

Whatever happened to my dynamic range?

IF YOUR TESTING RESULTS DON'T CLOSELY APPROXIMATE THE SILICON VENDOR'S SPECIFICATION CLAIMS, QUESTION YOUR ASSUMPTIONS BEFORE CONCLUDING THAT YOUR SUPPLIER IS INFLATING THE NUMBERS.

Recently, a customer who had implemented a design using a high-performance, 120-dB-dynamic-range ADC/DAC pair complained that he was getting only 113-dB performance. At first glance, this issue appears serious, but a relatively simple explanation exists: The dynamic range for audio converters is an SNR (signal-to-noise ratio) that you measure over a specified bandwidth with a signal that is -60 dBFS (decibels full-scale). You add 60 dB to the resulting measurement to reference the measurement to digital full-scale. The intent is to provide the specification for a full-scale SNR that excludes distortion components. The assumption is that the distortion components are negligible at this signal level and therefore do not require any processing to remove them.

The AES (Audio Engineering Society, www.aes.org), the IEC (International Electrotechnical Commission, www.iec.ch), and others publish this technique in most of their audio-testing standards. The specifications also include a requirement for a weighting filter that reflects the frequency sensitivity of the human ear over the 20-Hz to 20-kHz audio bandwidth. In summary, the goal of the audio dynamic range is to provide an easily measured full-scale SNR specification that reflects the sensitivity of human hearing.

Measuring audio-system dynamic range is a relatively simple

matter, thanks to the plethora of advanced test and measurement tools available from Audio Precision (www.ap.com), Rohde & Schwarz (www.rohde-schwarz.com), and other companies. However, several factors, including measurement bandwidth, sample rate, and weighting filters, have a direct impact on the measurement. A typical dynamic-range specification is an A-weighted, 120-dB figure that you measure from 10 Hz to 20 kHz at a 48-kHz sample rate. You must take into account each of these measurement parameters when comparing measured results with ADCs and DACs.

SAMPLE RATE AND MEASUREMENT BANDWIDTH

It is enlightening to review the relationship between SNR, measurement bandwidth, and sample rate for audio ADCs. One of the fundamental characteristics of quantizing an analog signal is that you can divide all of the signal energy at frequencies above the sample rate, F_s , by two to alias into the frequency region between dc and $F_s/2$. This signal energy includes noise from the analog-signal source, noise from the sampling networks, and quantization noise. Essentially, all signal energy exists between dc and $F_s/2$ within the digital domain. A subtle but important nuance therefore exists regarding audio measurements in which the standard 20-kHz upper-bandlimiting frequency does not extend to $F_s/2$.

For example, 48 kHz is a common audio-sample rate, in which the noise is distributed between dc and 24 kHz. However, with the measurement bandwidth limited to 20 kHz, the measurement therefore includes only 83% of the total bandwidth. It is a relatively simple matter to calculate the difference in the SNR measurements as a function of measurement bandwidth: $10\log(BW_1/BW_2)$, where BW is the bandwidth. This equation is valid only for white noise—that is, noise with a signal having equal power per unit of bandwidth. For example, at a 48-kHz sample rate, where $F_s/2$ is 24 kHz, the difference in the SNR measurement is nearly 0.8 dB when you bandlimit it to 20 kHz. However, with the same 20-kHz, bandlimited

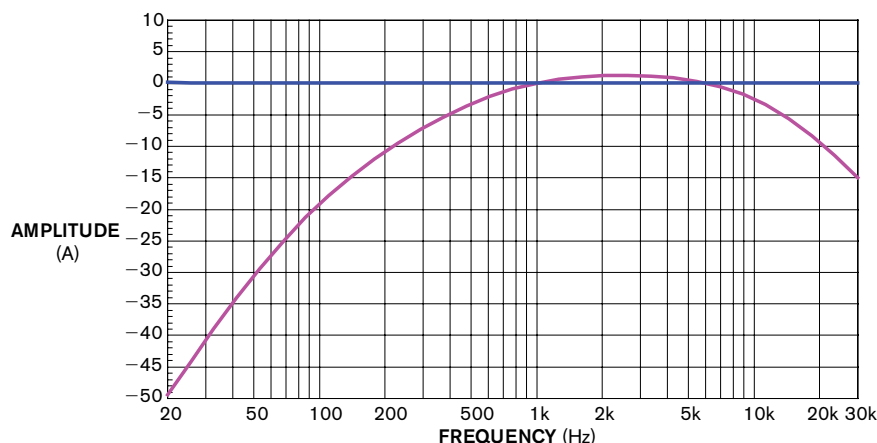


Figure 1 The frequency response of an A-weighting filter (purple) stacks up against a reference unweighted (blue) frequency-response plot (source equipment: Audio Precision).

measurement at a 44.1-kHz sample rate, the measurement includes almost 91% of the total noise. The difference in the SNR at 44.1 kHz is only 0.424 dB. Notice that a difference of 0.37 dB exists in the 20-kHz, bandlimited measurements between the 48- and 44.1-kHz sample rates.

So, ADC SNR with a bandwidth of dc to $F_s/2$ is the same for both the 44.1- and the 48-kHz sample rates. However, this equivalency no longer holds true when the measurement bandwidth is 20 kHz. This discrepancy should also give some insight about why audio-converter manufacturers typically specify performance at a 48-kHz rather than a 44.1-kHz sample rate.

WEIGHTING FILTERS AND ADCs

Dynamic-range specifications include a weighting filter that allows the measurement to correlate to human hearing. Although audio-testing standards mention several weighting filters, audio-converter manufacturers most commonly use the ANSI (American National Standards Institute, www.ansi.org) A-weighting filter (Figure 1). One of the more common measurement differences when comparing measured results with data-sheet specifications is to exclude the A-weighting filter. When you bandlimit the measurement to 20 kHz, there is a 2.5-dB difference between the weighted and the unweighted results, assuming that the noise is uniformly distributed at 20 kHz. Without the A-weighting filter, the 120-dB converter specification degraded to 117.5 dB. It is relatively easy to demonstrate these effects using the evaluation board for the

TABLE 1 CS5381 PERFORMANCE AT 44.1 AND 48 kHz

Measurement configuration	48-kHz sample rate	44.1-kHz sample rate
20-kHz bandwidth	117.5	117.2
20 kHz A-weighted	120	119.6
$F_s/2$	116.7	116.7
$F_s/2$ A-weighted	119.7	119.5

Cirrus Logic (www.cirrus.com) CS5381 ADC and the Audio Precision System 2 (Table 1). Notice that these measurement results differ by as much as 3.3 dB based on sample rate, measurement bandwidth, and weighting.

DAC DYNAMIC RANGE

The measurement issues for ADCs also apply to DACs, with the additional complication that the measurement is within the analog domain in which noise extends well beyond $F_s/2$. This broadband noise combines with the multiple measurement-bandlimiting options available in the measurement equipment to yield a multitude of valid measurements that do not accurately reflect converter-specification parameters. Recall that you can calculate the difference in a noise measurement as a function of bandwidth assuming that the noise is white.

To further complicate matters, highly oversampled delta-sigma DACs generate noise with a density that increases as the frequency increases. The delta-sigma-shaped out-of-band noise does not fit the definition of *white noise*. As a result, surprisingly large differences in dynamic-range measurements can occur as a function of measurement bandwidth. It is relatively easy to demonstrate these effects using, for example, the evaluation board for the Cirrus Logic CS4398 DAC and the Audio Precision System 2 (Table 2). These measurements, which came from a properly operating evaluation board meeting data-sheet specifications, differ by as much as 48 dB based on sample rate, measurement bandwidth, and weighting.

COMBINED ADC AND DAC DYNAMIC RANGE

A commonly overlooked characteristic of an ADC-plus-DAC system is that each converter is an independent noise source. The following equation represents the combined noise: $[(N_{\text{ADC}})^2 + (N_{\text{DAC}})^2]^{1/2}$, where the ADC noise is N_{ADC} and the DAC noise is N_{DAC} . The common misconception in this regard is that a system comprising equal-dynamic-range ADCs and DACs results in a combined specification equal to that of the individual converters. For example, a properly implemented and measured system with a 120-dB DAC and a 120-dB DAC yields a combined SNR specification of 117 dB. Again, it is relatively easy to demonstrate the possible outcomes using the Audio Precision System 2 and the evaluation boards for the CS5381 ADC and the CS4398 DAC (Table 3). Similar

TABLE 2 CS4398 PERFORMANCE AT 44.1 AND 48 kHz

Measurement configuration	48-kHz sample rate	44.1-kHz sample rate
22 kHz	117.6	117.5
22 kHz A-weighted	120.5	120.4
30 kHz	116.4	116
30 kHz A-weighted	120.5	120.4
80 kHz	100.4	96.4
80 kHz A-weighted	120.4	120.1
500 kHz	73.5	72
500 kHz A-weighted	119.9	119.2
20 kHz Brickwall	118.2	118
20 kHz Brickwall A-weighted	NA	NA

to the DAC measurements, these measurement results differ by as much as 45 dB based on sample rate, measurement bandwidth, and weighting.

REVISITING THE CUSTOMER'S COMPLAINT

Going back to the customer's original complaint, how do you determine the cause of the discrepancy? The first step is to understand which functional components are in the sig-

nal chain. I learned that the measured SNR was a combined ADC/DAC measurement between the analog input and the analog output. With that knowledge alone, I quickly located the 3 dB of the “missing” dynamic range: The combined performance measurement that the data sheet specifies is 117 dB. Continuing the discussion with the customer, I identified the configurations of sample rate, measurement bandwidth, and weighting filters. With this knowledge, I learned that the system operates at a 48-kHz sample rate, with a 22-kHz measurement bandwidth without the A-weighting filter. This configuration should result in a measurement of approximately 114.5 dB with properly implemented converters (**Table 3**). As if by magic, the customer and I found 5.5 dB of the missing dynamic range. Now, however, comes the hard part. What happened to that last decibel?**EDN**

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TABLE 3 CS5381-PLUS-CS4398 PERFORMANCE AT 44.1 AND 48 kHz

Measurement configuration	48-kHz sample rate	44.1-kHz sample rate
22 kHz	114.5	114.2
22 kHz A-weighted	117.2	116.9
30 kHz	113.6	113.3
30 kHz A-weighted	117.2	116.9
80 kHz	100.2	96.3
80 kHz A-weighted	117	116.7
500 kHz	73.5	72
500 kHz A-weighted	116.7	116.2
20 kHz Brickwall	114.9	114.7
20 kHz Brickwall A-weighted	NA	NA

the Audio Engineering Society; he wrote several convention papers and served as an invited speaker at several AES section meetings around the United States and as a speaker for design tutorials at the AES convention related to the implementation of delta-sigma converters. Before joining Crystal Semiconductor and Cirrus Logic, he worked as a systems-design engineer in the professional-audio industry. Green earned a bachelor's degree in electrical engineering from the University of Texas—Austin.