Optimum oscilloscope bandwidth and sample rate

the more you can see the more you can fix

This application note takes a look at signal frequency and pulse edge rise time to better understand their impact on the displayed signal using a digital storage oscilloscope.

What is Bandwidth?

To put it into context, let's start with by answering what an oscilloscope is. An oscilloscope is a device that captures and graphically represents an electrical signal change over time in its true original form. The display is calibrated to represent a voltage (vertical axis) over time (Horizontal axis). As the voltage changes over time, the number of changes (Cycles) over time can be represented as a frequency. F=1/time (Hertz). Much like with your hearing, as the frequency increases the oscilloscopes ability to accurately reproduce the signal voltage over time decreases. Therefore the critical question becomes, what is the maximum number of cycles (repeating events) that an oscilloscope can graphically reproduce in its true original form. An oscilloscope bandwidth specification answers this critical question.

As the frequency increases and the oscilloscopes ability to accurately reproduce the signal's true amplitude decreases. Manufacturers specify bandwidth as the highest frequency at which a sinusoidal input being reproduced on the display is attenuated by a maximum of 70.7 % of the signal's true amplitude, known as the 3 dB point. In other words, bandwidth is the maximum frequency at which the signal being displayed is still greater than 70.7 % of the actual amplitude of the signal being applied (or 0.707 times).
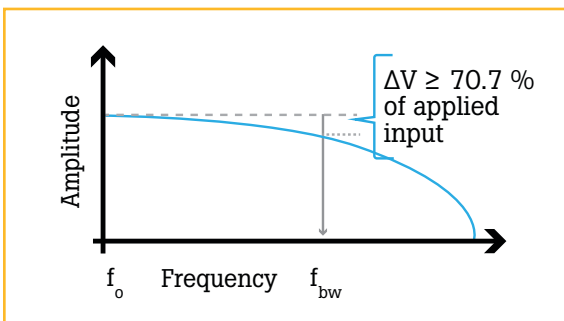
Capturing a sine wave

Capturing a sine wave in its purest form without any distortion would merely require an oscilloscope with an input bandwidth of some magnitude frequency greater than the frequency of the measured sine wave. Despite today's digital high technology components, engineers and technicians are still concerned with a waveform's overall shape, amplitude, time and presence of any disturbances. Selecting the right oscilloscope can mean the difference between having all of the necessary information, and overlooking critical details. While you may think the signal under test is good, in reality you might not be seeing everything about that waveform that truly exists.
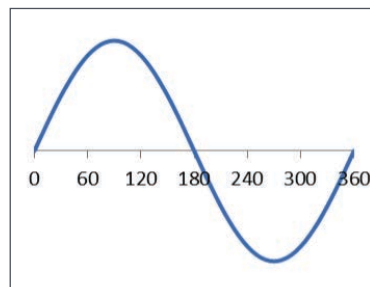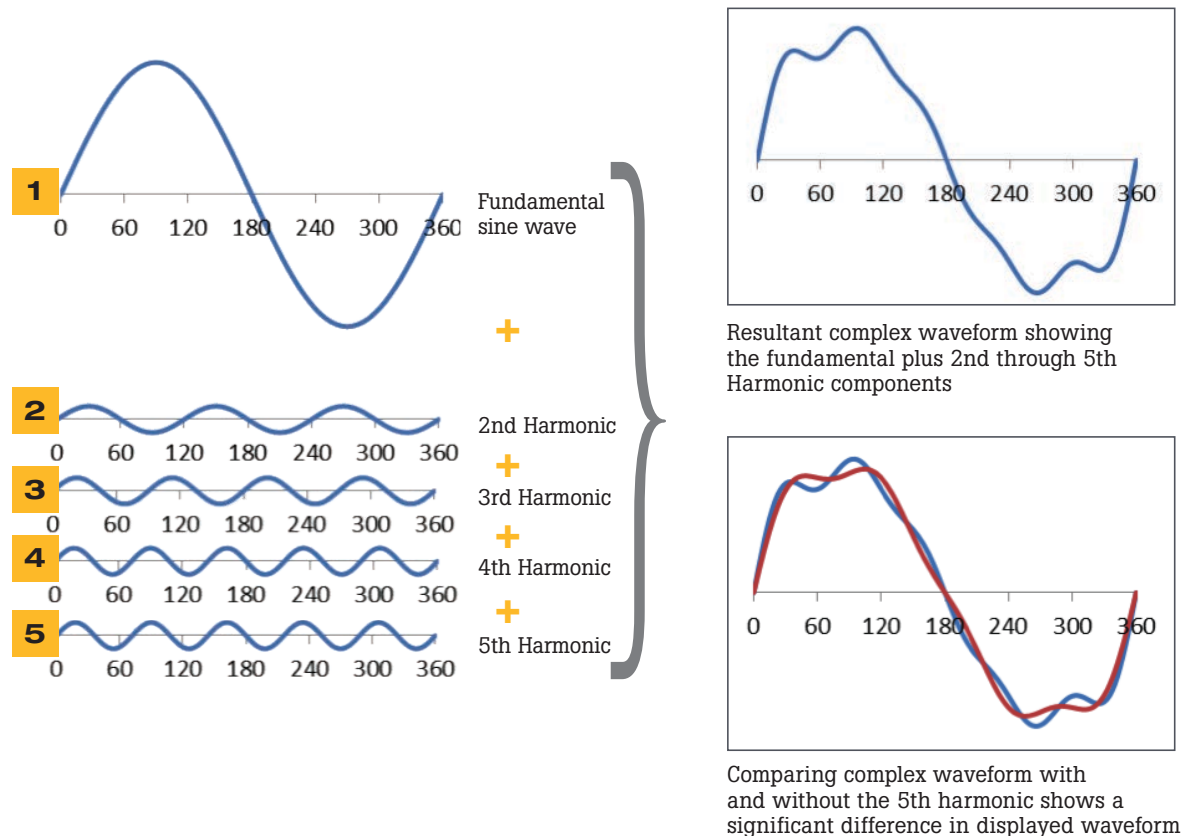

Sine wave in its purest form mathematically represented by $y(t) = A \sin(\omega t + \theta)$
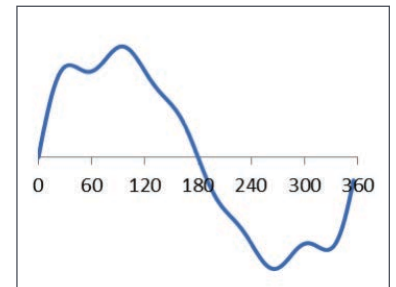
Distorted sine wave that is made up by the sum of some number of harmonic components

$\Delta V \geq 70.7\ \%$ of applied input

Amplitude

f_o Frequency f_{bw}

In the case of a repeating complex waveform or a sine wave that has been distorted, the waveform can be mathematically represented by the sum of the individual harmonic or frequency components. Using a spreadsheet we can plot each component [y(t)= A sin(ωt +θ)] along with the combined sum of individual components so that we can make simple visual comparisons to see the impact of oscilloscope bandwidth.

1 Fundamental sine wave

+

2 2nd Harmonic

+

3 3rd Harmonic

+

4 4th Harmonic

+

5 5th Harmonic

Resultant complex waveform showing the fundamental plus 2nd through 5th Harmonic components

Comparing complex waveform with and without the 5th harmonic shows a significant difference in displayed waveform
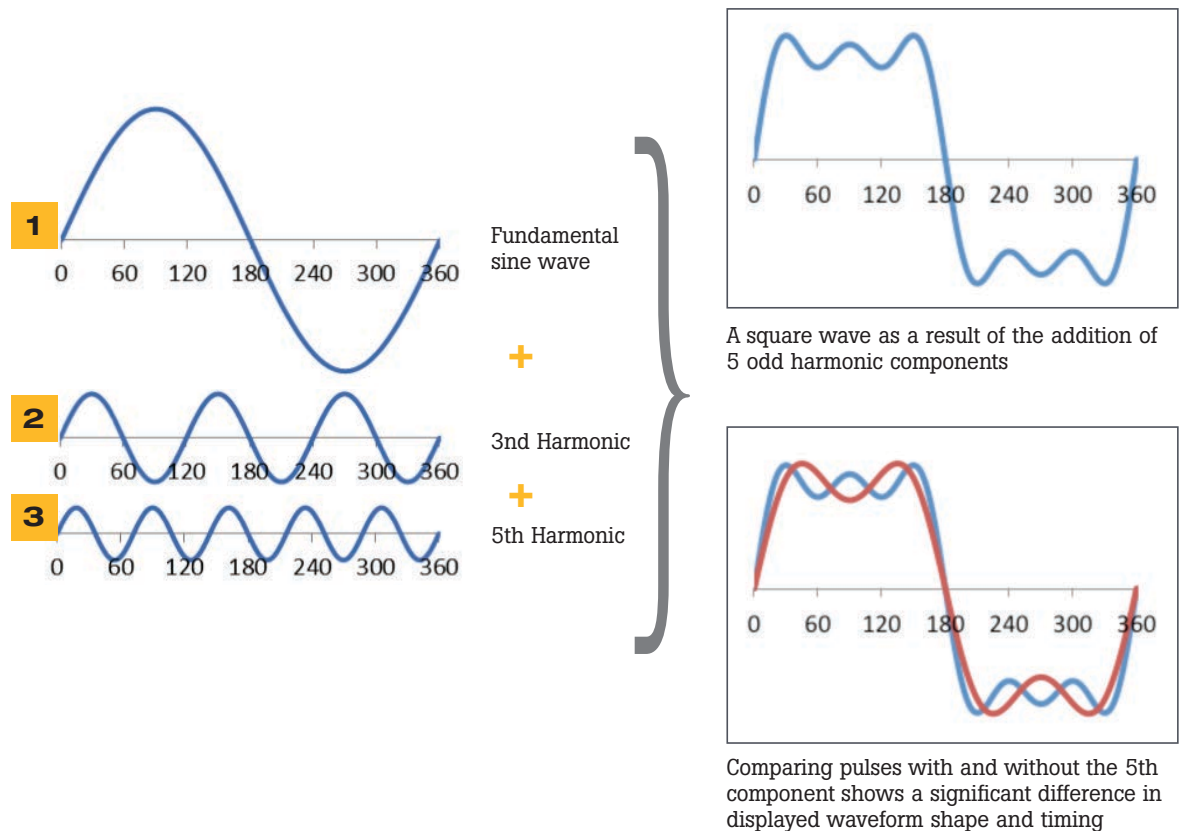
Comparing the resultant complex waveform with and without the 5th harmonic component reveals a significant difference in displayed shape. As a result the general rule of thumb is to select an oscilloscope with a bandwidth of five times the frequency of the measured sine wave.

Oscilloscope Bandwidth ≥ Highest Frequency Component of Signal X 5

Apart from the difference in overall waveform shape, inadequate oscilloscope bandwidth can result in some error in displayed amplitude level. By comparing an oscilloscope with a minimum of five times the bandwidth of the fundamental frequency to one that is only four times the frequency shows the difference in peak amplitudes, in this case we calculated an error of 7 %.
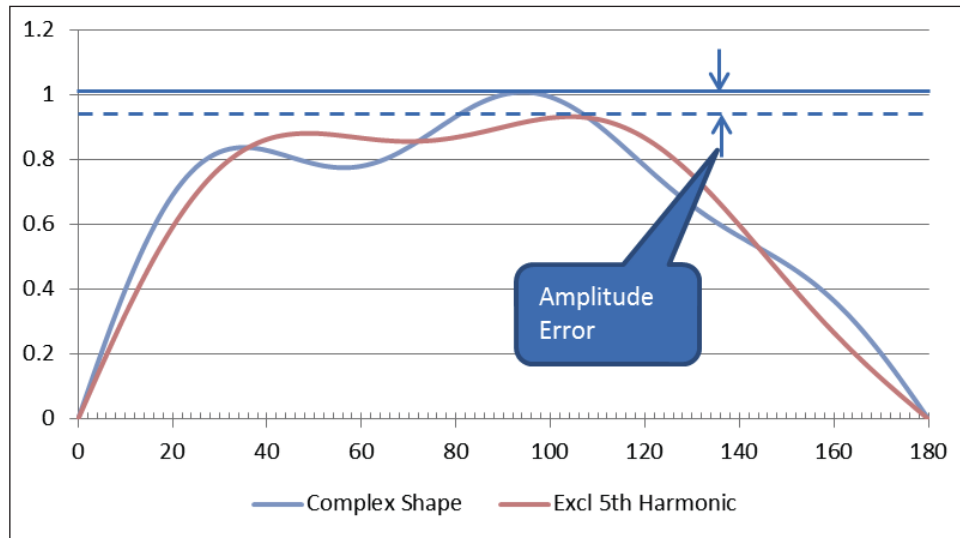
Next consider the impact of sample rate on horizontal time axis. In digital or analog pulse circuits the most common measurements that define the quality of a square wave or pulses are pulse width, rise time or change in voltage over time (dV/dt). A square wave with a fast edge can be represented by the sum of an infinite number of odd harmonic sine waves.

Fundamental sine wave

+

3nd Harmonic

+

5th Harmonic

A square wave as a result of the addition of 5 odd harmonic components

Comparing pulses with and without the 5th component shows a significant difference in displayed waveform shape and timing

An oscilloscope must have fast enough rise and fall response time performance to accurately capture and display the leading or trailing edges plus any reflections, transients or other common aberrations. Comparing a waveform that includes only harmonic components clearly shows how differently an oscilloscope might display the shape and edges. This difference could lead to significant error in the displayed waveform. Rise time performance of digital storage oscilloscopes is dependent on the analog input circuit and the analog to digital converter sample rate. An industry accepted general rule of thumb is to select an oscilloscope with a rise time performance of one fifth times the rise time of the measured sine wave.

Oscilloscope Rise Time ≤ Fastest Rise Time of Signal x 1/5

Zooming in to inspect signal edge using an oscilloscope with a rise time of less than one fifth the rise time of the signal under test shows a displayed rise time error of as much as 33 %.

The relationship between rise time and bandwidth can also be evaluated using another common formula, risetime=0.35/bandwidth. This proven formula takes the frequency response of typical 1GHz or less oscilloscopes into account. Furthermore additional errors from the probes, signal under test and the oscilloscope used in the entire measurement chain should be included in the analysis.

Modern commercial and industrial devices like medical imaging, radars, digital communications systems and

power inverters utilize microprocessors and semiconductor switching devices that run at clock speeds in the 100's of megahertz range or produce digital pulses operating with edge rise and fall times measured in the 10's of nano seconds. On top of the fast operating speeds, these devices are subject to the influence of EMI and environmental operating conditions that can cause impedance changes, imbalances and distortion resulting in the device operating incorrectly. Using an oscilloscope with enough bandwidth and rise time performance can mean the difference between quickly determining the root cause and being led astray. Always remember an oscilloscope with a faster rise time and wider bandwidth will more accurately capture and display the true waveform shape and critical details like signal noise, distortion or the peaks of transients or reflections.

Conclusion

Engineers and technicians confront challenges every day when making measurements on modern high speed electronic equipment and industrial power systems. Some of these measurements require you to deal with high voltages and currents operating at high frequencies, with fast edges that contain harmonic distortions or other fast signal anomalies. Bench oscilloscope alternatives may have the bandwidth and sample speeds needed, but they lack portability, safety or channel isolation. But, the new Fluke 190–504 has the best of both worlds, a hand–held portable electrically isolated 4 channel instrument with 500 MHz bandwidth and 5GS/s sample rate allowing engineers and technicians to make high speed measurements quickly, accurately and safely.
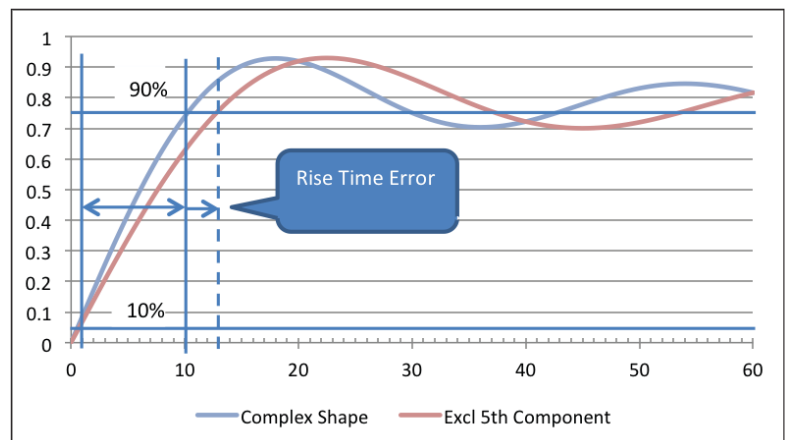
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