

Summary

The following section gives an overview of the basic characteristics of each of the major oscilloscopes probe types. In addition, a number of examples demonstrate how probe misuse can dramatically distort a given type of measurement.

Understanding the Probing Problem

Caution! Connecting your oscilloscope to a circuit or device can distort the measured waveforms.

Should oscilloscopes carry warning labels like this one? Perhaps. Oscilloscopes, like all measuring instruments, are subject to the classic measurement problem -- observability. The simple act of connecting an oscilloscope affects the measurement. It is important for users to understand this interaction and the impact it can have on a measurement. As oscilloscope technology has advanced, the tools and techniques for connecting the instrument to the measured device have become increasingly sophisticated. Early oscilloscopes, with bandwidths measured in 100's of KHz, were often connected to circuits with pieces of wire. Modern oscilloscopes employ a wide variety of connection techniques intended to minimize measurement errors. Users should be familiar with the characteristics and limitations of not only the oscilloscope, but also of the way in which it is connected to the device being measured.

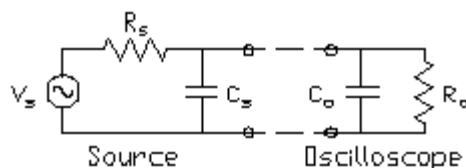


Figure 1: Model of a simple measuring system including a source and an oscilloscope

Consider how the connection of an oscilloscope can affect a measurement. The device being measured can generally be modeled as a Thevenin equivalent voltage source with some internal source resistance and capacitance. Likewise, the oscilloscope input circuits and the interconnections can be modeled as a load resistance with a shunt capacitance. This simple measurement system is shown in figure 1. When an oscilloscope is connected to a source, the loading effects of the

oscilloscope reduce the measured voltage. At low frequencies the loss is dependent on the ratios of the resistor values, R_s and R_o . At higher frequencies the source resistance and the capacitive reactance of C_s and C_o become a major factor in determining the loss. Another effect is the reduction of system bandwidth due to the capacitive loading of the oscilloscope. This also affects the dynamic timing measurements such as pulse risetime.

Oscilloscope designers have sought to minimize these effects by approaching the loading problem from two different points of view.

a. High impedance probes, using both passive and active circuits, are used to minimize loading effects by using either compensated attenuators or low capacitance, field effect transistors (FET) buffer amplifiers.

b. Input circuits with 50 Ohms internal terminations have been added to oscilloscopes for direct connections in high frequency applications. In these applications, most circuits are designed for a constant, 50 Ohms, load impedance. Low capacitance probes, designed to be terminated in 50 Ohms, minimize capacitive loading effects.

Which Probe for Which Application

In general, probes can be divided into three common classes. These are passive high impedance probes, passive low impedance probes and active probes. Each of the probe types offers advantages and disadvantages that should be considered carefully before selecting one for a particular measurement. Table 1 lists the three probe types and shows how they are suited for frequency response and input voltage.

Probe Type	Typical Useful Frequency Range	Typical Maximum Input Voltage
Passive, High Impedance (1 MOhm)	0 to 50 MHz	600 Volts
Passive, Low Impedance (500 Ohms)	0 to 8 GHz	20 Volts
Active	0 to 2 GHz	10 Volts

Table 1: Probe types, usable frequency ranges and input voltages

Unfortunately, knowing a probe's key specification (frequency range and maximum input voltage) is not sufficient for an engineer to select a probe for a given application. In fact, other probe characteristics (such as capacitance, impedance and bandwidth) have dramatic effect on a probe's overall performance. For example, the equivalent impedance of a probe is a function of the input signal frequency. Figure 2 shows the effect for the different probe types.

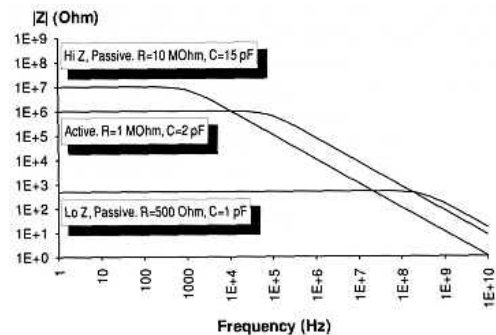


Figure 2: Probe equivalent impedance as a function of frequency. The dynamic characteristics of the probes make them suited to different applications. As a guide, table 2 lists a variety of different logic families and shows which probe type are commonly used

Probe Type	Logic Family
Passive, High Impedance (1 MOhm)	TTL (Standard, Low Power) with rise times > 5 ns CMOS with rise times > 5 ns)
Passive, Low Impedance (500 Ohms)	ECL (10kH, 100 k, ECLinPS) Low Impedance Transmission Lines
Active	Fast TTL (Standard, Low Power, High Speed) Fast CMOS (BiCMOS, FACT, HCMOS, etc.)

Table 2: Common probe types and their typical application

High Impedance Probes

a. General Description

High impedance (Hi-Z) probes are the most commonly used oscilloscope probes. They are available with attenuation factors of 10:1 (X10) and 100:1 (X100) and bandwidths of up to 350 MHz. However, it is important to point out that while the bandwidth may be as high as 350 MHz, in practice high impedance probes are typically used in applications where the signal frequency is below 50 MHz. The poor high frequency performance of these probes is due largely to the adverse effects of capacitance loading. Consider the typical X10 probe shown schematically in figure 3.

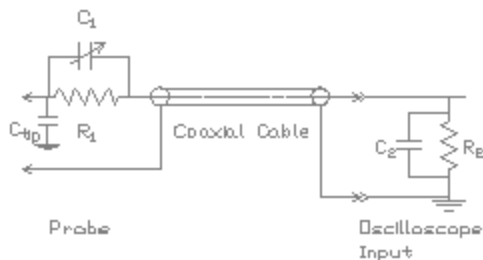


Figure 3: Simplified schematic diagram of a typical, X10, high impedance probe

The impedance input of a typical 300 MHz bandwidth oscilloscope consists of a 1 MOhm resistance in parallel with a 15 pF capacitor. Direct connection of the oscilloscope to a circuit by means of a coaxial cable or X1 probe will add an additional capacitive load, due to the cable, of approximately 50 pF per meter. The combination of the input and cable capacitance is approximately 65 pF. The oscilloscope input impedance is represented in the probe schematic by R_2 and C_2 . Both the oscilloscope and cable capacitances are represented by C_2 . The high impedance probe isolates the measured circuit by adding a large resistor, R_1 in this example, in series with the oscilloscope input. R_1 forms a resistive voltage divider with the oscilloscope input resistance, R_2 . The value of R_1 is set to 9 MOhm for a X10 probe and 99 MOhm for a X100 probe for an oscilloscope input resistance of 1 MOhm. Capacitor C_1 is adjusted so that the RC product, R_1C_1 , equals the product R_2C_2 . This compensates the probe so that it provides the desired attenuation at all frequencies. Therefore, before using any high impedance passive probe, the user should adjust C_1 with a 1 kHz square wave, to seek an optimal compensation. A typical X10 probe has an equivalent input impedance consisting of a 10 M resistance in parallel with 15 pF, where the 15 pF are partly due to the series of C_1 and C_2 and partly to the stray capacitance of the probe tip to ground, C_{tip} .

As previously mentioned, the high impedance probe is best suited for general purpose applications where the signal frequencies are below 50 MHz. These probes are relatively inexpensive and, since they use only passive components, they are mechanically and electrically rugged. In addition, they have a very wide dynamic range. The low end of the amplitude range is limited by the probe attenuation factor and the vertical sensitivity of the oscilloscope. The attenuation does, however, offer advantages in dealing with high level signals up to the maximum input voltage range, typically 600 Volts for 10:1 probes. Mechanically, these probes are available with a variety of convenient cable lengths and are

generally supplied with a wide variety of probe tips, adaptors, and ground leads.

b. How High Impedance Probes Affect Measurements

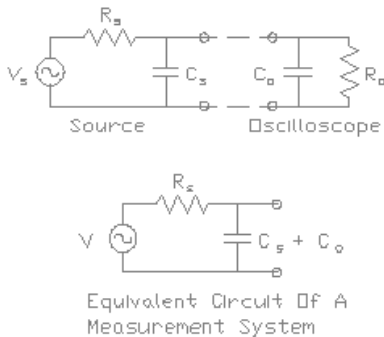


Figure 4: Deriving an equivalent circuit for a measurement system

When an oscilloscope is used to make measurements in a circuit or device, it is advantageous to anticipate how the device being measured is affected by the instrument. In most cases, it is possible to model the oscilloscope's input circuits, including the probes, and to quantify the loading effects and signal aberrations. The user's knowledge of the measured circuit, together with the oscilloscope manufacturer's characterization of the oscilloscope/probe specifications, can be combined to model the entire measurement system.

Consider the simplified measurement system model shown in figure 4. The actual circuits of the oscilloscope and of the high impedance probe have been reduced to an equivalent parallel resistor-capacitor (RC) circuit. Similarly, as was done in a previous discussion, the circuit being measured has been simplified and reduced to its Thevenin equivalent form. If the circuit's source resistance, R_s , is approximately 50 Ohms and the measurement is made using a conventional 10:1 high impedance probe, then it is reasonable to ignore the probe's

10 MOhm resistance, R_o . The equivalent circuit for the system now consists of a series resistance, R_s , and a shunt capacitance, with a value equal to the sum of the source, C_s , and the input capacitance of the probe/oscilloscope, C_o . From this simple model we can predict the effect of the oscilloscope on the risetime of the circuit. Using classical circuit analysis, the risetime, t_r , of this RC circuit in response to a step function input is related to the values of resistance and capacitance by the equation:

$$t_r = 2.2RC$$

The following example, using typical component values, will provide good insight into the effects of using a high impedance probe:

For: $R_s = 50$ Ohms, $C_s = 9$ pF, and $C_o = 15$ pF

The risetime of the source alone, t_{rs} , is:

$$t_{rs} = 2.2 (50) (9 \cdot 10^{-12}) = 1 \text{ ns}$$

The risetime of the source with the probe and oscilloscope connected, t_{ros} , is:

$$t_{ros} = 2.2 (50) (24 \cdot 10^{-12}) = 2.6 \text{ ns}$$

The act of connecting the probe increased the risetime by 160% due to the additional capacitance of the probe.

The additional capacitance also increases the loading on the generator, especially at higher frequencies. The capacitive reactance component of the load impedance varies inversely with frequency as described in the following equation:

$$X^o = \frac{1}{2\pi fC}$$

where the capacitive reactance, X_c , in Ohms, is an inverse function of frequency, f , in Hertz, and capacitance, C , in Farads. A simple calculation using the values from our previous example will show this increased loading. At a frequency of 100 MHz, the load impedance due to the total capacitance of 24 pF is:

$$X_c = \frac{1}{2\pi(100 \times 10^6)(24 \times 10^{-12})} = 66\Omega$$

Obviously, at frequencies above several kilohertz the capacitive loading becomes the major element loading the source. The 10 MOhm input resistance of the high impedance probe only applies at DC. On the basis of these two examples it should be obvious why so much effort is put into lowering the input capacitance of oscilloscope probes.

Another approach to characterize the effects of connecting a probe to a circuit is to consider how it affects the bandwidth of the circuit. The bandwidth of this RC circuit, actually a simple low pass filter, is the frequency at which the output voltage falls to 0.707 of the unloaded source voltage.

The following relationship is used to calculate the bandwidth, BW , in Hz, of this RC circuit, for resistance in Ohms and capacitance in Farads:

$$BW = \frac{1}{2\pi RC}$$

There is another classic equation which relates the risetime, t_r , in seconds, and bandwidth, BW , in Hertz, of this simple RC circuit model:

$$t_s = \frac{0.35}{BW}$$

The last equation is useful because many oscilloscope and probe specifications are described in terms of bandwidth and not risetime.

A knowledge of the risetime of each stage in a multi-stage, cascaded measurement can be used to estimate the composite risetime. The risetime of the composite system is the quadratic sum, i.e. the square root of the sum of the squares of the risetime of each element. For instance, the risetime of a signal shown on an oscilloscope screen, the measured risetime, includes the actual signal risetime as well as the risetime of the measurement system. It is possible, using the following relationship, to calculate the actual risetime of the signal, t_{sig} , based on the measured risetime, t_{meas} , and a knowledge of the system risetime, t_{sys} :

$$t_{sig} = \sqrt{t_{meas}^2 - t_{sys}^2}$$

To see how these equations can be used, consider the following practical example:

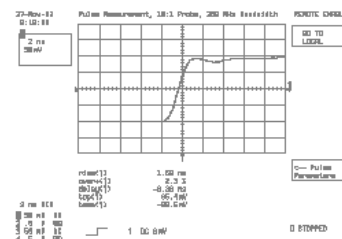


Figure 5: Risetime measurement of an edge

Low Capacitance Probes

A pulse risetime measurement is made with an oscilloscope using a 10:1 probe which has a bandwidth at "the probe tip" of >250 MHz. The goal is to estimate the actual risetime of the signal. The oscilloscope's parameter readout provides the measured value, as shown in figure 5. The oscilloscope manufacturer's specification provides a composite risetime for both the oscilloscope and the probe (assuming a 25 source impedance), combining both into a single value. The signal risetime can be estimated as follows:

$$t_{meas} = 1.69 ns$$

$$t_{sys} = \frac{0.35}{250 * 10^6} = 1.4 ns$$

$$t_{sys} = \sqrt{t_{meas}^2 - t_{sys}^2} = \sqrt{(1.69 * 10^{-9})^2} = 0.95 ns$$

Since the bandwidth of the oscilloscope and probe combination was only specified as a limiting value, i.e. >250 MHz, the calculated value is a lower limit. If a signal with known risetime and source impedance is measured, then it is possible using the same relationship, to determine the bandwidth of the oscilloscope "at the probe tip".

The dynamic performance of the high impedance probe is easily determined using the preceding equations. Keep in mind that these equations provide the first order estimation of a probe's behavior. In the last chapter, second order effects such as stray inductance in ground leads, will be discussed.

a. General Description

Another passive probe is the low capacitance or low impedance (Low-Z) probe. These probes are designed to provide 10:1 attenuation into an oscilloscope's 50W input termination. Where the high impedance probe uses capacitive compensation to provide flat frequency response with minimum capacitive loading, the low capacitance probe uses transmission line techniques to achieve extremely wide bandwidth with very low capacitance. A typical low capacitance probe is shown schematically in figure 6.

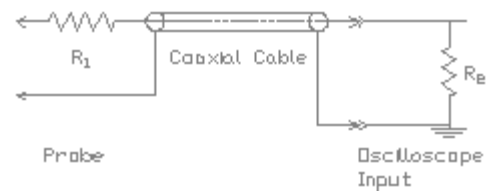


Figure 6: Simplified schematic diagram of a typical, X10, low capacitance probe

The oscilloscope input resistance, R_2 , provides a matched termination for the low loss coaxial cable. Ideally, the terminated cable presents a pure, 50W, resistive load to the input resistor, R_1 , at all frequencies. The probe input resistance and attenuation ratio is determined by the series resistor, R_1 . For a 10:1, 500W probe, its value would be 450W. Special care is taken in the mechanical design of these probes to minimize parasitic reactances. With careful design, the low capacitance probes have usable bandwidths to 8 GHz, risetimes of 50 ps, and an input capacitance of 0.5 pF. Since these probes are optimized mechanically for high frequency operation they do not offer any choice of probe tips or ground connections.

Low capacitance probes should be used for wide bandwidth or fast transient measurements in circuits that can drive 50W load impedances. For these applications, low impedance probes offer excellent frequency response and a relatively low cost. Another advantage of low impedance probes is that they do not require compensation to match the oscilloscope.

b. How Low Capacitance Probes Affect Measurements

A typical low capacitance probe provides 10:1 attenuation with an input capacitance of 1 pF and an input resistance of 500W. The relatively low input resistance of these probes restricts their use to measurement situations where the devices or circuits being investigated are designed to work in 50W loads. It is important to keep the low resistance of these probes in mind when using them. Consider the situation illustrated in the following figure:

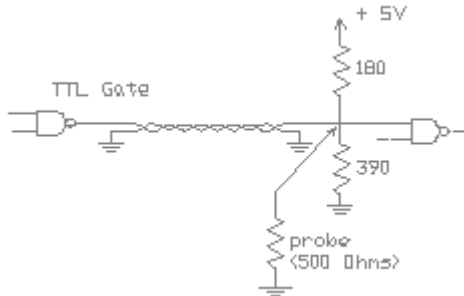


Figure 7: An example of poor probing technique using a low capacitance probe

Figure 7 shows a TTL logic gate being used to drive a transmission line. The line with 120W characteristic impedance is terminated by a resistor network which biases the gate at approximately 3.5 V. This type of termination is used because TTL can only source a few milliamps of current in the high state and the biasing helps increase noise immunity. If a 500 W, 10:1 probe is used to measure the signal at the receiving end it lowers the termination resistance to about 98 W and drops the bias to 2.7 Volts.

The probe loading reduces the noise immunity of the circuit and may cause it to behave intermittently. This type of measurement is best made with a low capacitance probe which will not degrade the line termination conditions. Table 3 lists the error in the measured voltage as a function of the input resistance of the probe, for the circuit shown above:

Probe Input Resistance	Measured Voltage	Error
500 W	2.7	20%
1000 W	3.0	11%
5,000 W	3.3	2%
10,000 W	3.38	1.2%
1 MW	3.41	0.1%

Table 3: Voltage error due to loading effects

While the user must be aware of the problems related to the use of low capacitance probes, this should not limit the general use of these probes in appropriate applications. These probes are well matched to measuring low impedance circuits found in power supplies, RF amplifiers, line drivers, and similar applications.

Many of the applications where low capacitance probes are used involve circuits which drive transmission lines. A common problem in such measurements is waveform distortion due to signal reflections or standing waves caused by improper termination. This is not a problem related to the probes, unless the probe itself is improperly terminated, but it occurs frequently enough to warrant discussion.

A transmission line terminated with a resistive load equal to the line's characteristic impedance is said to be "matched". A matched line has a driving point impedance which is independent of the line's length and equal to the characteristic impedance. So, a length of RG-58, a 50 W coaxial cable, terminated with 50 W, represents a purely resistive load to the circuit which drives it. If a transmission line is not terminated properly then it can distort an applied signal in a variety of ways. If the signal is continuous, the voltage and current will vary with distance along the line, resulting in a standing wave pattern. Driving such a line with transient signals, like step and pulse waveforms, results in signal reflections. The amplitude and timing of the reflected signals varies with the degree of mismatch and the length of the line. Reflected signals combine with the applied signal to produce highly distorted waveforms. The following figures show a measurement setup for observing distortion due to reflections and some typical types of distortion:

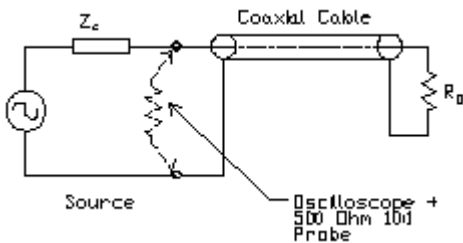


Figure 8: A measurement setup for observing signal distortion due to reflections.

Figure 8 shows a measurement setup where the variance of the termination resistor, R_0 , controls the amplitude and polarity of the reflected signal. The signal source generates a 1 MHz square wave with 1 ns transitions. The source impedance, Z_s , is set to match the cable's characteristic impedance, 50W. The oscilloscope, using a 10:1, 500W probe, is connected to the driving point of the cable.

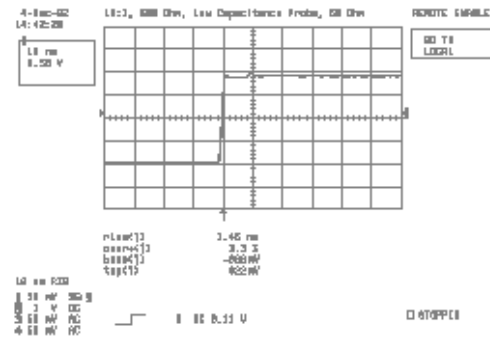


Figure 9: Waveform measured with a properly terminated coaxial line

Figure 9 shows the waveform measured with a properly terminated line. The pulse parameters listed at the bottom of the display show the top and base amplitudes of the pulse, as well as the risetime and positive overshoot. This is the desired waveform.

When a transmission line is not terminated in its characteristic impedance, then transient signals, such as step or pulse waveforms, are reflected from the cable end. The amplitudes of the reflected wave, V_r , and the incident wave, V_i , are related by the following equation:

$$\frac{V_r}{V_i} = \Gamma_r = \frac{(R_0 - Z_0)}{(R_0 + Z_0)}$$

Where R_0 is the termination resistance, Z_0 is the characteristic impedance of the cable, and T is the reflection coefficient of the termination.

In the examples that follow, three values of R_0 will be used, $R_0 = 0$ (a short circuit), $R_0 = \infty$ (an open circuit), and $R_0 = 75 W$. This will result in reflection coefficient values of -1, +1, and +1/3, respectively.

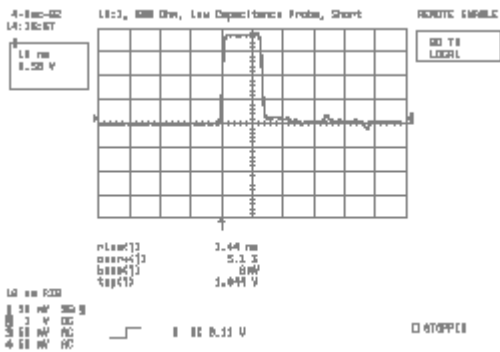


Figure 10: Reflection caused by a shorted cable

A shorted cable results in a reflection coefficient of -1. A step waveform with an amplitude of +1.8 Volts is reflected as a step with an amplitude of -1.8 Volts. The timing of the reflection depends on the length of the cable. The propagation delay of RG58, used in this example, is about 1.5 ns/foot. The delay between the incident and reflected wave is about 12 ns for the 4 foot cable length used. This can be observed in the width of the measured pulse (figure 10). Note that the original square wave edge has been distorted by the reflected wave into a narrow pulse. This is repeated for the negative-going edge, resulting in a negative pulse with the same width.

An open termination results in a reflected wave of the same amplitude and polarity. The reflected wave adds a second, delayed transition to the waveform. This produces the stair-step appearance in the resulting measured waveform (figure 11).

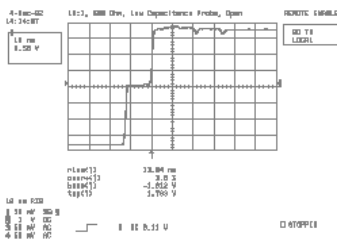


Figure 11: Reflection caused by an open circuit

When the termination is changed to 75 W, the size of the reflected wave is reduced in amplitude to 1/3 of the incident step size. This results in the waveform shown in figure 12.

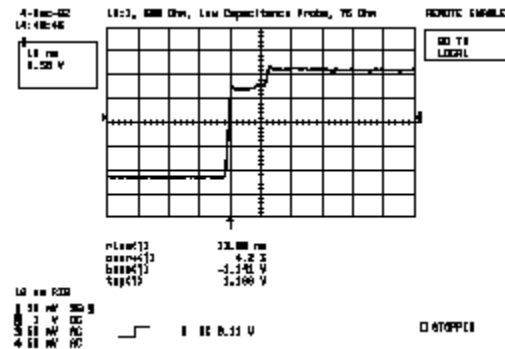


Figure 12.: Reflection caused by 75 ohm termination

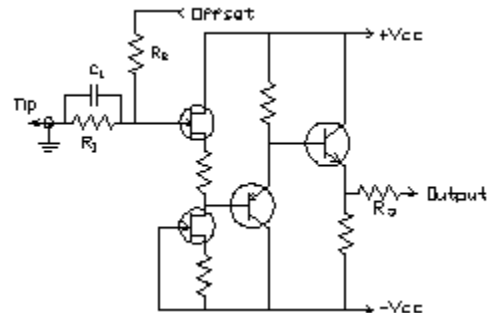


Figure13: Simplified schematic of a typical active (FET) probe

It is important to keep in mind that improperly terminated transmission lines can cause waveform distortion. Low capacitance probes, which use the characteristics of the transmission line to reduce input capacitance, must work in the specified load impedance, typically 50W. Impedance matching between the probe and oscilloscope is of paramount importance. As a result, low impedance probes should only be used with high bandwidth oscilloscopes that have good 50 W termination.

Active (FET) Probes

For applications that require high impedance and high frequency measurement (up to 2 GHz) the active probe is a vital tool. Active probes use the high input impedance of a field effect transistor amplifier to buffer the probe tip from the oscilloscope input. A typical active probe provides 1:1 voltage gain with an input resistance of 1 MW, input capacitance of 2.2 pF, and a bandwidth of 1 GHz. A simplified schematic of an active probe is shown in figure 14:

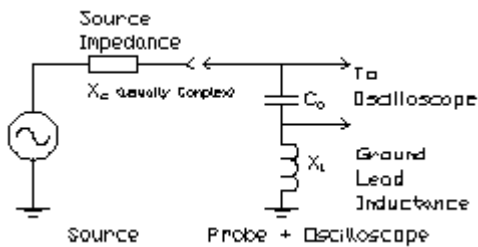


Figure 14: Measurement model including ground lead inductance

The key element in the probe is a field effect transistor configured as a source follower. This stage is followed by complementary bipolar transistors wired as emitter followers. The FET stage provides a very high input resistance, typically $> 10^{11}$. The probe's input resistance and capacitance are determined by the resistors R1 and R2, which, with C1, form a compensated attenuator. Note that provision is made for adjusting the offset voltage by applying a bias voltage through R2. The output resistor, R3, back terminates the output in 50 W and protects the output stage against accidental short circuits.

Active probes require a power source and have a more restricted dynamic range than passive probes. In fact, a major drawback with high bandwidth active probes is that they are easily damaged by over-voltage. Since active probes are much more expensive than their passive counterparts, users should be careful to ensure that they avoid this

problem. In practice, active probes fill the niche between high impedance probes and the low capacitance probes. Operating bandwidths of up to 2 GHz are supported with relatively high input impedance and the ability to drive relatively long cables. This latter capability, together with the ability to adjust offset and coupling at the probe tip, makes them ideal for ATE environments where the measuring instruments may be located at some distance from the device under test.

Probe Grounding and Waveform Fidelity

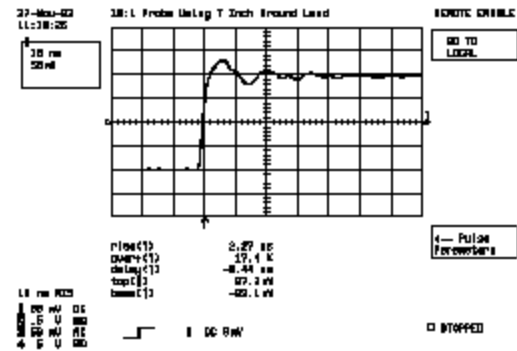


Figure 15: Measurement using a 10:1 probe with a 7 inch ground lead

As the frequency of measurements increases, the secondary effects such as probe ground lead inductance begin to have an effect on the measured waveform. The effects of ground lead inductance vary with both the inductance, related to the lead type and length, as well as the signal frequency content. Consider the simplified model in figure 15 which shows how ground lead inductance impacts a measurement. The probe ground lead provides a return path for the signal being measured. The ground lead inductance is a function of the lead geometry. A conventional wire lead contributes about 25 nH/inch, or 10 nH/cm. The inductance of a typical 10:1, high impedance probe ground lead is about 100 - 150 nH. This inductance, in series with the combined probe capacitance forms a series resonant circuit. For a typical probe capacitance of 15 pF, a 7 inch ground lead would provide 175 nH

resulting in a series resonant frequency of approximately 98 MHz. If the signal being measured has content at or near that frequency it will result in "ringing" and other wave shape aberrations. The next figure shows an actual measurement using a probe with a 7 inch wire ground lead. A LeCroy 9314 with a guaranteed bandwidth of 250 MHz at the probe tip was used for this measurement. The signal source was a 1 MHz square wave with a 1 ns risetime.

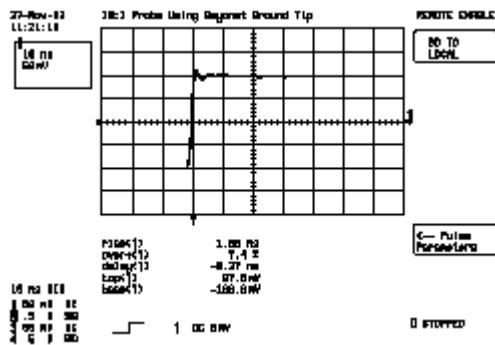


Figure 16: Measurement using a 10:1 probe with a bayonet ground lead

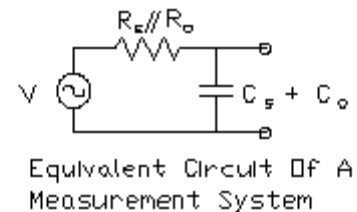
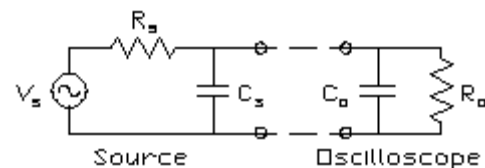
Note that there is an obvious overshoot and ringing on the waveform measured using the 7 inch ground lead (figure 16). The oscilloscope's pulse parameter readout of positive overshoot, over+, indicates an overshoot of 17.4%. A more subtle problem is that the measured risetime is 2.27 ns, somewhat greater than expected. A simple way to avoid this sort of error is to reduce the inductance of the ground lead. Shortening the lead will have the greatest effect. Figure 16 documents the result of replacing the long ground lead with a much shorter "bayonet" style ground lead. The reduced ground lead inductance is manifested in reduced overshoot, faster settling time, and a more reasonable risetime.

Conclusion

With modern electronics using faster analog and digital circuitry, the use of probes is becoming more complicated. As signal frequencies go higher, the effects of loading a circuit by touching it with a probe are more complicated. Engineers need to consider how they can minimize these adverse effects by ensuring that suitable probes and good probing technique are used in each different application. In addition, attention must be given to any necessary probe adjustments, in particular the impedance matching with the oscilloscope.

Helpful Equations For Probe Users

Calculating the Bandwidth and Risetime of Measurement Systems:



C_s Source capacitance in Farads

C_o Input capacitance of the oscilloscope or probe, in Farads

R_s Source resistance, in Ohms

f Source frequency, in Hertz

t_{xxx} Risetime, in seconds

BW Bandwidth (-3 dB), in Hertz

Risetime, tr:

$$t_r = 2.2R_s(C_s + C_0)$$

Bandwidth, BW:

$$BW = \frac{1}{2\pi R_s(C_s + C_0)}$$

Risetime as a Function of Bandwidth:

$$t_r = \frac{0.35}{BW}$$

Determining the System Risetime from the Risetimes of the Oscilloscope and the Probe:

$$t_{sys} = \sqrt{t_{probe}^2 + t_{scope}^2}$$

Estimating the Signal Risetime from the Risetimes of the Measured Signal and System:

$$t_{sig} = \sqrt{t_{meas}^2 - t_{sys}^2}$$

Calculating Signal Attenuation as a Function of Frequency:

$$Attenuation = \frac{1}{\sqrt{1 + (2\pi f R_s(C_s + C_0))^2}}$$