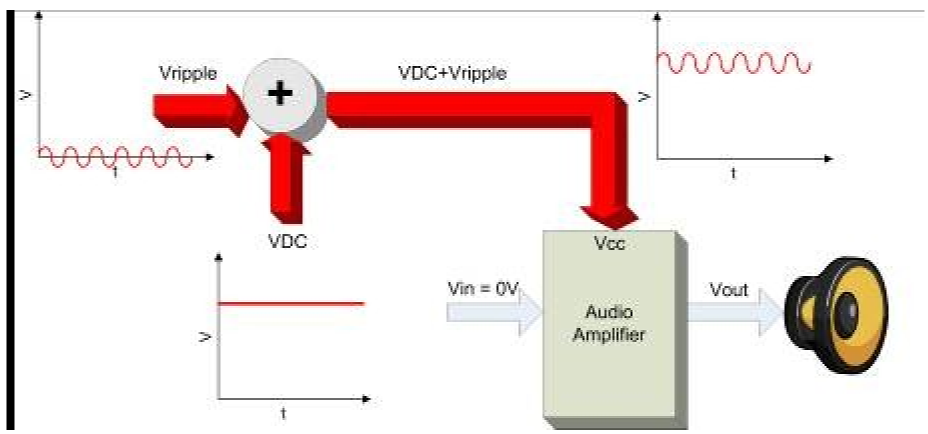

Figure 1. Traditional PSRR measurement

Figure 2 shows the traditional PSRR measurement on a Class-D BTL audio amplifier.

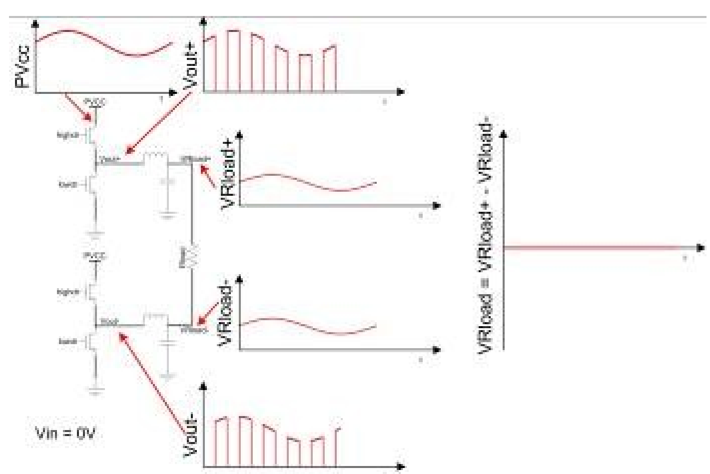

Figure 2. BTL Class-D PSRR measurement with LC filters

The supply noise is clearly present on the output, both before and after the reconstruction filter. However, note that the noise is present and in-phase across the load. So when you measure the PSRR, the Vout+ and Vout– ripple cancel each other, yielding a false indication of supply rejection.

But it's clear that the amplifier is passing the supply noise directly to the outputs. This PSRR measurement is not giving you any indication of how good, or not so good, the amplifier is at rejecting the supply noise. Where the PSRR measurement breaks down is the inputs are AC-grounded during the measurement. In the real world, the amplifier is playing music. This is where things start to get interesting.

When playing audio, the power-supply noise gets mixed/modulated with the incoming audio signal and its resulting distortion is spread throughout the audio band to varying degrees. The inherent canceling effect of the BTL configuration can no longer remove the noise. The industry came up with a really cool-sounding name for this, intermodulation distortion (IMD). IMD is the result of two or more signals of different frequencies being mixed together, forming additional signals at frequencies that, generally are not at harmonic frequencies (integer multiples) of either.

Before discussing how to address the deficiencies of the PSRR measurement, let's first talk about feedback. If you have had your coffee and are following along with this argument, it should come as no surprise that Class-D amplifiers inherently have problems with supply noise. This would be a major problem if not for feedback. (In high-end audio applications, open-loop amplifiers sound great, but that is a different story. They typically have very stable, high-performing supplies and much higher cost targets.) To compensate for supply-noise sensitivity, designers either design a system with a well-regulated supply, which adds cost; or use a Class-D amplifier that has feedback (also known as a closed-loop amplifier).

Today, in the consumer electronics market, the majority of analog-input Class-D amplifiers are closed-loop. But it's a different story with the digital-input I^2S amplifiers. I^2S amplifiers connect directly to the audio processor or audio source via a digital bus. This reduces cost and improves performance by eliminating the unnecessary digital-to-analog conversion.

Unfortunately, there are not a lot of closed-loop I^2S amplifiers on the market today, as it is fairly difficult to construct a feedback loop that samples the PWM output and sums it back with the incoming I^2S digital audio stream. In an analog-feedback system, you sum the analog output with the analog input, so it's much easier to implement. But as the I^2S market evolves, the majority of I^2S amps should follow the same path as the analog-input amps and adopt feedback architectures.

IMD offers a better metric

Clearly, PSRR is not a valid measurement of supply rejection for BTL Class-D amplifiers. So what is one to do? Back to that cool sounding term, *intermodulation*. We need to measure the intermodulation distortion generated while playing audio and its corresponding THD+N profile.

Before doing this, let's go back to SE architectures. In a SE architecture, whether it is Class AB, Class-D or even Class-Z, you don't get the canceling effects of a BTL architecture, since one end of the speaker is connected to the amplifier, and the other is connected to ground. So in a SE architecture, the traditional PSRR measurement provides a good indication of supply-noise rejection, whether talking about Class-AB or Class-D amplifiers.

Now let's get into the lab and take some data. Below are a series of measurements where we analyze and compare power-supply ripple IMD in an open-loop and closed-loop I^2S amplifier. A digital 1-kHz tone is injected into the amplifier's inputs and a 100-Hz, 500-mV_{pp} ripple signal is injected onto the supply. Observe IMD by taking an FFT of the differential outputs with the audio precision built-in FFT functions.

Figure 3 shows the IMD measurement of a closed-loop I^2S amplifier. Note the 1-kHz input signal and almost non-existent sidebands. The feedback loop is doing a good job of suppressing the intermodulation distortion.

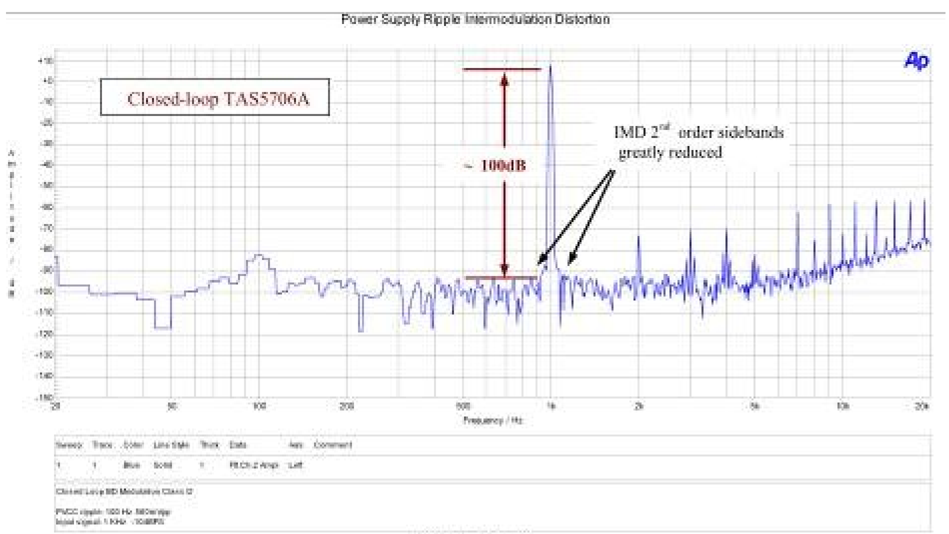

Figure 3. TAS5706 closed-loop intermodulation sweep

The same IMD measurement is shown in **Figure 4**, but this time taken on an I^2S open-loop amplifier. The sidebands at 900 Hz and 1.1 kHz are very pronounced since there is no feedback to suppress the IMD.

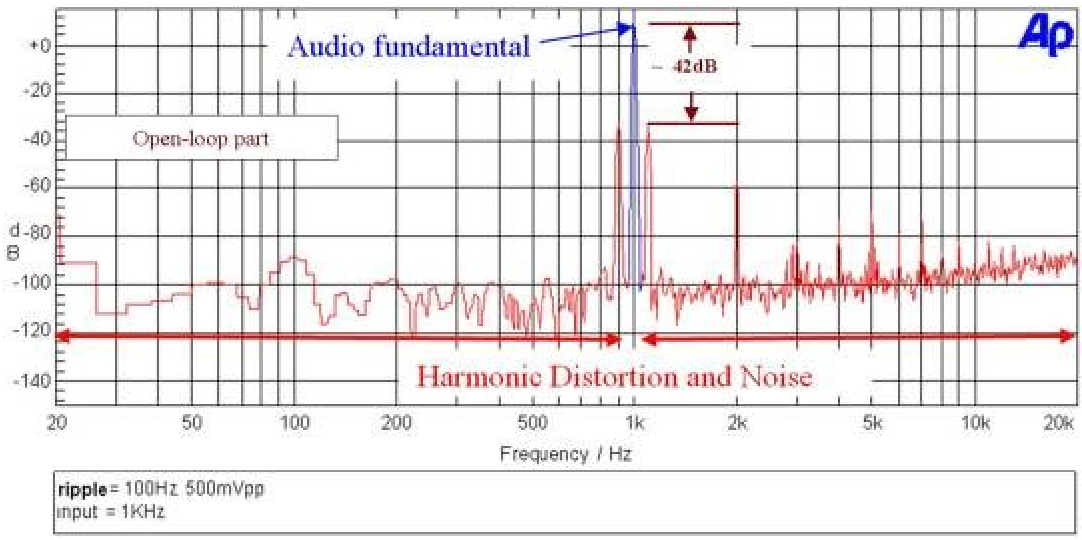

Figure 4. Open-loop intermodulation sweep

Now, to the good stuff! In Figure 3 and Figure 4, you can clearly see the effects of the power supply noise IMD. But in terms of audio quality, IMD is a hard measurement to get your "qualitative hands" around. One option is to run the same experiment, but now measure the THD+N profile, which we will do in the next two measurements. The THD+N is measured with a 1-kHz digital audio signal and 500-mV_{pp} power supply ripple. The supply ripple frequency is varied from 50 Hz to 1 kHz.

In **Figure 5**, see the THD+N sweep of the open-loop part at different power supply ripple frequencies.

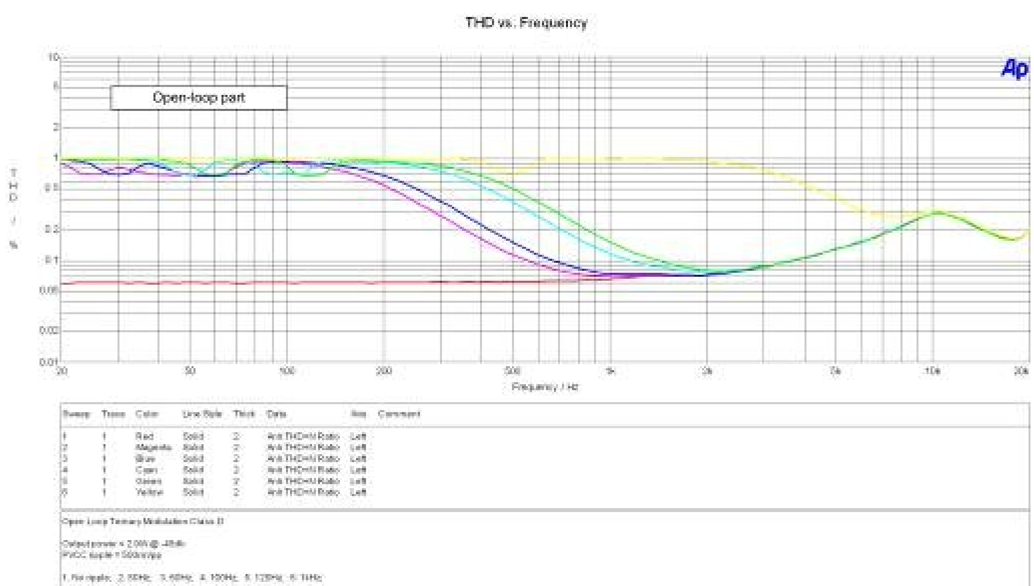

Figure 5. Open-Loop: THD+N vs. frequency at different PVCC ripple frequencies

The red line indicates the amplifier’s performance with a no ripple present on the supply, representing the ideal case. The other curves represent ripple frequencies varying from 50 Hz to 1 kHz. Note that as the ripple frequency increases, the frequency bandwidth affected by the distortion also increases. Note that the open-loop performance is very good with a well-regulated supply; however, that increases cost and can be problematic in today’s hyper-competitive world of consumer electronics.

See the same THD+N sweeps in **Figure 6**, but now on the closed-loop amplifier. Feedback is suppressing the intermodulation distortion, so you don’t see any ripple noise effect on the audio performance.

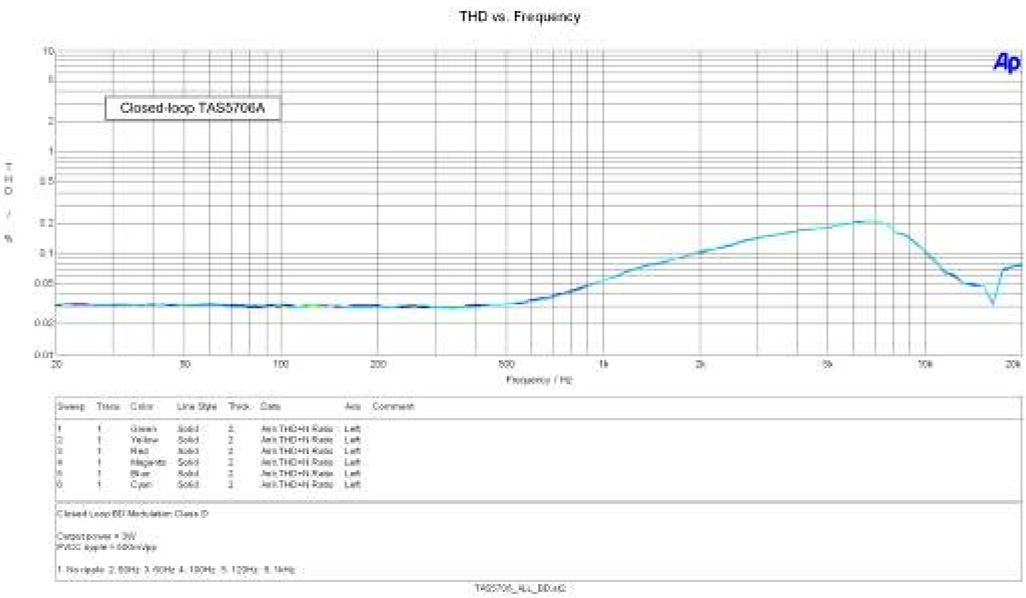

Figure 6. Closed-Loop: THD+N versus frequency at different PVCC ripple frequencies

Conclusion
In this article, we reviewed the traditional method of measuring PSRR and showed why it is ineffective in measuring the effects of power-supply ripple in BTL Class-D amplifiers. The inherent canceling effects of the BTL output configuration, coupled with a lack of audio signal present during the measurement, yields a false reading. This is a critical deficiency of the specification, as supply-noise rejection performance is extremely important in selecting a Class-D amplifier, especially in seeing the performance differences between digital-input (I^2S) closed-loop and open-loop amplifiers. To get a more-accurate picture of the supply noise rejection, you need to look at the IMD and THD+N performance with a 1-kHz audio signal at the inputs and noise injected on the supply.

Finally, we showed how the closed-loop Class-D amplifier was able to compensate for the power-supply noise, while the open-loop amplifier was not. In the hyper-competitive consumer electronics market cost is king, and the ability of closed-loop architectures to reduce system cost is a very important design consideration.

References

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