Use Synchronous Detection to Make Precision, Low Level Measurements

by Luis Orozco, systems applications engineer, Analog Devices, Inc.

Synchronous detection is a useful technique for extracting low level signals buried below the noise floor with many instrumentation applications. Some examples include measuring very small resistance, measuring light absorption or reflection in the presence of strong background light, or even making strain measurements in the presence of high noise levels.

Many electrical and physical systems have increasing noise as the frequency approaches dc. For example, op amps have 1/f noise, and open air light measurement systems are subject to noise from changing ambient light conditions due to the sun, incandescent bulbs, fluorescent lamps, and other sources of illumination. If you can move the measurement away from these low frequency noise sources, you can achieve a higher signal-to-noise ratio and detect much weaker signals. For example, if you wish to measure the amount of light reflected off a surface, modulating the light source at a few kHz will make it possible to measure signals that would otherwise be buried in the noise at lower frequencies. Figure 1 shows how modulating the signal makes the difference between being below the noise floor and having a recoverable measurement.

There are several methods for modulating a sensor's excitation signal. The easiest modulation scheme is to turn the excitation signal repeatedly on and off. This works well for driving LEDs and other types of excitation, such as the voltage going to a strain gage bridge. It works especially well when the excitation source is not easy to modulate electronically, such as the incandescent bulbs used in many spectroscopy instruments. In this case, modulation is as easy as chopping the light with a mechanical disk.

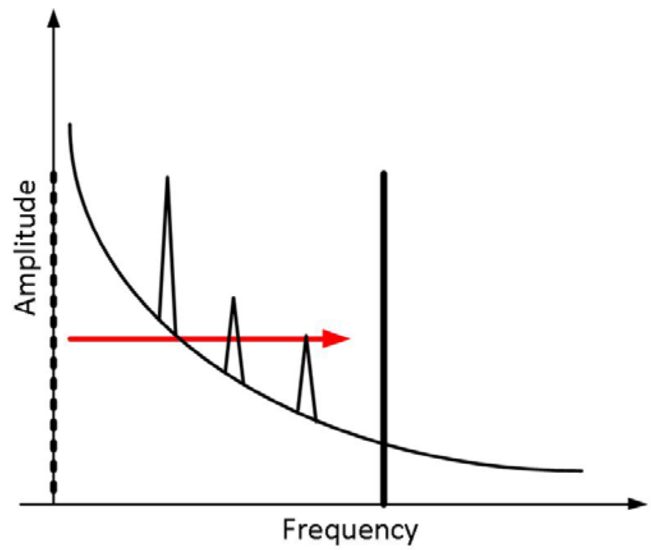

Figure 1. Modulating the Signal to Move It Away from Noise Sources

To recover the signal from Figure 1, you could simply design a narrow band-pass filter to remove all but the frequency of interest, and then measure the amplitude of the signal. In practice, it is very challenging to design very narrow (high Q) band-pass filters with discrete components. If the specifications call for an extremely narrow filter, it may even be impossible. Alternatively, you can use synchronous demodulation to move the modulated signal back to dc while filtering out other signals that are not synchronized to the reference signal. An instrument that uses this technique is called a lock-in amplifier.

A simple way to describe a lock-in amplifier is to start with the application shown in Figure 2. A light source modulated at 1 kHz illuminates a test surface, and a photodiode measures how much light reflects off the surface, which is proportional to the amount of contamination that has accumulated. Assume that both the reference signal and the measurement are sine waves (of the same frequency and phase, but different amplitudes). Assume the amplitude of the reference signal driving the photodiode is fixed, and the amplitude of the measurement changes with the amount of light reflected (in other applications, this would correspond to the physical parameter you are measuring).

The result of multiplying two sine waves together is a signal with frequency components at the sum and difference of the two input sine waves. In this case, the two sine waves have the same frequency, and Equation 1 shows how the result is one signal at dc and another at twice the original frequency (the negative sign indicates it has 180° of phase shift). A low-pass filter removes everything but the dc component of the signal.

The advantage of using this technique is more evident if you consider a noisy input signal. The output of the multiplication stage will still result in only the signal at the modulation frequency moving back to dc, with all other frequency components moving to other, non-dc frequencies. For example, Figure 3 depicts a system with strong noise sources at 50 Hz and 2.5 kHz, and a very weak signal of interest modulated with a sine wave at 1 kHz.

$$Asin(2\pi f_m t) \times B\ sin(2\pi f_m t) = \frac{1}{2}AB \times \overset{1}{\cancel{cos(2\pi \times (f_m - f_m) \times t)}} - \frac{1}{2}AB \times cos(2\pi \times (f_m + f_m) \times t)$$

$$= \tfrac{1}{2}AB - \tfrac{1}{2}ABcos(2\pi 2 f_m t) \qquad \text{(Equation 1)}$$

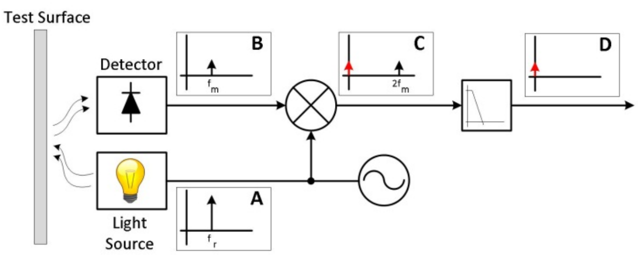

Figure 2. Measuring Surface Contamination with a Lock-In Amplifier

The result of multiplying the input with the reference is a signal at dc, and other signals at 950 Hz, 1.05 kHz, 1.5 kHz, 2 kHz, and 3.5 kHz. The dc signal contains the desired information, so you can use a low-pass filter to remove all of the other frequencies.

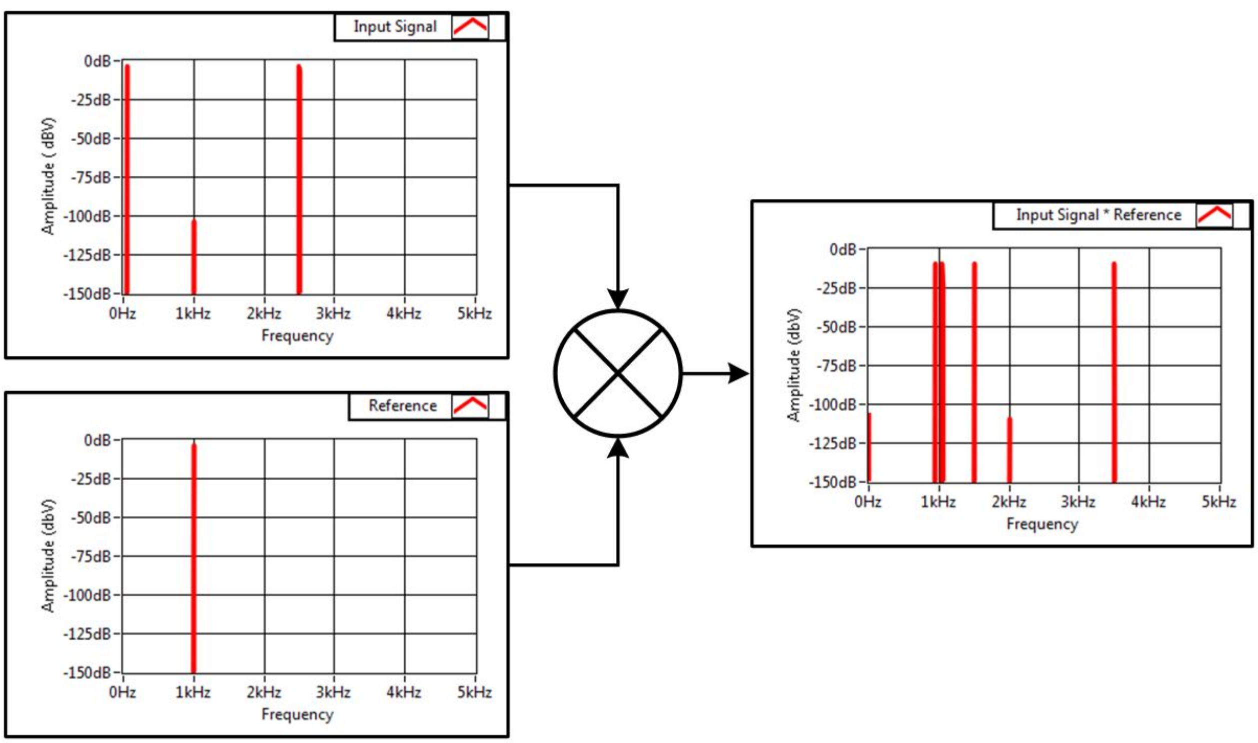

Figure 3. Synchronous Demodulation Picks Out a Weak, 1 kHz Signal in the Presence of Strong Noise Sources at 50 Hz and 2.5 kHz

Any noise components that are close to the signal of interest will appear at frequencies close to dc, so it is important to pick a modulation frequency that does not have strong noise sources near it. If this is not possible, then you will need a low-pass filter with a very low cutoff frequency and sharp response, at the expense of a long settling time.

PRACTICAL LOCK-IN IMPLEMENTATIONS

Generating a sine wave to modulate the signal source can be impractical, and some systems use a square wave instead. Generating a square wave excitation is much simpler than generating a sine wave, because it can be done with something as simple as a microcontroller pin that toggles an analog switch or a MOSFET.

The circuit of Figure 4 is an easy way to implement a hardware-based lock-in amplifier. A microcontroller or other digital device generates a square wave excitation signal that causes the sensor to respond. In the case of a photodiode, the first amplifier would be a current-to-voltage converter, while a strain gage bridge would require an instrumentation amplifier.

The same signal that excites the sensor controls the ADG619 SPDT switch. When the excitation signal is positive, the ADG619 configures the amplifier for a gain of +1. When the excitation is negative, the ADG619 configures the amplifier for a gain of −1, which essentially “flips” the negative side of the square wave. This is mathematically equivalent to multiplying the measured signal times the reference square wave. The output RC filter removes any signals at other frequencies, and the output voltage is a dc signal equal to half the peak-to-peak voltage of the measured square wave.

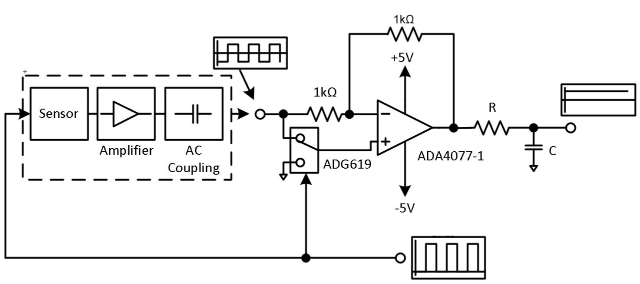

Figure 4. Lock-In Amplifier Using Square Wave Excitation

Although the circuit is simple, it is important to pick the right op amp for the job. The input ac coupling stage removes most of the input noise at low frequencies, but any 1/f noise and offset error from the last amplifier are not filtered out. The ADA4077-1 has 250 nV p-p of noise from 0.1 Hz to 10 Hz and 0.55 μV/ °C of offset drift, making it an ideal candidate for this application.

Using a square wave-based lock-in amplifier requires a simple circuit, but its noise rejection performance is inferior to a system using sine waves. Figure 5 shows the frequency domain representation of using a square wave as the sensor excitation and reference signal. A square wave is made up of an infinite sum of sine waves at the fundamental and all odd harmonics. Multiplying two square waves of the same frequency involves multiplying each sine component of the reference times each sine component of the measured signal. The result is a dc signal that contains energy from every harmonic of the square wave. Any unwanted signals that appear at any odd harmonic frequency will not be filtered out (although it will be scaled down depending on which harmonic it falls in). When designing a square wave-based lock-in amplifier, it is important to pick a modulation frequency with harmonics that are not at any frequency or harmonics of known noise sources. For example, instead of picking a 1 kHz modulation frequency (the 20th harmonic of 50 Hz), pick 1.0375 kHz, which does not coincide with harmonics of 50 Hz or 60 Hz.

Even with this drawback, the circuit is simple and low cost. Using a low noise amplifier and picking the right modulation frequency can still result in a great improvement over trying to make a dc measurement.

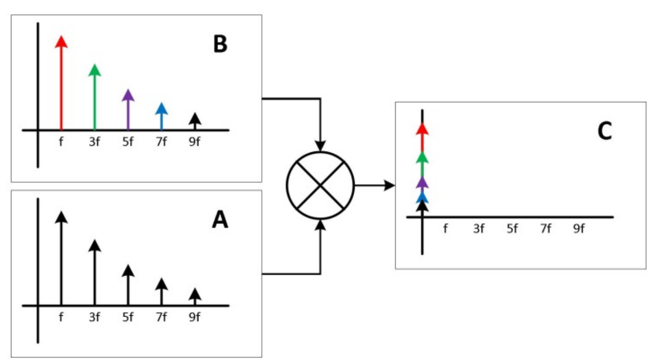

Figure 5. If the Input Signal (A) and the Reference (B) Are Both Square Waves, Multiplying Them Together (C) Effectively Demodulates Every Harmonic of the Input Signal

A SIMPLE, INTEGRATED ALTERNATIVE

The circuit of Figure 4 requires an op amp, analog switch, and some discrete components, plus a reference clock from a microcontroller. An alternative to this circuit is to use an integrated synchronous demodulator like the ADA2200. Figure 6 shows the internal blocks of the ADA2200, which include a buffered input, a programmable IIR filter, and a multiplier. It also includes a block that shifts the reference signal by 90°, which makes it easy to measure or compensate for phase shifts between the reference clock and input signal.

The benefits of this operation are explained in detail in the following section.

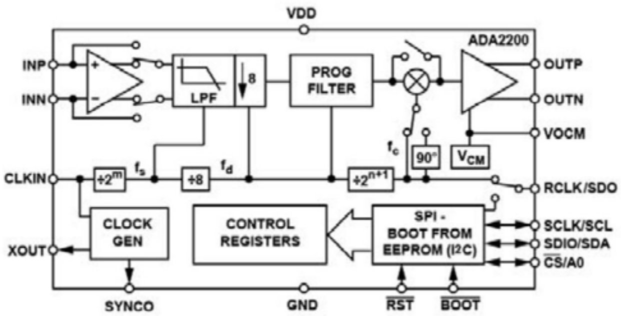

Figure 6. ADA2200 Internal Architecture

Implementing a lock-in detection circuit with the ADA2200 simply requires applying a clock frequency that is 64 times the desired reference frequency. The default configuration of the programmable filter is for a band-pass response, removing the need to ac couple the signal as in the circuit of Figure 4. The ADA2200's sampled analog output will generate images around multiples of the sampling rate. You can use an RC filter followed by a Σ-Δ ADC to remove these images and measure only the demodulated dc component of the signal.

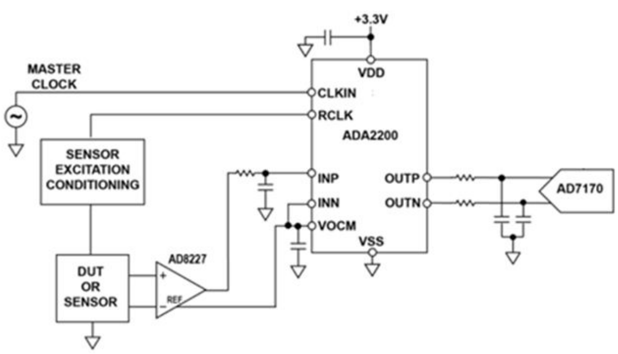

Figure 7. Lock-In Amplifier Implementation with the ADA2200

IMPROVING THE SQUARE WAVE LOCK-IN CIRCUIT

Figure 8 shows an improvement to a square wave modulated circuit. If you excite the sensor with a square wave, but now multiply the measured signal with a sine wave of the same frequency and phase, only the signal content at the fundamental frequency will move to dc, while all of the other harmonics will move to non-dc frequencies. This makes it easy to use a low-pass filter and eliminate everything but the dc component of the measured signal.

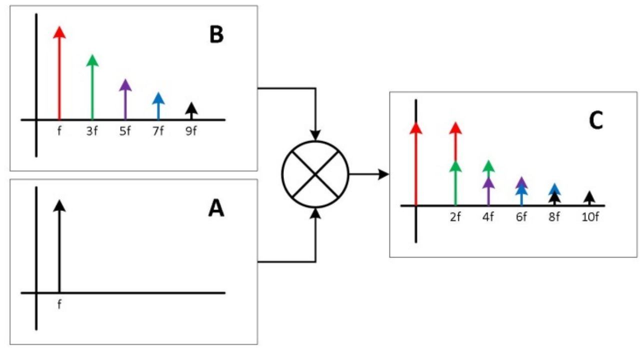

Figure 8. Using a Sine Wave as the Reference Signal Prevents Noise from Demodulating to DC

One additional difficulty is that if there is any phase shift between the reference signal and the measured signal, the result of multiplying the two together will result in a lower amplitude output than if they were perfectly in phase. This can occur if the sensor signal conditioning circuit includes any filters (which introduce phase delay). With an analog lock-in amplifier, the only way to address this is to include additional phase compensation circuits in the reference signal path. This is not trivial, because the circuit needs to be adjustable to compensate for different phase delays, and will vary with temperature, component tolerance, etc. An easier alternative is to add a second multiplication stage that multiplies the measured signal with a 90° phase shifted version of the reference. The result of this second stage will be a signal proportional to the out of phase component of the input. Figure 9 shows this concept.

The outputs of the low-pass filters after the two multiplier stages are low frequency signals proportional to the in-phase (I) and quadrature (Q) components of the input. To calculate the magnitude of the input signal, simply take the sum of the squares of the I and Q outputs. An additional benefit of this architecture is that you can also calculate the phase between the excitation/reference signal and the input.

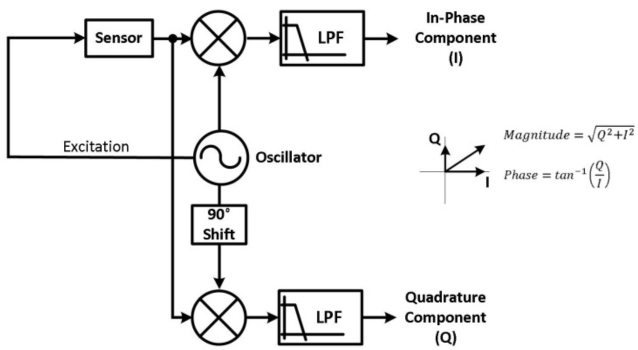

Figure 9. Using a Quadrature Version of the Reference Signal to Calculate Magnitude and Phase

All of the systems discussed so far generate a reference signal that excites a sensor. One final refinement to the lock-in amplifier is to allow an external signal to act as a reference. For example, Figure 10 shows a system that uses a broadband incandescent light to test the optical properties of a surface. A system like this can measure parameters such as the reflectivity of mirrors, or the amount of contamination on a surface. It is much simpler to use a mechanical chopper disk to modulate an incandescent source than to apply electronic modulation. A cheap position sensor close to the chopper disk generates a square wave reference signal to feed the lock-in amplifier. Rather than using this signal directly, a phase-locked loop generates a sine wave of the same frequency and phase as the input reference. One caveat of this approach is that the internally generated sine wave must have low distortion.

Although this system could be implemented using a discrete PLL and multipliers, using an FPGA to implement the lock-in amplifier functions results in several performance benefits. Figure 11 shows a lock-in amplifier built with an FPGA using a front end based on the ADA4528-1 zero-drift amplifier and an AD7175 24-bit Σ-Δ ADC. An application like this does not need very high bandwidth, so we can set the lock-in amplifier's equivalent noise bandwidth to 50 Hz. The device under test is again any sensor that can be excited externally. The ADA4528-1 is configured with a noise gain of 20 to take advantage of the full scale range of the ADC (arbitrarily set for this example). Although dc errors do not affect the measurement, it is still important to minimize offset drift and 1/f noise because they will decrease the available dynamic range, especially when the amplifier is configured for high gain. The ADA4528-1's 2.5 µV of worst case input offset error represents only 10 ppm of the AD7175's full scale input range (with a 2.5 V reference). The digital high-pass filter after the ADC removes any dc offset and very low frequency noise. To calculate the output noise, we need to know the voltage noise density of the AD7175. The data sheet specifies the ADC noise at 5.9 µV rms with an

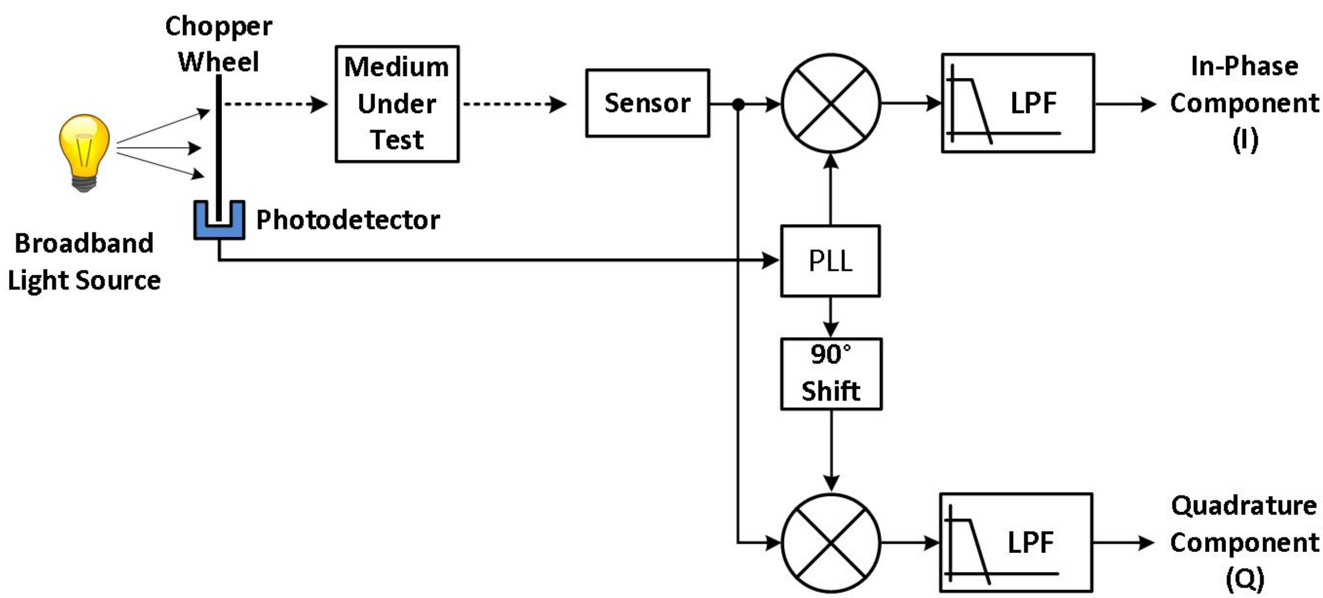

Figure 10. Using a PLL to Lock on to an External Reference Signal

output data rate of 50 kSPS, using the Sinc5 + Sinc1 filter and with the input buffer enabled. The equivalent noise bandwidth with these settings is 21.7 kHz, which results in a voltage noise density of 40 nV/√Hz. The broadband input noise of the ADA4528 is 5.9 nV/√Hz, which appears at the output as 118 nV/√Hz resulting in a combined noise density of 125 nV/√Hz. Since the digital filter has an equivalent noise bandwidth of only 50 Hz, the output noise is 881 nVrms. With a ±2.5 V input range, this results in a system with 126 dB of dynamic range. We can trade off bandwidth for dynamic range by adjusting the frequency response of the low-pass filter. For example, setting the filters for an equivalent noise bandwidth of 1 Hz results in 143 dB of dynamic range, and setting the bandwidth to 250 Hz results in 119 dB of dynamic range.

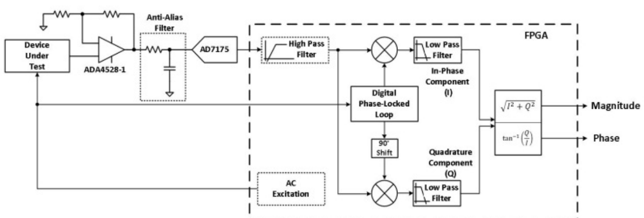

Figure 11. FPGA-Based Lock-In Amplifier

The digital phase-locked loop generates a sine wave locked to the excitation signal (which can be an external signal, or internally generated in the FPGA, and does not have to be a sine wave). Any harmonics in the reference sine wave will also multiply with the input signal, demodulating noise and other unwanted signals present at the harmonic frequencies, just like when two square waves are multiplied together (see Figure 5). One advantage of generating this reference sine wave digitally is that it is relatively easy to generate a very low distortion signal simply by adjusting the number precision. For example, Figure 12 shows four digitally generated sine waves using 4-, 8-, 16-, and 32-bit precision. Obviously, using 4-bit precision results in performance not much different from the case in Figure 5, but the situation quickly improves by using higher precision numbers. At 16 bits of precision, it would take some effort to generate an analog signal with such low total harmonic distortion (THD), and at 32 bits, where the THD is over −200 dB, it would be impossible to match with an analog circuit. In addition, because these are digitally generated signals, they are perfectly repeatable. Once the data has been converted to the digital domain and enters the FPGA, there is no additional noise or drift to take into account.

After the multipliers, the low-pass filters remove any high frequency components and output the in-phase and quadrature components of the signal. Continuing with the assumption that the equivalent noise bandwidth of the filters is only 50 Hz, there is no reason to deliver data at the original sampling rate of 250 kSPS. The low-pass filters can include a decimation stage to reduce the output data rate. The last step in the process is to calculate the magnitude and phase of the input signal from the in-phase and quadrature components.

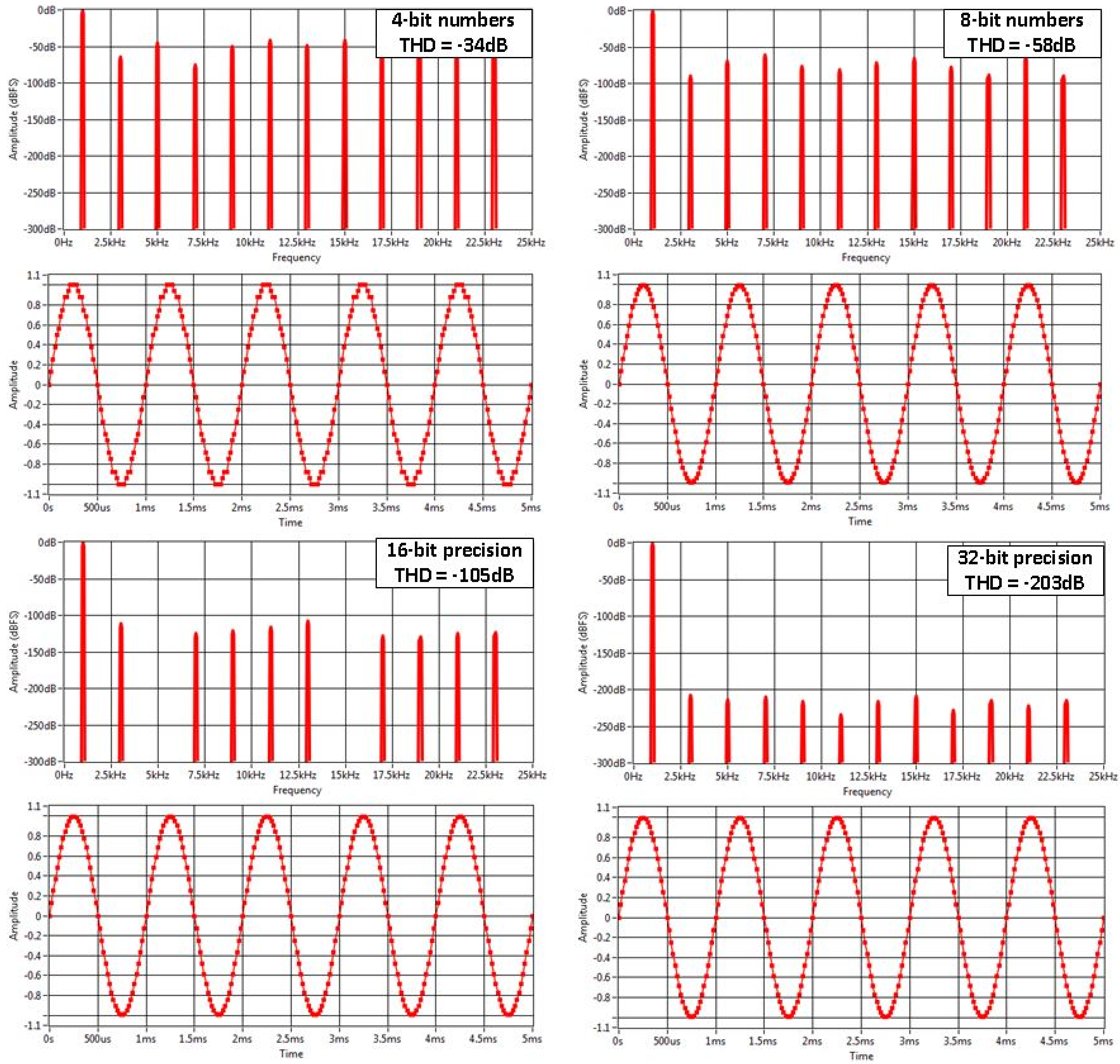

Figure 12. Numerically Generated Sine Waves with Different Number Precision

SUMMARY

Small, low frequency signals buried in the noise floor can be difficult to measure, but applying modulation and lock-in amplifier techniques can result in high precision measurements. In its simplest form, a lock-in amplifier can be an op amp that switches between two gains. Although this does not result in the lowest noise performance, the simplicity and low cost of the circuit still make it very attractive when compared with a simple dc measurement. An improvement from this circuit is to use a sine wave reference and a multiplier, but this can be challenging to implement in the analog domain. For the ultimate performance, consider using a low noise, high resolution Σ-Δ ADC, such as the AD7175, to digitize the input signal, and then generate the reference sine wave, and all of the other elements of the lock-in amplifier in the digital domain.

AUTHOR

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