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Sampling Quality

Overview

This tutorial is part of the National Instruments Measurement Fundamentals series. Each tutorial in this series, will teach you a specific topic of common measurement applications, by explaining the theory and giving practical examples. This tutorial covers the basics of analog sampling quality.

Also, watch an online demonstration on analog sampling quality here.

For the complete list of tutorials, return to the NI Measurement Fundamentals Main page.

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Resolution

Resolution is defined as the smallest amount of input signal *change* that an instrument or sensor can detect reliably. Resolution can be expressed as a %, x parts out of y, or most conveniently, as bits. Resolution is determined by the instrument noise (either circuit or quantization noise) and the smallest change that is detectable by the display system of the instrument. For example, if you have a noiseless digital multimeter that has 5 ½-displayed digits and is set to the 20 V input range, the resolution of this digital multimeter is 0.1 mV. This can be determined looking at the change associated with the least significant digit. Now, if this same digital multimeter had 10 counts of peak-to-peak noise, then the effective resolution is decreased to 1 mV, because any signal change less then 1 mV is indistinguishable from the noise.

Product Info:
The **NI 4071 FlexDMM and 1000 V Digitizer** has a maximum resolution of 26 bits (7½ digits)

In case of an analog-to-digital converter (ADC), resolution refers to the number of binary levels the ADC can use to represent a signal. To figure out the number of binary levels available based on the bits of resolution you simply take $2^{\text{bits of resolution}}$. Therefore, the higher the resolution, the more levels you will have to represent your signal. For instance, an ADC with 3-bit resolution can measure 2^3 or 8 voltage levels, while an ADC with 12-bit resolution can measure 2^{12} or 4096 voltage levels. Even though ADCs are not made with only 3-bit resolution let us further examine our example of a 3-bit ADC. The lowest voltage level will correspond to 000, the next highest to 001, and so on all the way up to 111.

To illustrate this point, image how a sine wave would be represented if it is passed through ADCs with different resolutions. Figure 1 below compares a 3-bit ADC and a 16-bit ADC. As described earlier, a 3-bit ADC can represent 8 discrete voltage levels. A 16-bit ADC can represent 65,536 discrete voltage levels. The representation of the sine wave with a 3-bit resolution looks more like a step function than a sine wave. However, the 16-bit ADC provides a clean looking sine wave. One way to think of resolution is by considering your television screen. The higher the resolution of the screen, the more pixels you have to show the picture which corresponds to a better quality picture. Another way to think of resolution is by considering the amount of colors your computer monitor uses to display an image. If you are only using 3-bit color the picture is choppy and makes it difficult to distinguish details, but if you use 16-bit color the picture is smooth and looks great. Keep in mind that resolution is a fixed quantity of an ADC, and it depends on the measurement device that you use.

Product Info:
The **NI 5922 Flexible Resolution Digitizer** has a resolution ranging from 16 bits at 15 MS/s to 24 bits at 500 kS/s

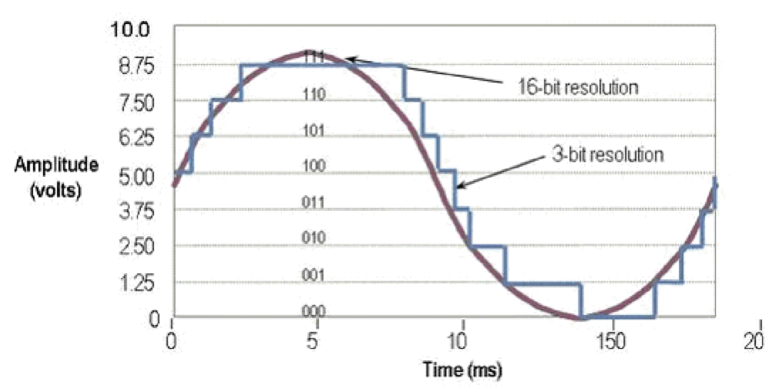

Figure 1 Digital image of a sine wave obtained by 3-bit and 16-bit ADC

NI High-Speed Digitizers typically offer 8-24 bits of resolution, NI Dynamic Signal Acquisition devices and Digital Multimeters offer 16-26 bit resolution, and NI M-series Data Acquisition devices offer 12-18 bits of resolution.

Measurement Sensitivity

Sensitivity is defined as a measure of the *smallest signal* the instrument can measure at the lowest range setting of the instrument. Sensitivity is not related to resolution. For example, an 8-bit analog meter could have more sensitivity than a 16-bit Data Acquisition board. As another example, a digital multimeter with a lowest measurement range of 10 V may be able to detect signals with 1 mV resolution but the smallest detectable voltage it can measure may be 15 mV. In this

Product Info:
The **NI 4071 FlexDMM and 1000 V Digitizer** has sensitivities of 10 nV, 1 pA

case, the digital multimeter has a resolution of 1 mV but a sensitivity of 15 mV.

Accuracy and Example Accuracy Calculations

Accuracy is defined as a measure of the capability of the instrument to *faithfully* indicate the value of the measured signal. This term is not related to resolution; however, it can never be better than the resolution of the instrument. How you specify the accuracy of your measurement is dependant the type of measurement instrument your using. A digital multimeter is often specified as:

(% Reading) + Offset
or
(% Reading) + (% Range)
or
±(ppm of reading + ppm of range)

For example, assume a digital multimeter set to the 10 V range is operating 90 days after calibration at 23ºC ±5ºC, and is expecting a 7 V signal. The accuracy specifications for these conditions state ±(20 *ppm of reading* + 6 *ppm of range*). To determine accuracy of the digital multimeter under these conditions, use the following formula:

Accuracy = ±*(20 ppm of reading + 6 ppm of range)*

Accuracy = ±(20 ppm of 7 V + 6 ppm of 10 V)

Accuracy = ±((7 V(20/1,000,000) + (10 V(6/1,000,000))

Accuracy = 200 µV

Therefore, the reading should be within 200 µV of the actual input voltage. Accuracy can also be defined in terms of the deviation from an ideal transfer function as follows:

A data acquisition device is often specified as:

AbsoluteAccuracy = Reading · (GainError) + Range × (OffsetError) + NoiseUncertainty
GainError = ResidualAIGainError + GainTempco × (TempChangeFromLastInternalCal) + ReferenceTempco × (TempChangeFromLastExternalCal)

OffsetError = ResidualAIOffsetError + OffsetTempco × (TempChangeFromLastInternalCal) + INL_Error

For example, on the 10 V range, the absolute accuracy at full scale of an NI 628X M-series data acquisition device is as follows:

GainError = 40 ppm + 17 ppm × 1 + 1 ppm × 10
GainError = 67 ppm

OffsetError = 8 ppm + 11 ppm × 1 + 10 ppm
OffsetError = 29 ppm

$$\text{NoiseUncertainty} = \frac{60\ \mu\text{V} \cdot 3}{\sqrt{100}}$$

NoiseUncertainty = 18 µV

AbsoluteAccuracy = 10 V × (GainError) + 10 V × (OffsetError) + NoiseUncertainty
Absolute Accuracy = 980 µV

It is important to note that the accuracy of an instrument depends not only on the instrument, but also on the type of signal being measured. If the signal being measured is noisy, the accuracy of the measurement gets adversely affected.

Difference between Precision and Accuracy

Precision is defined as a measure of the *stability* of the instrument and its capability of resulting in the same measurement over and over again for the same input signal. It is given by:

Precision = $1 - |X_n - Av(X_n)| / |Av(X_n)|$

where X_n = the value of the nth measurement

and $Av(X_n)$ = the average value of the set of *n* measurement.

For instance, if you are monitoring a constant voltage of 1 V, and you notice that your measured value changes by 20 µV between measurements then your measurement precision is

Precision = (1 – 20 µV/ 1 V) × 100 = 99.998 %

This specification is most valuable when you are using the voltmeter to calibrate a device or performing relative measurements. Figure 2 demonstrates the difference between accuracy and precision. Accuracy refers to how closely a measured value agrees with the actual value while precision refers to how closely individual measurements agree with each other.

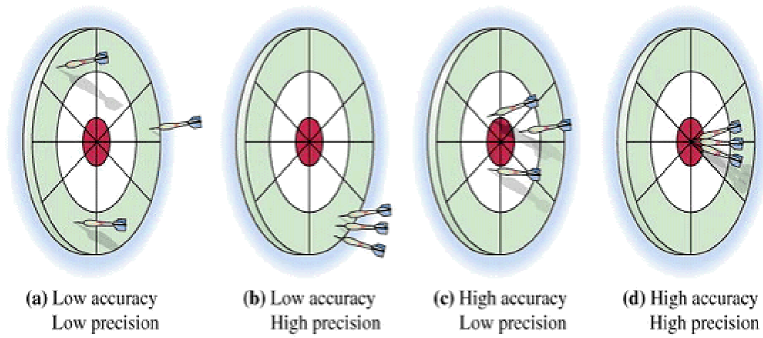

Figure 2 Accuracy versus Precision

Noise and Noise Sources

Noise is any unwanted signal that interferes with the desired signal. Noise interferes with the measurement by inducing uncertainty that tends to be time-variant. It can be random or periodic. Noise may either be transient in nature, have fixed frequencies such as harmonic or mixer products, or be broadband random noise. Noise is sometimes considered separately from accuracy specifications, because averaging and other techniques can be used to reduce it in the measurement. However, other times it is included in the accuracy specifications. Footnotes in the specifications will tell you if it is included or not.

Sources of Noise

There are various sources of noise in instrumentation. Noise that is a result of the source (or Device Under Test) itself are called *Intrinsic*. These noise sources can be due to thermal sources, like the noise of a resistor, or can be 1/F in nature, which is caused by semiconductor devices. Also, noise can come from the outside world, such as from power lines, lights in the room, motors, and radio frequency sources (radio transmitters, cell phones, radio stations, etc).

Thermal Noise

An ideal electronic circuit produces no noise of its own, so the output signal from the ideal circuit contains only the noise that was in the original signal. But real electronic circuits and components do produce a certain level of inherent noise of their own. Even the simple fixed-value resistor is noisy.

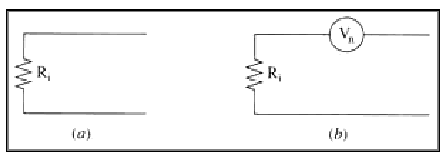

Figure 3 Resistor noise, (a) Ideal, noise-free resistor. *(b)* Practical resistor has internal thermal noise source

Figure 3a shows the equivalent circuit for an ideal, noise-free resistor. The inherent noise is represented in Figure 3b by a noise voltage source, Vn, in series with the ideal, noise-free resistance, Ri. At any temperature above absolute zero (0°K or about -273°C), electrons in any material are in constant random motion. Because of the inherent randomness of that motion, however, there is no detectable current in any one direction. In other words, electron drift in any single direction is cancelled over short time periods by equal drift in the opposite direction. Electron motions are therefore statistically de-correlated. There is, however, a continuous series of random current *pulses* generated in the material, and those pulses are seen by the outside world as a noise signal. This signal is called by several names: Johnson noise, thermal agitation noise, or thermal noise.

The expression for Johnson noise is:

$$(V_n)^2 = 4KTRB\ V^2/Hz$$

where

V_n is the noise voltage (V)
K is Boltzmann's constant (1.38 X 1023 J/°K)
T is the temperature in degrees Kelvin (°K)
R is the resistance in ohms (Ω)
B is the bandwidth in hertz (Hz)

With the constants collected, and the expression normalized to 1 kΩ*,* the above equation reduces to:

$$V_n = 4\sqrt{\frac{R}{1\ k\Omega}}\ \frac{nV}{\sqrt{Hz}}$$

The evaluated solution of the above equation is normally read *nanovolts per square root hertz.* In this equation, a 1 MΩ resistor will have a thermal noise of 126 nV/ ÖHz. The important thing to note is that noise increases with temperature and resistance, but as a square root function. So you would have to quadruple the resistance to double the noise of that resistor.

Flicker or 1/F noise

Semiconductor devices tend to have noise that is not flat with frequency. It rises at the low end. This is called 1/F noise, Pink Noise, Excess Noise or Flicker Noise. 1/F noise also occurs in many physical systems other than electrical. Examples are proteins, reaction times of cognitive processes, and even earthquake activity.

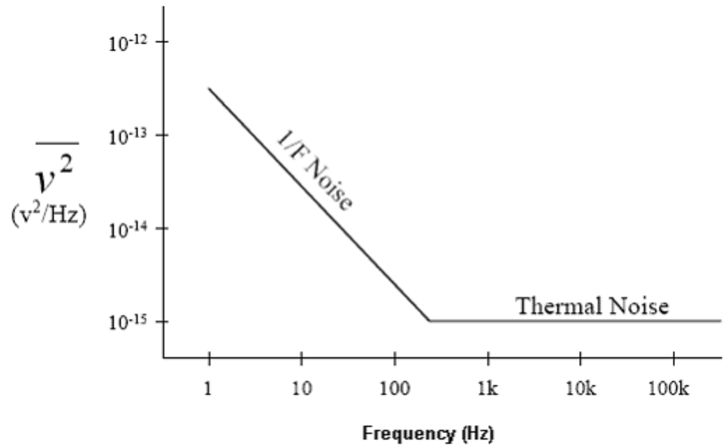

Figure 4 Noise spectrum profile when 1/F noise and Thermal noise are present

Noise Reduction Strategies

Although noise is a serious problem for the designer, especially when low signal levels are present, a number of commonsense approaches can be used to minimize the effects of noise on a system. For example:

1. Keep the source resistance and the amplifier input resistance as low as possible. Using high value resistances will increase thermal noise proportionally.

2. Total thermal noise is also a function of the bandwidth of the circuit. Therefore, reducing the bandwidth of the circuit to a minimum will also minimize noise. But this job must be done mindfully because signals have a Fourier spectrum that must be preserved for accurate measurement. The solution is to match the bandwidth to the frequency response required for the input signal.

3. Prevent external noise from affecting the performance of the system by appropriate use of grounding, shielding, cabling, careful physical placement of wires and filtering.

4. Use a low-noise amplifier in the input stage of the system.

5. For some semiconductor circuits, use the lowest DC power supply potential that will do the job.

Relevant NI products

Customers interested in this topic were also interested in the following NI products:

- LabVIEW Graphical Programming Environment
- SignalExpress Interactive Software Environment
- Digitizers
- Dynamic Signal Acquisition (DSA)
- Digital Multimeter (DMM)
- Data Acquisition (DAQ)

For the complete list of tutorials, return to the NI Measurement Fundamentals Main page.