MEASURING DISTORTION IN SWITCHING AMPLIFIERS

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Presented at the AES 27th International Conference on Efficient Audio Power Amplification (September 2005)

ABSTRACT

The distortion performance of switching amplifiers (a.k.a. "Class-D" amplifiers) has rapidly improved in recent years. Unfortunately they still exhibit a form of high-frequency non-linearity that is not clearly revealed by traditional THD+N and SMPTE-IMD tests. The Twin-Tone IMD measurement technique provides an excellent way to measure this form of distortion.

INTRODUCTION

Recent advances in switching amplifier design and pulse width modulation ("PWM") techniques have led to dramatic reductions in non-linear distortion. Indeed, it has become difficult to distinguish some switching amplifiers from their linear cousins based solely on THD+N and SMPTE/DIN IMD testing. However, new technologies always seem to bring new forms of imperfection that must be identified, measured, and addressed. Switching amplifiers have been no exception.

THD+N TESTING

Total Harmonic Distortion and Noise ("THD+N") is perhaps one of the single most useful measures of amplifier performance. It is easy to define and understand conceptually. It is also practical to implement in automated test and measurement equipment. Results can be expressed as a single number, but more frequently are shown as a graph versus output amplitude or signal frequency.

At its most basic level, THD+N measures the impurity in a sine-wave signal. A near perfect sine wave is applied to the amplifier being tested. The output is then analyzed for the presence of components not present in the original signal within a prescribed measurement bandwidth. Beside the harmonics of the original signal, THD+N includes wideband noise, ac mains related products ("hum"), and other spurious content. A perfect amplifier should add nothing to its output signal that was not present in the input signal.

THD+N can be measured using several techniques. The most common is to begin by removing the fundamental test frequency component with a notch filter (either in the analog or digital domain). The left over residue is then measured with an RMS voltmeter having a controlled bandwidth. Because noise is included in a THD+N reading, the measurement bandwidth must always be specified in order to make meaningful comparisons with other data.

Another technique is based upon the FFT. Very basically, the algorithm performs an RMS summation of all FFT bins between a given lower and upper bandwidth limit, <u>excluding</u> a segment of bins surrounding the fundamental test tone. The result can be scaled directly into a percentage or dB result by dividing by this first summation by the RMS summation of the excluded FFT bins surrounding the fundamental tone. Usually the band from about 0.75 to 1.25 of the fundamental is excluded to correlate with the typical Q-factor of analog notch filters. Deviations from this algorithm become necessary at very low frequencies due to the discrete bin widths of the FFT.

The relative simplicity of THD+N measurements is also one of its weaknesses. Because THD+N is a bandwidth limited measurement, all information about a non-linearity will be lost if the harmonics fall outside of the pass-band. In a 20 kHz bandwidth limited system, this places a practical upper fundamental limit of ≈6 kHz, if at least one even and odd order harmonic are to be included in the measured THD+N.

The best commercially available audio analyzers currently guarantee residual THD+N performance below -112 dB using an analog notch filter. Measurements using the FFT technique are typically 5-10 dB worse, limited by A/D converter performance. However, it is possible to perform an FFT-based measurement on the output of the analog notch filter and eliminate this limitation.

THD+N VS. AMPLITUDE SWEEPS

Single point measurements convey very little information about an amplifier's performance because THD+N typically varies significantly as a function of both signal amplitude and frequency. If we pick a specific test frequency, an amplitude sweep with show three distinct regions of behavior as seen in Figure 1.

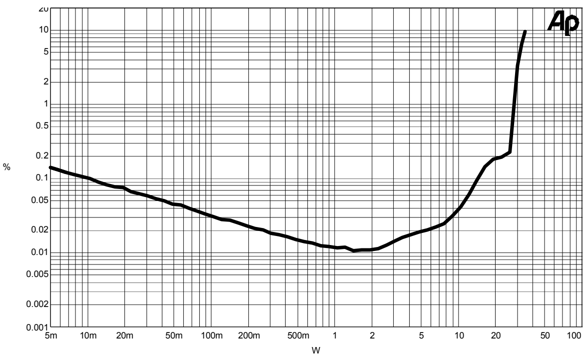

Figure 1. 1 kHz THD+N vs. Amplitude (20 kHz BW)

At low output amplitudes, the THD+N is limited by noise and residual "hum" products related to the ac mains. Since these tend to be constant, THD+N will vary in a reciprocal fashion to amplitude when expressed as a percentage of the output. With the amplifier shown in Figure 1, this region exists below about 1 Watt.

As the signal level is increased, THD+N will typically flatten and show a flat or somewhat broadly increasing characteristic. Certain linear designs that switch the raw dc supply voltages (class-G, etc.) to improve efficiency at lower output levels will sometimes show abrupt jumps in THD+N in this region. In Figure 1, this region exists from 1 Watt to about 25 Watts.

As the signal level continues to be swept upwards, the amplifier will eventually encounter clipping or some form of signal compression. Clipping is clearly seen in Figure 1 as a rapid increase in THD+N above ≈26 Watts. Amplifiers with compression circuits will not display hard clipping, however the THD+N performance in this region can still show a rise depending upon the distortion performance of the compression circuit.

THD+N VS. FREQUENCY SWEEPS

THD+N behavior can also be examined as a function of frequency at constant amplitude. This is a particularly powerful form of testing because it usually reveals insight into the non-linear behavior of an amplifier at its frequency extremes. Many switching amplifiers exhibit a rising THD+N characteristic followed by abrupt drops with increasing frequency as shown in Figure 2.

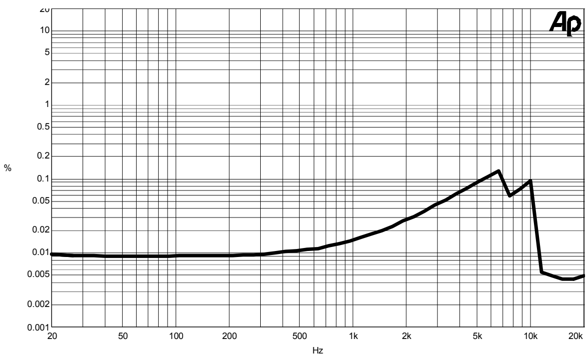

Figure 2. THD+N vs. Frequency (20 kHz BW)

The generally increasing characteristic is usually the consequence of one or more forms of non-linearity in the output stage and/or pulse width modulator, combined with a decreasing amount of feedback with frequency. For the graph shown in Figure 2, the measurement bandwidth was 20 kHz. Thus, the abrupt change in THD+N around 7 kHz corresponds with the loss of measurement sensitivity to the third harmonic. The next major transition just above 10 kHz corresponds to the loss in measurement sensitivity to the second harmonic. The THD+N measurements above 10 kHz really only show the noise floor and any spurious content that happens to fall below 20 kHz.

The key point here is that the amplifier is undoubtedly non-linear at 20 kHz. We just cannot see it using this type of distortion test. If we take the portion of the THD+N curve below 6 kHz and extrapolate its rising characteristic to 20 kHz, one could estimate its approximate magnitude (perhaps 0.6%). Using a higher bandwidth THD+N measurement might reveal this behavior, if the out-of-band noise were sufficiently low.

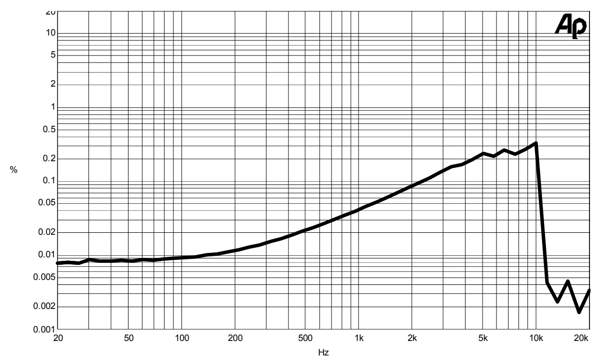

Figure 3. THD+N vs. Frequency (20 kHz BW)

Figure 3 shows a graph of THD+N versus frequency for a different amplifier that is dominated by 2nd harmonic distortion. Here we see only one significant drop in the THD+N characteristic at the 10 kHz point corresponding to the loss in the sensitivity to second harmonic (same 20 kHz bandwidth limited measurement). The curve shows hints of much smaller drops around 7 kHz (loss of the 3rd harmonic) and 5 kHz (loss of the 4th harmonic) indicating the presence of those harmonics, but they are small in comparison to the 2nd harmonic. Again, if we extrapolate the shape of the curve upwards, one might reasonably estimate the existence of a dominantly 2nd harmonic producing non-linearity at 20 kHz having a magnitude around 0.8%.

An increasing THD+N characteristic at low frequencies is less common. It usually indicates a thermal distortion mechanism. At low frequencies, the audio signal itself may be sufficient to modulate the power dissipation, hence the temperature of critical gain setting resistors. This problem is particularly exacerbated with the ever-decreasing size and lower power ratings of surface mount components! Unless low temperature coefficient resistors are specified, the signal dependent temperature variations will cause the gain of the amplifier to be modulated, thus resulting in distortion. Typically this type of distortion is dominantly 3rd harmonic due to fact that the instantaneous power dissipation is a function of the signal voltage squared. Transformer coupled circuits can also give rise to low frequency distortion.

THD SPECTRUMS

THD+N sweeps can convey a lot of information about the nature of a distortion producing non-linearity. Examining the spectrum of the distortion reveals even more insight.

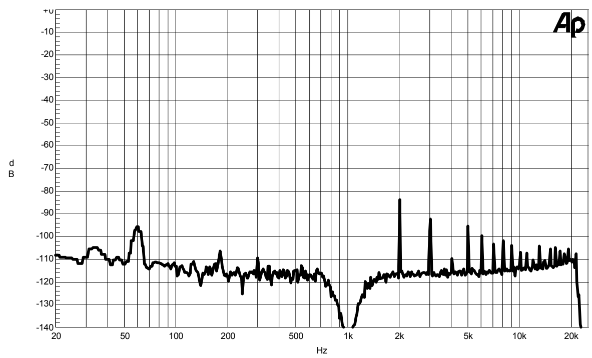

Figure 4. Output spectrum at 2 Watts, 1 kHz

Figure 4 shows the FFT spectrum of the same amplifier as shown in Figure 1 and Figure 2, but taken at an output power level of 2 Watts. 0 dB equals the amplitude of the output 1 kHz fundamental before it was removed by the notch filter.

Here we see the harmonic structure contains both even and odd order products with the 2nd harmonic being dominant. Besides the harmonics, one can also see components related to the 60 Hz ac mains. We also see the noise floor is not flat. There is gradual rise at low frequencies suggesting the presence of a 1/f noise mechanism in the amplifier input stage. There is also a rise towards the upper end of the spectrum caused by noise shaping of the pulse width modulator. The abrupt drop in noise above 20 kHz is caused by one of the analyzer's bandwidth limiting filters that was enabled during this test.

SMPTE IMD TESTING

SMPTE intermodulation distortion is widely used in power amplifier evaluation because it is a very sensitive indicator of basic transfer function non-linearity. It is sensitive to both even (asymmetrical) and odd (symmetrical) orders of non-linearity. The test signal consists of a LF tone (typically 50 Hz to 250 Hz) and a HF tone (usually 6 kHz, 7 kHz, or 8 kHz) mixed in a 4:1 amplitude ratio. Amplifier non-linearity will cause the LF tone to produce amplitude modulation (AM) sidebands surrounding the HF test tone.

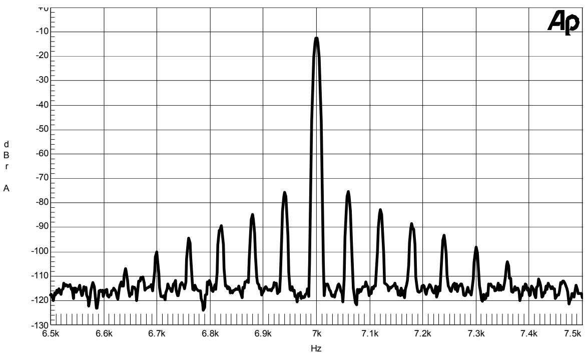

Figure 5. SMPTE IMD spectrum at 2 Watts

Figure 5 shows an expanded spectrum around the upper tone of a 60 Hz + 7 kHz test signal. The IMD products are seen as the sidebands surrounding 7 kHz at intervals of the 60 Hz lower test tone.

SMPTE IMD can be measured from an FFT spectrum, however some cautions are in order when using this technique. Frequency domain sidebands surrounding the HF tone can arise from both amplitude modulation (AM) and frequency modulation (FM). It is impossible to distinguish between the two forms of modulation unless a complex FFT is performed that gives the necessary phase information. When testing electrical devices such as amplifiers, it is usually safe to assume that intermodulation sidebands are the result of AM, hence true SMPTE IMD. This same statement cannot be made when testing acoustic transducers where the physical motion of an element of the device can cause frequency-modulation effects.

One also must be very careful in calibrating SMPTE IMD results. Historically, SMPTE IMD is expressed as the percentage of amplitude modulation of the HF tone. 0 dB on the graph in Figure 5 corresponds to the RMS amplitude of the total composite test signal in which the LF tone is 12 dB higher than the HF tone. The spectrum of a 100% amplitude modulated signal theoretically contains a pair of equal amplitude sidebands that are exactly 50% or -6.02 dB below the amplitude of the HF carrier. Thus an RMS summation of the sideband amplitudes must be referenced to a level that is –3.01 dB below that of the HF carrier for numerically correct results.

More commonly, SMPTE IMD is measured using a special set of analyzer circuits that directly perform an amplitude demodulation on the HF tone after having first removed the LF tone with a suitable high-pass filter. To limit the effects of noise, only amplitude modulation products falling in the range of 40 Hz to 500 Hz are measured.

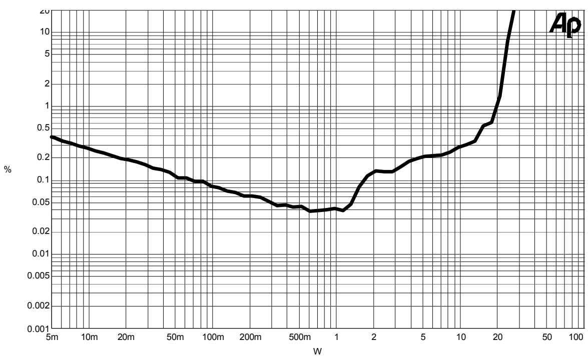

Figure 6. SMPTE IMD vs. Amplitude

Figure 6 shows the SMPTE IMD characteristic of the same amplifier shown in all of the previous graphs except Figure 3. It shows a similar shape to the swept 1 kHz amplitude THD+N (Figure 1).

SMPTE IMD usually does not reveal any hints about amplifier behavior at its frequency extremes. Thermal distortion mechanisms that might show up in low frequency THD tests are largely diminished at the 50-250 Hz lower test tone frequencies of the SMPTE test signal. Sensitivity to high frequency non-linearity is similarly poor because the 7-8 kHz upper test tone is typically well below the upper bandwidth limit of the system.

"TWIN-TONE" IMD TESTING

Twin-tone IMD testing provides the best way to examine high frequency amplifier linearity in a bandwidth limited system. By applying a test signal consisting of two equal amplitude sine waves near the upper bandwidth limit, the amplifier is stressed by a high slew rate signal with most of its energy where it has the least amount of feedback. Although 19 kHz and 20 kHz are often suggested, the author prefers testing with 18 kHz and 20 kHz tones because it produces clear and easy to interpret FFT displays. The very slight difference in peak slew rate is not likely to cause significant differences in measured distortion.

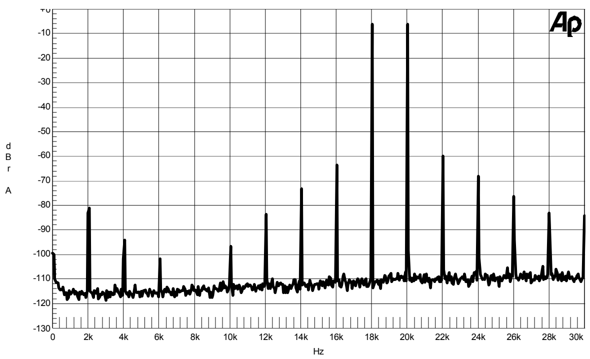

Figure 7. Spectrum of twin-tone distortion

Figure 7 shows the same amplifier as seen in most of the previous graphs. Even order intermodulation products caused by an asymmetry in the amplifier's non-linearity show up as simple difference frequency products. Thus, if 18 kHz and 20 kHz test tones are used, the 2nd order product will appear at 2 kHz. The 4th order product will be at 4 kHz, 6th order product at 6 kHz, etc. Odd order intermodulation products show up as offset sidebands to the two test tones. For example, 3rd order IMD will appear at both 16 kHz and 22 kHz, 5th order at 14 kHz and 24 kHz, etc. Even and odd order products will collide near the center of the spectrum, however these are usually quite insignificant compared to the 2nd and 3rd order components. Figure 7 confirms the suspicion that both even and odd order non-linearity exist at 20 kHz as suggested by the extrapolation of the THD+N versus frequency characteristic in Figure 2.

OUTPUT L-C FILTER DISTORTION

The odd-order IMD levels of -60 dB to -70 dB seen in Figure 7 are common in switching amplifiers having an output L-C filter. The design of these filters presents some tough challenges. Its primary mission is to prevent radio frequency interference ("RFI") from exceeding regulatory limits. The L-C filter also prevents losses in amplifier efficiency by isolating any capacitive components in the load, for example the stray capacitance between wires in a long length of speaker cable.

The inductor must be able to pass large amounts of audio power with a minimum of loss because it is directly in series with the output. It also must have a high self-resonant frequency to give good high frequency attenuation. These design constraints usually result in the inductor being made with a ferromagnetic core such as ferrite. Unfortunately such materials are typically quite nonlinear.

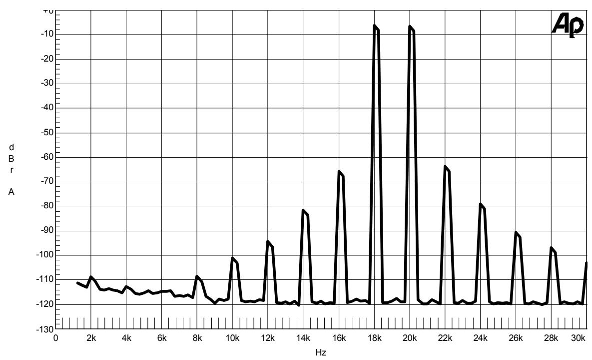

Figure 8. Distortion of an L-C filter

Figure 8 shows the distortion of a L-C low-pass filter constructed with a ferrite core inductor. The symmetrical non-linear properties of the iron bearing core material cause odd order IMD products. Compare this characteristic to that in Figure 7. An air core inductor would be extremely linear, but it is usually are not feasible due to wire size considerations. Perhaps we can hope that more linear ferromagnetic materials will be discovered in the future.

The State-of-the-Art?

Some newer switching amplifier designs now place the L-C filter within the overall feedback loop. Although this must be done with considerable finesse to maintain stability, this technique offers significant reductions in the distortion caused by the non-linear inductor.

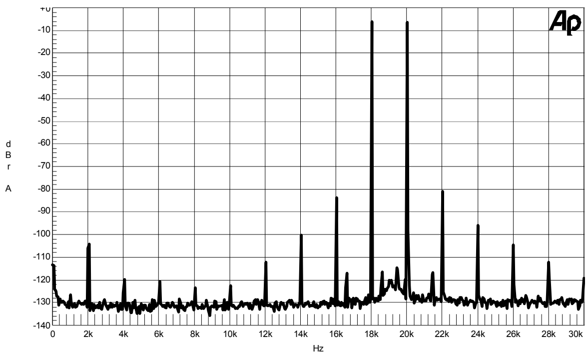

Figure 9. Twin Tone Distortion, prototype design

Figure 9 shows the twin-tone IMD performance of a certain manufacturer's prototype design using this technique. It shows a remarkable reduction in distortion compared to the amplifier seen in Figure 7.

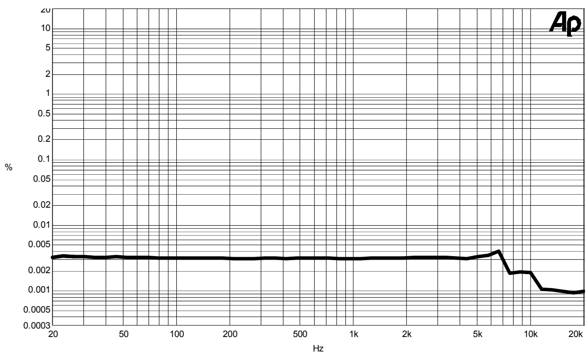

Figure 10. THD+N vs Frequency, prototype design

Figure 10 shows the THD+N versus frequency performance of the same prototype unit. Note the very flat and extremely low THD+N characteristic over most of the audio band. Both Figures 9 and 10 reflect truly impressive performance.

Special Precautions when measuring Distortion in Switching Amplifiers

Switching amplifiers can cause some nasty problems when connected to test and measurement equipment. The inherent peak slew rate of the raw output signal vastly exceeds the input capability of any known audio analyzer. Even if the amplifier contains an L-C filter for radio frequency interference suppression, the remaining small artifacts in the output can still have enough high frequency energy to provoke slew rate limiting non-linearity within the input stage of the audio analyzer.

The only practical solution is to insert a pair of passive low-pass filters between the amplifier output and the analyzer input. These filters must be properly designed and constructed with components that remain linear at power amplifier output voltage levels. Commercial filters are now available for this purpose. At least one unit provides <0.1 dB error at 20 kHz and >50 dB attenuation at or above 250 kHz (see Reference 3). It has <0.05 dB of insertion loss, and can be used with almost any brand of audio analyzer.

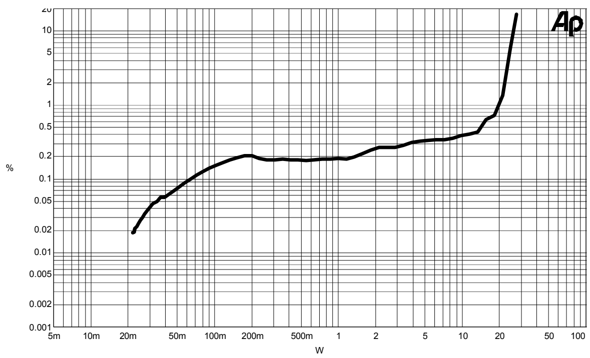

Figure 11. SMPTE IMD without passive filter

Figure 11 shows how these switching artifacts can interfere with analyzer measurements. It is a plot of the same SMPTE IMD sweep seen in Figure 6 (page 4) but without the recommended passive filters in series with the analyzer input. All IMD measurements below 15 Watts are seen to be in error. Indeed, the measurement of output power level is so seriously wrong at low amplitudes that it totally changes the shape of the graph.

BANDWIDTH LIMITING OF MEASUREMENTS

The pulse width modulators of many switching amplifiers operate in a fashion similar to sigma-delta converters, using noise-shaping techniques to obtain better performance in the audio band. This causes the noise floor of the amplifier to rise quite rapidly above the audio band. Because this can affect the accuracy of THD+N and other low amplitude measurements, very sharp bandwidth limiting should be employed.

A good recommendation to follow is the bandwidth limiting requirements specified in AES-17 for converter testing. For a given measurement bandwidth, F_{bw}, the standard requires the response be $\leq$–60 dB at $\geq 1.20F_{bw}$. Thus, for example, if the measurement bandwidth is 20 kHz the response must be $\leq$-60 dB at $\geq$24 kHz.

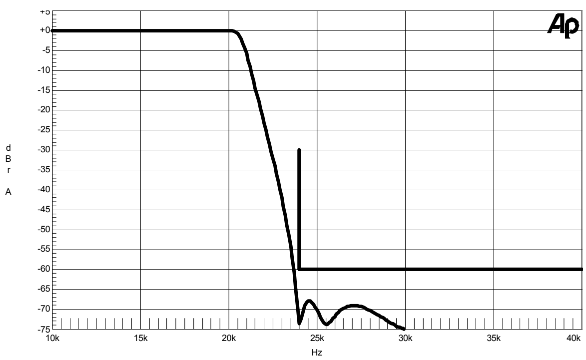

Figure 12. AES17 bandwidth limiting characteristic

Figure 12 shows the typical response of a popular audio analyzer. It is important not to confuse this bandwidth limiting with the recommended passive filters in series with the input. The passive filters are intended to remove high frequency components that can provoke non-linearity in the analyzer input stage. The AES17 low-pass filter insures that certain measurements have a suitably sharp roll-off characteristic.

CONCLUSIONS

Switching power amplifiers have evolved to the point where their distortion performance is truly noteworthy. However they can still have a significant high frequency distortion caused inductor non-linearity in the output L-C filter. This distortion is not easily seen with THD+N or SMPTE IMD tests. The twin-tone IMD test provides a good tool for examining this imperfection, and it should be included in evaluations of amplifier performance.

Precautions must be taken to insure the integrity and accuracy of switching amplifier measurements. The introduction of passive low-pass filters in series with the audio analyzer is strongly recommended.

REFERENCES

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[2] *Challenges in Measuring Class-D Amplifiers*, B. Hofer, 12th Regional AES Convention, Tokyo, 2005. (Preprint number unavailable.)

[3] Audio Precision AUX-0025 Filter Accessory. See www.audioprecision.com for more details.

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