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Noise and Spurious in Digital Systems and Digitized Signals

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This tutorial reviews the systematic and incidental sources of noise that are unique to both all-digital circuitry and A/D and D/A conversion processes

We are all aware of the rapidly increasing use of digital circuitry in communications equipment, instruments, and other traditionally analog systems. The digital portion of those systems began as post-processing analysis, and has gradually migrated up the signal chain to real-time baseband signal processing, to IF and up/down conversion stages, and to feedback and other control circuitry. Although still largely developmental, there are radio systems that directly digitize the input RF and present the final transmitted signal to a power amplifier (or the antenna for low-power, short range operation).

This tutorial article will review the issue of noise inherent to, or caused by, digital circuitry. The sources of noise in digital systems are different than the physical and thermal sources familiar to analog/RF/microwave engineers. Of course, these sources are present in all electronic circuitry, including digital, but there are additional causes of noise that must be understood if desired system performance is to be achieved.

Noise and Spurious Signals

To discuss digitially-based noise, we need to modify the traditional definition of noise. Noise is almost always defined as being random, while digitally-based "noise" is deterministic, that is, it can (in theory) be computed mathematically.

It can be argued that the noise sources discussed here are, in fact, all spurious signals, determined by the repetition rate, rise/fall time, amplitude and waveform shape of the electronic signal at various points in the digital circuitry. However, the number of these discrete spurious signals is sufficiently large that the net effect is much like random noise, not just a collection of well-defined spurs.

Like analog systems, there will be a number of discrete spurs that are much greater than the residual noise level, or *noise floor*. Much effort in digitial circuits and analog/digital interface design goes toward minimizing these discrete spurs. Now, let's look at the major sources of noise and spurious signals in digital circuits.

Clock Feedthrough and Harmonics

The first group of unwanted signals is quite obvious—the system clock(s) and harmonics. Harmonic energy is high, as we learned in our Linear Systems or advanced math classes. A square wave, which is closely approximated by a digital clock bit stream, includes the discrete frequency components of the fundamental and odd-order multiples. These signals have significant amplitude through several harmonics and can be the source of troublesome spurious signals at the various frequencies.

The simplest means of dealing with clock artifacts is to choose a clock frequency with fundamental and harmonic frequencies outside the passband of the system. With a high frequency system and a relatively low-frequency clock, such as for a baseband signal processor, this can be difficult. For example, a 50 MHz-clocked DSP for a 2.0-2.1 GHz system will have several harmonics in the passband. Fortunately, the high order of these harmonics means that the levels will be low, however, they may be readily detected by a sensitive receiver. Special care is needed in layout, power supply decoupling, and clock distribution circuitry to minimize radiation or conduction of clock signals into other parts of the system. In a channelized system, the problems can be eased somewhat if a clock frequency can be selected that causes these harmonics to fall between channels.

Data Truncation Errors

Figure 1 illustrates a problem in the digital representation of an analog signal—finite sampling of an infinite-resolution waveform. Fig. 1(a) shows a sine wave along with several sampling points. Fig. 1(b) takes those sample points and simply "connects the dots" in a piecewise linear fashion to reconstruct a waveform from the various data points. Fig. 1(c) shows another method of reconstruction with a step function centered on each data point.

It is clear from this illustration that any means of reconstructing a waveform from a series of digital words will have discontinuities, which have energy content (spurious signals) at frequencies and amplitudes determined by the repetition rate, rise/fall times and magnitude of the amplitude transition.

Much of this spurious energy lies above the fundamental frequency of the signal being sampled/reconstructed. A filter at the upper edge of the signal bandwidth can eliminate many of the unwanted products. At lower frequencies in the passband, the larger number of samples will create fewer spurious signals. However, there remain some spurious products, including subharmonics (division of the fundamental due to the sampling process) that will be present in the desired passband.

A key design objective is to select the sampling rate, input filtering and output filtering to minimize the level of these artifacts. If the signal bandwidth will permit, oversampling can

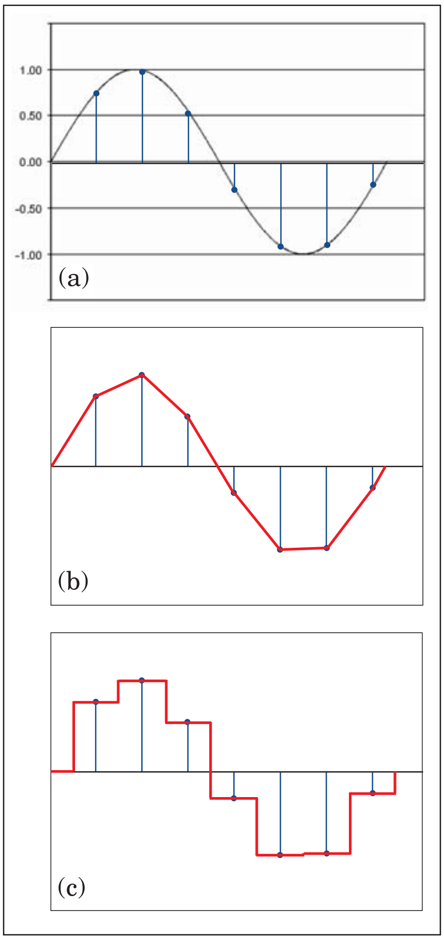

Figure 1 · (a) Sampled sine wave, (b) linear piecewise reconstruction, and (c) stepped reconstruction.

minimize the spurious content. For example, the audio compact disc uses a 44.1 kHz sampling rate to obtain a low distortion (actually, distortion + noise) output up to 20 kHz.

Timing and Threshold Effects—Jitter and LSB Uncertainty

The operation of an analog-to-digital converter (ADC) obtains its signal samples as in Fig. 1(a), while a digital-to-analog converter (DAC) operates much like the process shown in Fig. 1(c). Accuracy of the process depends on precise timing and amplitude of the sampling and reconstruction circuitry.

DAC operation is much less critical than ADCs, due to their simpler architecture. ADCs, on the other hand, have several key performance limitations. One is accuracy at low signal levels. The input signal for a step of one least significant bit (LSB) is very small, and can be skewed by noise on the input signal, as well as the analog noise figure of the input circuitry of the ADC. This uncertainty means that some sampling (and reconstruction) steps will be slightly incorrect in a random manner, effectively adding noise to the output.

This problem can be minimized by using an ADC with greater resolution than required, and discarding the uncertain least significant one or two bits. However, this reduces the total input voltage range (dynamic range) of the ADC, which may not be acceptable in a communications system.

Timing is another potential problem area in ADCs. A small time error in sampling can result in a data word that represents the wrong level in a changing waveform. This is the same type of error as LSB uncertainty and results in additional noise. High performance ADCs usually address this issue through careful design.

Another timing issue is jitter, due to phase noise of the system clock or uncertain digital thresholds and propagation delays. Intuitively, it is easy to assume that this is a small source of errors, since highly stable frequency sources are commonly available. However, at high sampling rates—100s of MHz—a little math makes it clear that even 1 ps of jitter is significant and will increase the uncertainty of the digitizing process and increase the noise.

Summary

This tutorial has identified the sources of unwanted signals and noise in digital circuitry. Like typical thermal or semiconductor noise in analog systems, the net effect is a reduction in system dynamic range.

As digital circuitry becomes more common in traditional analog designs, these noise issues will also become commonplace.