Ask The Applications Engineer—13

CONFUSED ABOUT AMPLIFIER DISTORTION SPECS?

by Walt Kester

Q. *I've been looking at your amplifier data sheets and am confused about distortion specifications. Some amplifiers are specified in terms of second- and third-harmonic distortion, others in terms of* total harmonic distortion *(THD) or* total harmonic distortion plus noise *(THD+N), still others have some of these specifications as* well as two-tone intermodulation distortion *and* third-order intercept. *Can you please clarify?*

A. Because the amplifier is fundamental to a wide range of uses, it is natural that many application-specific specifications have evolved as new amplifiers have been developed to meet those needs. So—as you so rightly pointed out—distortion may be specified in various ways; the spec depends on how distortion is defined by users for the particular application. Some distortion specifications are fairly universal, while others are primarily associated with specific frequency ranges and applications.

But there is some standardization of the basic definitions, so let's talk about them first. Harmonic distortion is measured by applying a spectrally pure sine wave to an amplifier in a defined circuit configuration and observing the output spectrum. The amount of distortion present in the output is usually a function of several parameters: the small- and large-signal nonlinearity of the amplifier being tested, the amplitude and frequency of the input signal, the load applied to the output of the amplifier, the amplifier's power supply voltage, printed circuit-board layout, grounding, power supply decoupling, etc. So you can see that any distortion specification is relatively meaningless unless the exact test conditions are specified.

Harmonic distortion may be measured by looking at the output spectrum on a spectrum analyzer and observing the values of the second, third, fourth, etc., harmonics with respect to the amplitude of the fundamental signal. The value is usually expressed as a ratio in %, ppm, dB, or dBc. For instance, 0.0015% distortion corresponds to 15 ppm, or –96.5 dBc. The unit "dBc" simply means that the harmonic's level is so many dB below the value of the "carrier" frequency, i.e., the fundamental.

Harmonic distortion may be expressed individually for each component (usually only the second and third are specified), or they all may be combined in a root-sum-square (RSS) fashion to give the *total harmonic distortion* (THD).

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_s}$$

where

V_s = signal amplitude (rms volts)
V_2 = second harmonic amplitude (rms volts)
V_n = *nth* harmonic amplitude (rms volts)

The number of harmonics included in the THD measurement may vary, but usually the first five are enough. You see, the RSS process causes the higher-order terms to have negligible effect on the THD, if they are 3 to 5 times smaller than the largest harmonic $[\sqrt{0.10^2 + 0.03^2} = \sqrt{0.0109} = 0.104 \approx 0.10]$.

The expression for THD+N is similar; simply add the noise in root-sum-square fashion (V_{noise} = rms value of noise voltage over the measurement bandwidth).

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2 + V_{noise}^2}}{V_s}$$

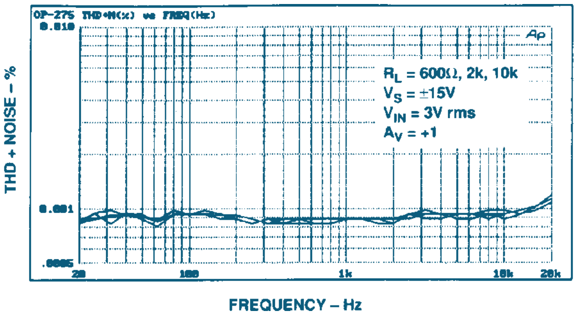
It should be evident that THD+N ≈ THD if the rms noise over the measurement bandwidth is several times less than the THD, or even the worst harmonic. It is worth noting that if you know only the THD, you can calculate THD+N fairly accurately using the amplifier's voltage- and current-noise specifics. (Thermal noise associated with the source resistance and the feedback network may also need to be computed). But if your rms noise level is significantly higher than the level of the harmonics, and you are only given the THD+N specification, you cannot compute the THD.

Special equipment is often used in audio applications for a more-sensitive measurement of the noise and distortion. This is done by first using a bandstop filter to remove the fundamental signal. The total rms value of all the other frequency components (harmonics and noise) is then measured over an appropriate bandwidth. The ratio to the fundamental is the THD + N spec.

Q. *How are the distortion specs looked at over the various frequency ranges and applications?*

A. I think the best way is to start at the low frequency end of the spectrum and work our way up; that will make it easier to see the underlying method.

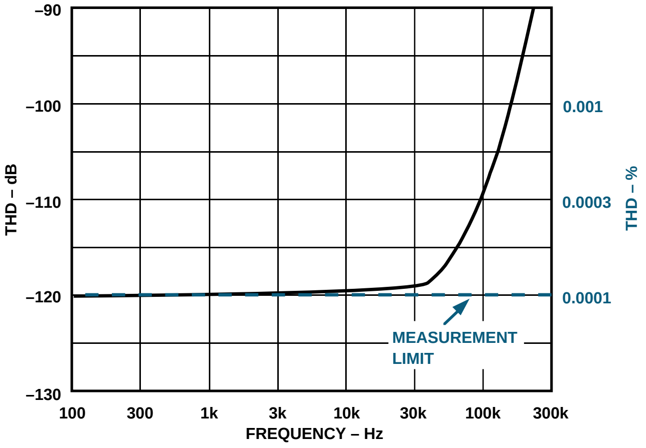
Audio-frequency amplifiers are a good place to start. Types used here (such as the OP-275*) are optimized for low noise and low distortion within the audio bandwidth (20 Hz to 20 kHz). In audio applications, total harmonic distortion plus noise (THD+N) is usually measured with specialized equipment such as the Audio Precision System One. The output signal amplitude is measured at a given frequency (e.g., 1 kHz); then, as above, the fundamental signal is removed with a bandstop filter and the system measures the rms value of the remaining frequency components, which contain both harmonics and noise. The noise and harmonics are measured over a bandwidth that will catch the highest harmonics, usually about 100 kHz. The measurement is swept over the frequency range for various conditions. THD+N results for OP-275 are plotted here as a function of frequency.



The signal level is 3 V rms, and the amplifier is connected as a unity-gain follower. Notice that a THD+N value of 0.0008% corresponds to 8 ppm, or –102 dBc. The input voltage noise of the OP-275 is typically 6 nV/$\sqrt{\text{Hz}}$ @ 1 kHz and, integrated over a 100-kHz bandwidth, yields an rms noise level of 1.9 μV rms. For a 3-V rms signal level, the corresponding signal-to-noise ratio is 124 dB. Because the THD is considerably greater than the noise level, the THD component is the primary contributor.

Q. *I noticed that Analog Devices recently introduced another low-noise, low-distortion amplifier (AD797) and that it is specified in THD, not THD+N. The actual specification quoted at 20 kHz is –120 dB. What gives?*

A. Actually, we are not trying to be misleading here. The distortion is at the limits of measurement of the available equipment, and the noise is even lower—by 20 dB! Here is the measured THD of the AD797 as a function of frequency.

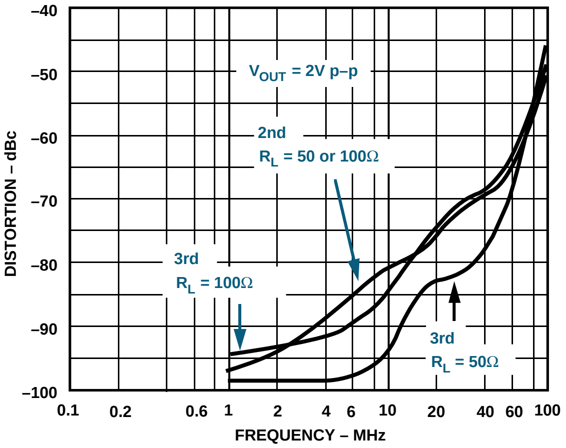


The measurement was made with a spectrum analyzer by first filtering out the fundamental sine-wave frequency ahead of the analyzer. This is to prevent overdrive distortion in the spectrum analyzer. The first five harmonics were then measured and combined in a root-sum-square fashion to get the THD figure. The legend on the graph indicates that the measurement-equipment "floor" is about –120 dB; hence at frequencies below 10 kHz, the THD may be even less.

For noise, multiply the voltage noise spectral density of the AD797 (1 nV/$\sqrt{\text{Hz}}$) by the square root of the measurement bandwidth to yield the device's rms noise floor. For a 100-kHz bandwidth, the noise floor is 316 nV rms, corresponding to a signal-to-noise ratio of 140 dB for a 3-V rms output signal.

Q. *How is distortion specified for high frequency amplifiers?*

A. Because of the increasing need for wide dynamic range at high frequencies, most wideband amplifiers now have distortion specifications. The data sheet may give individual values for the second and third harmonic components, or it may give THD. If THD is specified, only the first few harmonics contribute significantly to the result. At high frequencies, it is often useful to show the individual distortion components separately rather than specifying THD. The AD9620 is a 600-MHz (typical –3-dB bandwidth) low distortion unity-gain buffer. Here are graphs of the AD9620's second and third harmonic distortion as a function of frequency for various loading conditions.

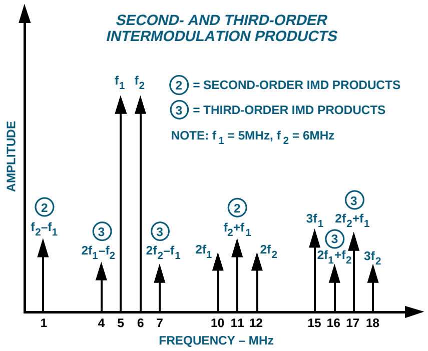


Q. *What are two-tone intermodulation products, and how do they differ from harmonic distortion?*

A. When two tones are applied to an amplifier that is non-linear, the nonlinearity causes them to modulate one another, producing intermodulation distortion (IMD) in the form of frequencies known as intermodulation products. (For the mathematical development of this concept, see Reference 1). For two tones at frequencies, f_1 and f_2 (where $f_2 > f_1$), the second- and third-order IM products occur at the following frequencies:

Second Order: $f_1 + f_2, f_2 - f_1$
Third Order: $2f_1 + f_2, 2f_2 + f_1, 2f_2 - f_1, 2f_1 - f_2$

If the two tones are fairly close together, the third-order IMD products at the difference frequencies, $2f_2 - f_1$ and $2f_1 - f_2$, may be especially troublesome because—as the figure shows —they are hard to filter out. Notice that the other second- and third-order IMD products—which occur at substantially higher or lower frequencies—can be filtered (if the only frequencies of interest are in the neighborhood of f_1 and f_2).



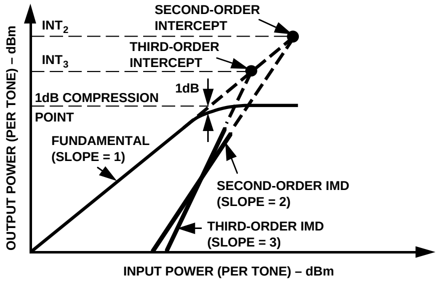
Two-tone intermodulation-distortion specifications are of especial interest in r-f applications and are a major concern in the design of communications receivers. IMD products can mask out small signals in the presence of larger ones. Although IMD has been rarely specified in op amps operating at frequencies less than 1 MHz, many of today's dc op amps are wideband types that can operate usefully at radio frequencies. For this reason, it is becoming common to see IMD specifications on fast op amps.

Q. *What are the second- and third-order intercept points, and what is their significance?*

A. Usually associated with r-f applications, these specs provide figures of merit to characterize the IMD performance of the amplifier. The higher the intercept power, the higher the input level at which IMD becomes significant—and the lower the IMD at a given signal level.

Here's how it is derived: Two spectrally pure tones are applied to the amplifier. The output signal power in a single tone (in dBm) and the relative amplitudes of the second-order and third-order products (referenced to a single tone) are plotted (and extrapolated) here as a function of input signal power.

INTERCEPT POINTS, GAIN COMPRESSION, IMD



If you go through the mathematical analysis [1], you will find that if device nonlinearity can be modeled by a simple power-series expansion, the second-order IMD amplitudes tend to increase by 2 dB for every 1 dB of signal increase. Similarly, the third-order IMD amplitudes increase 3 dB for every 1 dB of signal increase. Starting with a low-level two-tone input signal and taking a few IMD data points, you can draw (and extrapolate) the second- and third-order IMD lines shown on the diagram.

Beyond a certain level, the output signal begins to soft-limit, or compress (coinciding with the increasing visibility of IMD products). If you extend the second- and third-order IMD lines, they will intersect the extension of the output/input line; these intersections are called the second- and third-order intercept points. The projected output power values corresponding to these intercepts are usually referenced to the output power of the amplifier in dBm.

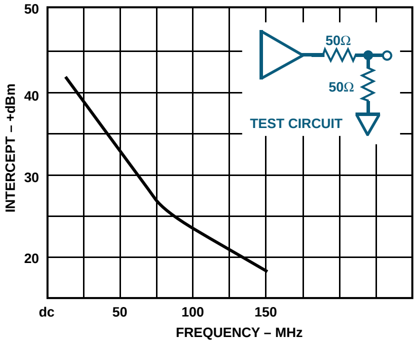
Since the slope of the third-order IMD amplitudes is known (3 dB/dB), if the intercept is also known, the third-order products at any input (or output) level can be approximated. For a higher intercept, the line moves to the right (same slope), showing lower 3rd-order products for a given input level. Many r-f mixers and "gain blocks" have 50-Ω input and output impedances. The output power is simply the power that the device transfers to a 50-Ω load. The output power is calculated by squaring the rms output voltage (V_o) and dividing by the load resistance, R_L. The power is converted into dBm as follows:

$$\text{Output power} = 10\log_{10}\frac{\dfrac{V_0^{\,2}}{R_L}}{1\,\text{mW}}\ \text{dBm}$$

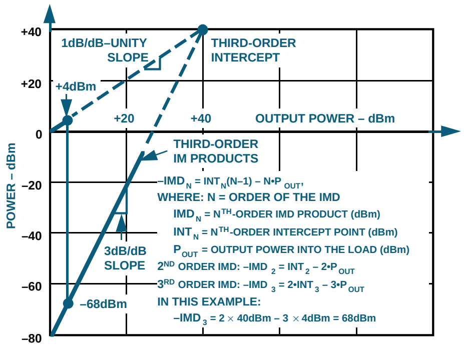
Since an op amp, on the other hand, is a low-output-impedance device, for most r-f applications, the output of the op amp must be source- and load-terminated. This means that the actual op amp output power has to be 3 dB higher than the power delivered to the load, as calculated from the above formula. In this type of application, it is customary to define the IMD products with respect to the *output power actually delivered into the 50-Ω load* rather than the actual op-amp output power.

Another parameter that may be of interest is the 1-dB compression point, shown in the figure. This is the point at which the output signal has started to limit and is attenuated by 1 dB from the ideal input/output transfer function.

The figure below is a plot of the third-order intercept power values for the AD9620 buffer amplifier as a function of input frequency. Its data can be used to approximate the actual value of the third order intermodulation products at various frequencies and signal levels.



Assume the op amp output signal is at 20 MHz with 2 V peak-to-peak into a 100-Ω load (50-Ω source and load terminations). The voltage into the 50-Ω load is therefore 1 volt peak-to-peak, with a power of 2.5 mW, corresponding to +4 dBm. The value of the third-order intercept at 20 MHz—from the graph—is +40 dBm. This permits a graphical solution, as shown below. For an output level of +4 dBm, the third-order IMD products, based on an extrapolation of the slope of 3 back from the intercept, amount to –68 dBm, or 72 dB below the signal.



This analysis assumes that the op-amp distortion can be modeled with a simple power series expansion as described in Reference 1. Unfortunately, op amps don't always follow simple models (especially at high frequencies), so the third-order intercept specification should primarily be used as a figure of merit, rather than a substitute for measurements. ▶

REFERENCES

1. Robert A. Witte, "Distortion Measurements Using a Spectrum Analyzer," *RF Design,* September 1992, pp. *75-84. (not available from ADI)*
2. *High Speed Design Seminar,* 1996. Norwood, MA: Analog Devices, Inc.
3. 1992 *Amplifier Applications Guide.* Norwood, MA: Analog Devices, Inc.