Signal Integrity

The Significance of Signal Integrity

The key to any good oscilloscope system is its ability to accurately reconstruct a waveform – referred to as **signal integrity**. An oscilloscope is analogous to a camera that captures signal images that we can then observe and interpret. Two key issues lie at the heart of signal integrity.

- When you take a picture, is it an accurate picture of what actually happened?
- Is the picture clear or fuzzy?
- How many of those accurate pictures can you take per second?

Taken together, the different systems and performance capabilities of an oscilloscope contribute to its ability to deliver the highest signal integrity possible. Probes also affect the signal integrity of a measurement system.

Signal integrity impacts many electronic design disciplines. But until a few years ago, it wasn't much of a problem for digital designers. They could rely on their logic designs to act like the Boolean circuits they were. Noisy, indeterminate signals were something that occurred in high-speed designs – something for RF designers to worry about. Digital systems switched slowly and signals stabilized predictably.

Processor clock rates have since multiplied by orders of magnitude. Computer applications such as 3D graphics, video and server I/O demand vast bandwidth. Much of today's telecommunications equipment is digitally based, and similarly requires massive bandwidth. So too does digital high-definition TV. The current crop of microprocessor devices handles data at rates up to 2, 3 and even 5 GS/s (gigasamples per second), while some memory devices use 400-MHz clocks as well as data signals with 200-ps rise times.

Importantly, speed increases have trickled down to the common IC devices used in automobiles, VCRs, and machine controllers, to name just a few applications. A processor running at a 20-MHz clock rate may well have signals with rise times similar to those of an 800-MHz processor. Designers have crossed a performance threshold that means, in effect, almost every design is a high-speed design.

Without some precautionary measures, high-speed problems can creep into otherwise conventional digital designs. If a circuit is experiencing intermittent failures, or if it encounters errors at voltage and temperature extremes, chances are there are some hidden signal integrity problems. These can affect time-to-market, product reliability, EMI compliance, and more.

Why is Signal Integrity a Problem?

Let's look at some of the specific causes of signal degradation in today's digital designs. Why are these problems so much more prevalent today than in years past?

The answer is speed. In the "slow old days," maintaining acceptable digital signal integrity meant paying attention to details like clock distribution, signal path design, noise margins, loading effects, transmission line effects, bus termination, decoupling and power distribution. All of these rules still apply, but…

Bus cycle times are up to a thousand times faster than they were 20 years ago! Transactions that once took microseconds are now measured in nanoseconds. To achieve this improvement, edge speeds too have accelerated: they are up to 100 times faster than those of two decades ago.

This is all well and good; however, certain physical realities have kept circuit board technology from keeping up the pace. The propagation time of inter-chip buses has remained almost unchanged over the decades. Geometries have shrunk, certainly, but there is still a need to provide circuit board real estate for IC devices, connectors, passive components, and of course, the bus traces themselves. This real estate adds up to distance, and distance means time – the enemy of speed.

It's important to remember that the edge speed – rise time – of a digital signal can carry much higher frequency components than its repetition rate might imply. For this reason, some designers deliberately seek IC devices with relatively "slow" rise times.

The lumped circuit model has always been the basis of most calculations used to predict signal behavior in a circuit. But when edge speeds are more than four to six times faster than the signal path delay, the simple lumped model no longer applies.

Circuit board traces just six inches long become transmission lines when driven with signals exhibiting edge rates below four to six nanoseconds, irrespective of the cycle rate. In effect, new signal paths are created. These intangible connections aren't on the schematics, but nevertheless provide a means for signals to influence one another in unpredictable ways.

At the same time, the intended signal paths don't work the way they are supposed to. Ground planes and power planes, like the signal traces described above, become inductive and act like transmission lines; power supply decoupling is far less effective. EMI goes up as faster edge speeds produce shorter wavelengths relative to the bus length. Crosstalk increases.

In addition, fast edge speeds require generally higher currents to produce them. Higher currents tend to cause ground bounce, especially on wide buses in which many signals switch at once. Moreover, higher current increases the amount of radiated magnetic energy and with it, crosstalk.

Viewing the Analog Origins of Digital Signals

What do all these characteristics have in common? They are classic **analog** phenomena. To solve signal integrity problems, digital designers need to step into the analog domain. And to take that step, they need tools that can show them how digital and analog signals interact.

Digital errors often have their roots in analog signal integrity problems. To track down the cause of the digital fault, it's often necessary to turn to an oscilloscope, which can display waveform details, edges and noise; can detect and display transients; and can help you precisely measure timing relationships such as setup and hold times.

Understanding each of the systems within your oscilloscope and how to apply them will contribute to the effective application of the oscilloscope to tackle your specific measurement challenge.

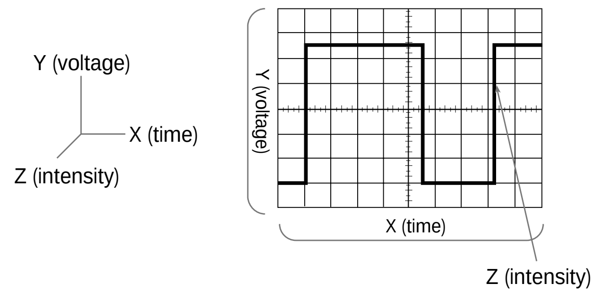

Figure 2. *X, Y, and Z components of a displayed waveform.*

The Oscilloscope

What is an **oscilloscope** and how does it work? This section answers these fundamental questions.

The oscilloscope is basically a graph-displaying device – it draws a graph of an electrical signal. In most applications, the graph shows how signals change over time: the vertical (Y) axis represents **voltage** and the horizontal (X) axis represents **time**. The **intensity** or brightness of the display is sometimes called the Z axis. (See Figure 2.)

This simple graph can tell you many things about a signal, such as:

- The time and voltage values of a signal
- The frequency of an oscillating signal
- The "moving parts" of a circuit represented by the signal
- The frequency with which a particular portion of the signal is occurring relative to other portions
- Whether or not a malfunctioning component is distorting the signal
- How much of a signal is direct current (DC) or alternating current (AC)
- How much of the signal is noise and whether the noise is changing with time

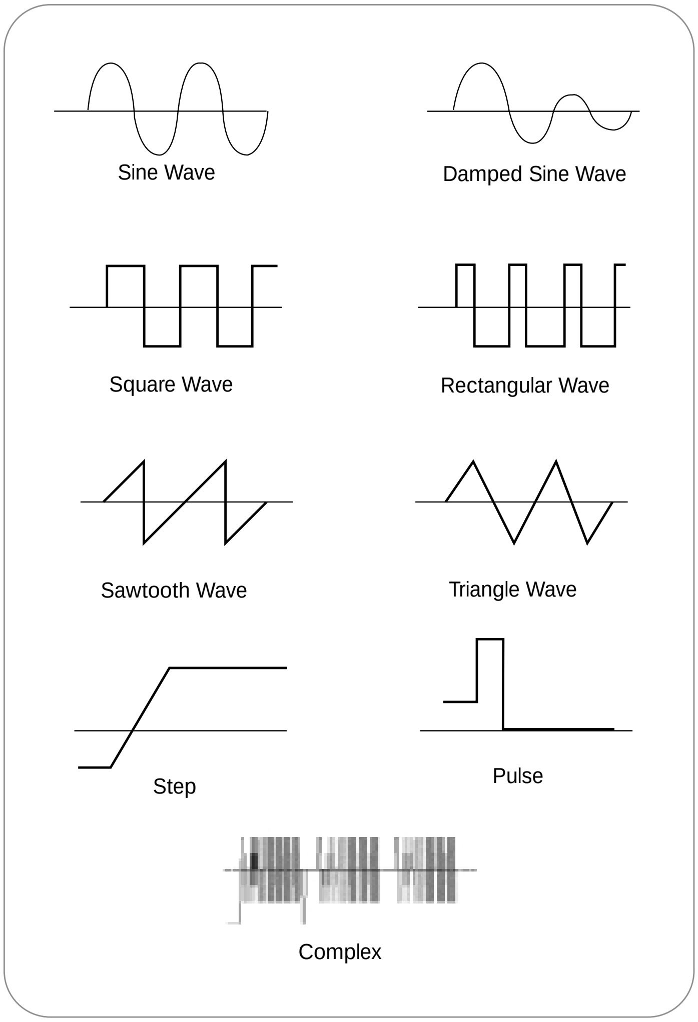

Figure 3. *Common waveforms.*

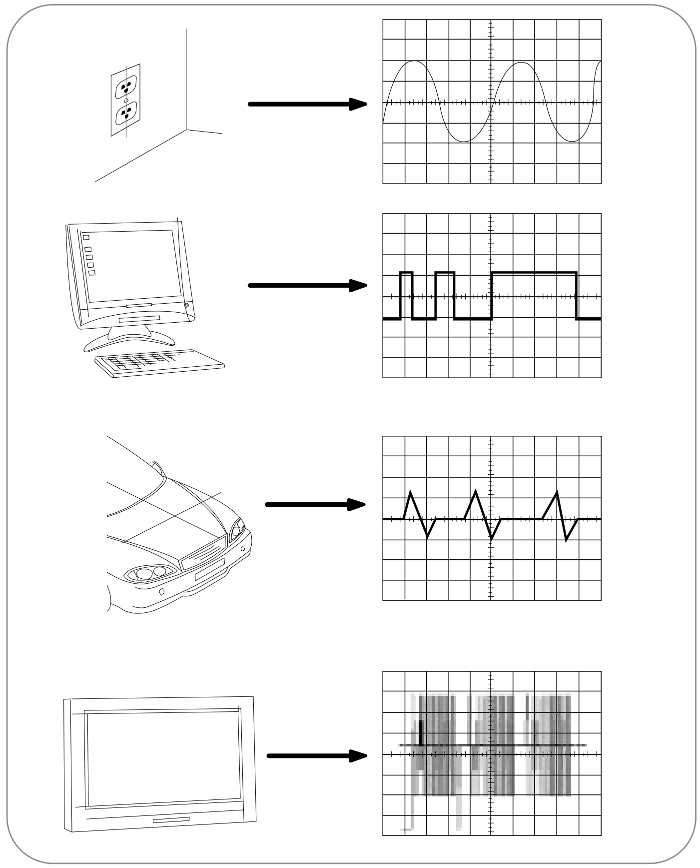

Figure 4. *Sources of common waveforms.*

Understanding Waveforms and Waveform Measurements

The generic term for a pattern that repeats over time is a **wave** – sound waves, brain waves, ocean waves, and voltage waves are all repetitive patterns. An oscilloscope measures voltage waves. One **cycle** of a wave is the portion of the wave that repeats. A **waveform** is a graphic representation of a wave. A voltage waveform shows time on the horizontal axis and voltage on the vertical axis.

Waveform shapes reveal a great deal about a signal. Any time you see a change in the height of the waveform, you know the voltage has changed. Any time there is a flat horizontal line, you know that there is no change for that length of time. Straight, diagonal lines mean a linear change – rise or fall of voltage at a steady rate. Sharp angles on a waveform indicate sudden change. Figure 3 shows common waveforms and Figure 4 displays sources of common waveforms.

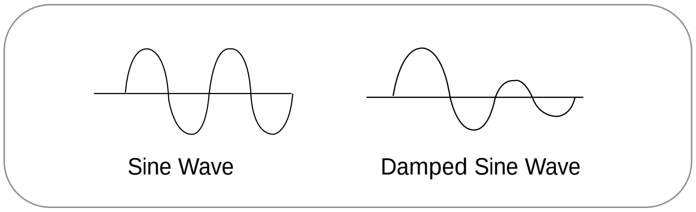

Figure 5. Sine and damped sine waves.

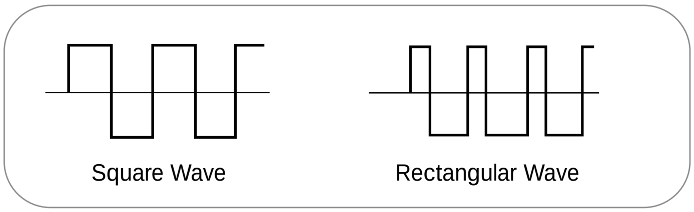

Figure 6. Square and rectangular waves.

Types of Waves

You can classify most waves into these types:

- Sine waves
- Square and rectangular waves
- Triangle and saw-tooth waves
- Step and pulse shapes
- Periodic and non-periodic signals
- Synchronous and asynchronous signals
- Complex waves

Sine Waves

The **sine wave** is the fundamental wave shape for several reasons. It has harmonious mathematical properties – it is the same sine shape you may have studied in high school trigonometry class. The voltage in your wall outlet varies as a sine wave. Test signals produced by the oscillator circuit of a signal generator are often sine waves. Most AC power sources produce sine waves. (AC signifies alternating current, although the voltage alternates too. DC stands for direct current, which means a steady current and voltage, such as a battery produces.)

The **damped sine wave** is a special case you may see in a circuit that oscillates, but winds down over time. Figure 5 shows examples of sine and damped sine waves.

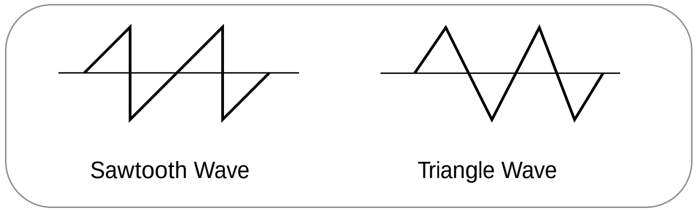

Figure 7. Sawtooth and triangle waves.

Square and Rectangular Waves

The **square wave** is another common wave shape. Basically, a square wave is a voltage that turns on and off (or goes high and low) at regular intervals. It is a standard wave for testing amplifiers – good amplifiers increase the amplitude of a square wave with minimum distortion. Television, radio and computer circuitry often use square waves for timing signals.

The **rectangular wave** is like the square wave except that the high and low time intervals are not of equal length. It is particularly important when analyzing digital circuitry. Figure 6 shows examples of square and rectangular waves.

Sawtooth and Triangle Waves

Sawtooth and **triangle waves** result from circuits designed to control voltages linearly, such as the horizontal sweep of an analog oscilloscope or the raster scan of a television. The transitions between voltage levels of these waves change at a constant rate. These transitions are called **ramps**. Figure 7 shows examples of saw-tooth and triangle waves.

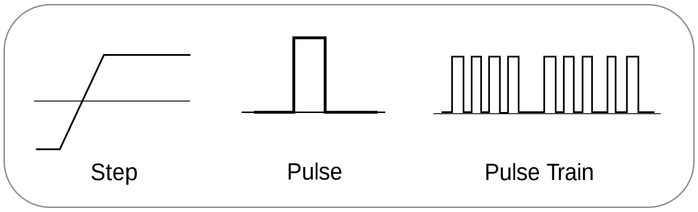

Figure 8. *Step, pulse and pulse train shapes.*

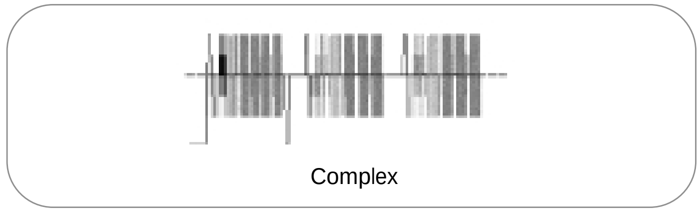

Figure 9. *An NTSC composite video signal is an example of a complex wave.*

Step and Pulse Shapes

Signals such as **steps** and **pulses** that occur rarely, or non-periodically, are called **single-shot** or **transient signals**. A step indicates a sudden change in voltage, similar to the voltage change you would see if you turned on a power switch.

A pulse indicates sudden changes in voltage, similar to the voltage changes you would see if you turned a power switch on and then off again. A pulse might represent one bit of information traveling through a computer circuit or it might be a **glitch**, or defect, in a circuit. A collection of pulses traveling together creates a **pulse train**. Digital components in a computer communicate with each other using pulses. Pulses are also common in x-ray and communications equipment. Figure 8 shows examples of step and pulse shapes and a pulse train.

Periodic and Non-periodic Signals

Repetitive signals are referred to as **periodic signals**, while signals that constantly change are known as **non-periodic** signals. A still picture is analogous to a periodic signal, while a moving picture can be equated to a non-periodic signal.

Synchronous and Asynchronous Signals

When a timing relationship exists between two signals, those signals are referred to as **synchronous**. Clock, data and address signals inside a computer are an example of synchronous signals.

Asynchronous is a term used to describe those signals between which no timing relationship exists. Because no time correlation exists between the act of touching a key on a computer keyboard and the clock inside the computer, these are considered asynchronous.

Complex Waves

Some waveforms combine the characteristics of sines, squares, steps, and pulses to produce waveshapes that challenge many oscilloscopes. The signal information may be embedded in the form of amplitude, phase, and/or frequency variations. For example, although the signal in Figure 9 is an ordinary composite video signal, it is composed of many cycles of higher-frequency waveforms embedded in a lower-frequency **envelope**. In this example, it is usually most important to understand the relative levels and timing relationships of the steps. To view this signal, you need an oscilloscope that captures the low-frequency envelope and blends in the higher-frequency waves in an intensity-graded fashion so that you can see their overall combination as an image that can be visually interpreted. Analog and digital phosphor oscilloscopes are most suited to viewing complex waves, such as video signals, illustrated in Figure 9. Their displays provide the necessary frequency-of-occurrence information, or intensity grading, that is essential to understanding what the waveform is really doing.

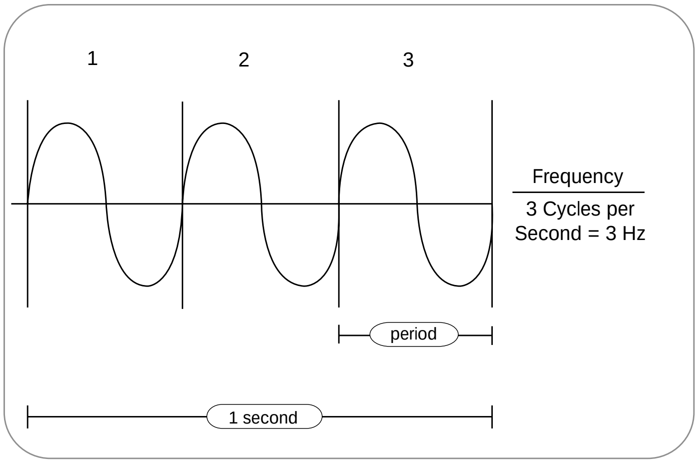

Figure 10. *Frequency and period of a sine wave.*

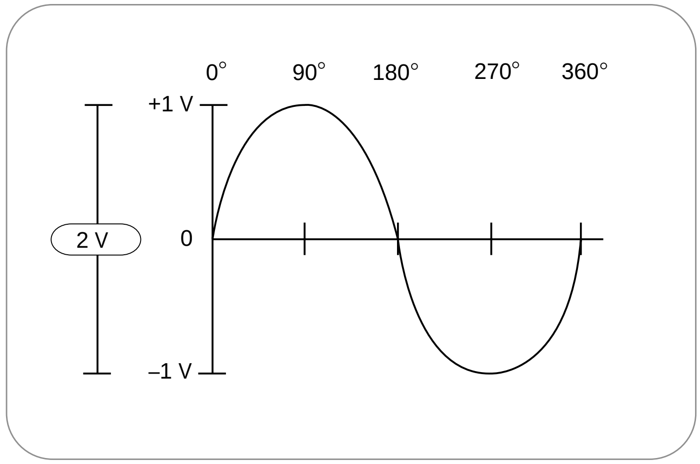

Figure 11. *Amplitude and degrees of a sine wave.*

Waveform Measurements

Many terms are used to describe the types of measurements that you make with your oscilloscope. This section describes some of the most common measurements and terms.

Frequency and Period

If a signal repeats, it has a **frequency**. The frequency is measured in Hertz (Hz) and equals the number of times the signal repeats itself in one second, referred to as cycles per second. A repetitive signal also has a **period** – this is the amount of time it takes the signal to complete one cycle. Period and frequency are reciprocals of each other, so that 1/period equals the frequency and 1/frequency equals the period. For example, the sine wave in Figure 10 has a frequency of 3 Hz and a period of 1/3 second.

Voltage

Voltage is the amount of electric potential – or signal strength – between two points in a circuit. Usually, one of these points is ground, or zero volts, but not always. You may want to measure the voltage from the maximum peak to the minimum peak of a waveform, referred to as the peak-to-peak voltage.

Amplitude

Amplitude refers to the amount of voltage between two points in a circuit. Amplitude commonly refers to the maximum voltage of a signal measured from ground, or zero volts. The waveform shown in Figure 11 has an amplitude of 1 V and a peak-to-peak voltage of 2 V.

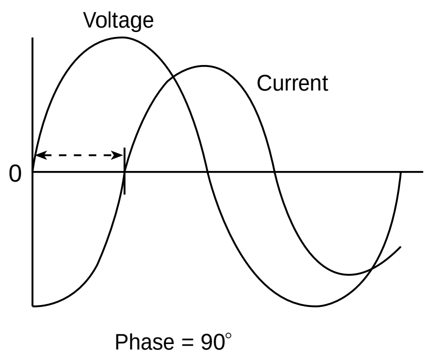

Figure 12. *Phase shift.*

Phase

Phase is best explained by looking at a sine wave. The voltage level of sine waves is based on circular motion. Given that a circle has 360°, one cycle of a sine wave has 360°, as shown in Figure 11. Using degrees, you can refer to the phase angle of a sine wave when you want to describe how much of the period has elapsed.

Phase shift describes the difference in timing between two otherwise similar signals. The waveform in Figure 12 labeled "current" is said to be 90° out of phase with the waveform labeled "voltage," since the waves reach similar points in their cycles exactly 1/4 of a cycle apart (360°/4 = 90°). Phase shifts are common in electronics.

Waveform Measurements with Digital Oscilloscopes

Modern digital oscilloscopes have functions that make waveform measurements easier. They have front-panel buttons and/or screen-based menus from which you can select fully automated measurements. These include amplitude, period, rise/fall time, and many more. Many digital instruments also provide mean and RMS calculations, duty cycle, and other math operations. Automated measurements appear as on-screen alphanumeric readouts. Typically these readings are more accurate than is possible to obtain with direct graticule interpretation.

Fully automated waveform measurements available on some digital phosphor oscilloscopes include:

- Period
- Frequency
- Width +
- Width –
- Rise time
- Fall time
- Amplitude
- Extinction ratio
- Mean optical power
- Duty cycle +
- Duty cycle –
- Delay
- Phase
- Burst width
- Peak-to-peak
- Mean
- Cycle mean
- Cycle area
- High
- Low
- Minimum
- Maximum
- Overshoot +
- Overshoot –
- RMS
- Cycle RMS