Oscilloscope Probes:Theory and Practice

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1 Introduction

Measuring an electrical signal inevitably affects that signal. This applies to *all* measurements, including the display of an oscilloscope waveform. Affecting the signal cannot be totally eliminated, but it can be minimized sufficiently that the effect is unimportant. Then the measured result is a sufficiently accurate representation of the real signal.

It is therefore critical for the measurement engineer to understand the effect of the instrument on the signal.

A x10 scope probe (figure 1) is useful in several applications:

- To reduce *loading effect* on the circuit under test

- To compensate for the effect of test cable capacitance

- To permit the measurement of large voltages

The paper discusses these applications in detail. For those who wish to skip the explanations, the results are summarized in section 8 on page 4.

Figure 1: PK-8100 Oscilloscope Probe

2 Example: Voltmeter Loading Effect

Consider the circuit of figure 2, one volt in series with a resistance of 1MΩ. (That is, the *Thevenin Equivalent* is a circuit with an open-circuit voltage of 1 volt, and an internal resistance of 1MΩ.) Suppose an ideal voltmeter, which presents an open circuit to the measurement circuit, is used to measure the voltage. There is no current through an ideal voltmeter, so there is no voltage drop in the resistor, and the voltage at the terminals of the voltmeter is 1 volt. The voltmeter shows a reading of 1 volt, the correct result.
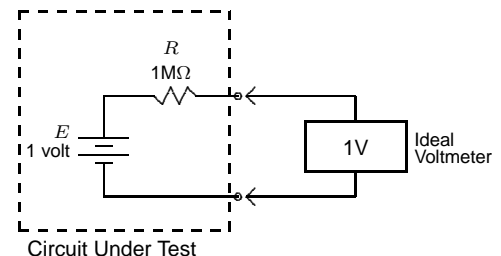

Figure 2: Loading Example 1

Now consider figure 3. The same measurement is attempted with a voltmeter that presents a load of say, 2MΩ to the circuit. Then the 1MΩ internal resistance and the 2MΩ voltmeter resistance R_{meter} form a voltage divider and the meter reading will be 0.666 volts. This is a misleading result caused by the *loading effect* of the voltmeter.

Back in the days of moving-coil meters loading effect was a major issue: moving coil meters require significant current to operate so their relatively low resistance compromised the voltage reading. These days, most electronic voltmeters appear as a very large input resistance, and loading effect isn't an issue.
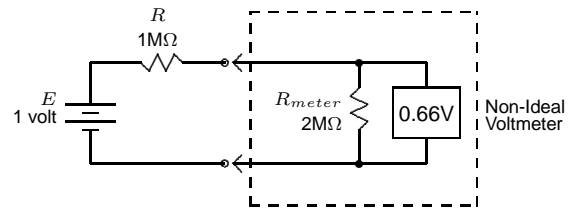

Figure 3: Loading Example 2

3 Loading Effect and The Oscilloscope

The input circuit of a general-purpose oscilloscope consists typically of a 1MΩ resistor in parallel with a small capacitance, perhaps 30pF [1].

Let's consider the effect of this 1MΩ resistance in parallel with 20pF of capacitance (the input impedance of the Syscomp DSO-101 oscilloscope).

At low frequencies, the capacitance appears as an open circuit, so the input resistance is on its own. To make an accurate measurement, we must ensure that the source resistance (the Thevenin resistance of the circuit) is much less than 1MΩ. For example, to obtain 1% accuracy, the source resistance must not exceed 10kΩ.

Now consider the situation at a high frequency. At 2MHz, a 20pF capacitor has an impedance of approximately 4000Ω. For an accurate amplitude measurement,

Figure 4: Coaxial Test Lead

the source resistance must be much less than this. In many situations, that's not going to be the case.

In the frequency domain, a signal that is flat over the frequency range of interest would appear to decrease at high frequencies. In the time domain, the edges of a pulse waveform would show excessive rise and fall times.

4 Coaxial Test Lead

In addition to the input capacitance of the scope, a coaxial test lead (figure 4) has significant capacitance. Coax has the advantage that it shields the measurement signal from electrostatic interference, but it does have an inherent capacitance. For example, RG58/8 coax has a capacitance of 26.4pF/ft. A three foot length of this coax, plus the

[1]Some oscilloscopes are equipped with - or have the option of - a 50Ω input resistance. This is far too low a resistance for general purpose work. It's intended for applications where the oscilloscope input must present a 50Ω input resistance to match a 50Ω transmission line. Matching the impedance of the measurement circuit prevents reflections at the oscilloscope input connector.

20pF input circuit capacitance of the oscilloscope, present the circuit with a total load of 100pF. At a frequency of 2MHz, the input impedance is about 800 ohms. This is *significant* capacitive loading: it may even cause the circuit to malfunction[2].

5   Reducing Loading: The x10 Scope Probe

The electrical equivalent circuit of the x10 scope probe shown in figure 1 on page 1 is a 9MΩ resistor in parallel with a small adjustable capacitor, shown as R_p and C_p in figure 5.

At low frequencies, where we can ignore the effect of the circuit capacitances, the 9MΩ probe resistance and 1MΩ scope input resistance are in series and present the circuit under test with a total resistance of 10MΩ. *The x10 probe reduces the resistive loading on the circuit by a factor of 10.*

Now, what will be the value of the adjustable capacitance in the probe? We can get that by the following reasoning: in order for the frequency response to be flat, the ratio of the probe impedance to the input impedance must be constant over frequency. That is, the probe capacitive reactance must be 9 times the scope input capacitive reactance. Now capacitive reactance is inversely proportional to capacitance, so the probe capacitance is $20/9 = 2, 2$pF. The measurement circuit sees a total capacitance C_t formed by the two capacitors in series.
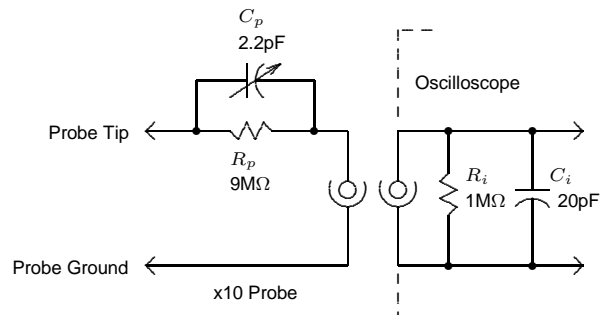

Figure 5: x10 Probe Circuit

$$\frac{1}{C_t} = \frac{1}{C_{in}} + \frac{1}{C_{probe}}$$

from which $C_t = 2$pF.

The x10 probe reduces the capacitive loading by a factor of ten.[3]

(This relationship is shown in analytical form in equation 6 of the appendix on page 7.)

As a by-product, the probe impedance and the oscilloscope input impedance function as a frequency invariant (flat frequency response) voltage divider which reduces the signal amplitude by a factor of 10. For large and medium amplitude signals, one can simply increase the scope vertical scale factor by 10 to compensate. However, very small signals may be attenuated out of sight.

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[2]If you're lucky, it will cause a malfunctioning circuit to start working, but that contravenes Murphy's Law.

[3]This is a simplified analysis that ignores the effect of the capacitance of the probe cable. In fact, the capacitive load is not as low as this simplified theory would indicate, but it is less than it would be for an ordinary coaxial cable connected to the oscilloscope. For example, in the PK-8100 ×10 probe of figure 1 , the capacitance presented to the circuit is 15pF. This compares to something like 100pF for an ordinary coax cable directly into the scope.

6 Probe Compensation

The compensation capacitance (C_p in figure 5) of the $\times 10$ probe must be adjusted to suit the input capacitance of the oscilloscope. This requires adjusting the compensation each time the probe is moved to a different scope. To compensate the probe, it is driven with a square wave[4]. The resultant scope display will appear as one of the three waveforms in figure 6.

The upper display is *under-compensated*; the compensation capacitance is too small. In the lower display, it is *over-compensated*, the compensation capacitance is too large. The centre display is the Goldilocks version: just right.

These square waves indicate the response of the probe over a range of frequencies. The upper waveform, with its undershoot, corresponds to a depressed high-frequency response. The lower waveform corresponds to an emphasized high-frequency response. The centre waveform corresponds to a flat frequency response.

The compensation capacitance may typically be found in one of three locations:

Figure 6: Probe Compensation Adjustment

- As a screwdriver adjustment in the body of the probe (visible as the small dot on the probe body in figure 1).

- As a screwdriver adjustment in the base of the probe cable, where the cable plugs into the scope.

- As a coaxial capacitor adjustment in the probe. In this case, the probe body includes a locking ring, which is rotated to unlock the compensation adjustment. Part of the probe is then rotated to adjust the probe compensation. When the compensation is correct, the locking ring is re-tightened.
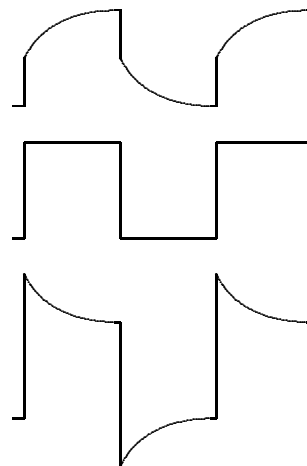
7 Caution: The $\times 1/\times 10$ Switch

Many oscilloscope probes include a $\times 1/\times 10$ switch. This is convenient, but it must be understood that *the resistive and capacitive load on the circuit increase significantly in the $\times 1$ position*. As well, the compensation capacitance has no effect in the $\times 1$ position.

For example, the PK-8100, 100MHz scope probe presents a load capacitance of 15pF to the circuit in the $\times 10$ position and 46pF plus the scope input capacitance (for a total of something in the order of 70pF) in the $\times 1$ position.

8 Summary: When to Use a Scope Probe

You should use a scope probe for measurements when:

- The circuit impedance is approaching the input impedance of the scope, or

- The measurement includes high frequencies or fast edges and it's important to measure these accurately, or

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[4]On the DSO-101 scope, this squarewave must be provided by a signal generator. On some oscilloscopes, a suitable square wave is provided at a front-panel test point labelled *Cal* or *Probe*.

- The input capacitance of the scope causes the test circuit to malfunction. (This is frequently the case for circuits operating at radio frequencies. An RF oscillator will change frequency or simply stop operating.)

- You need to minimize the length of the ground return lead, or

- The measurement voltage exceeds the range of the scope.

You do not need a scope probe – and can use two separate leads or a shielded test cable (figure 4) – when:

- The circuit impedance is much less than the input impedance of the scope, and

- The frequencies being measured are low or accurate measurement of rise time is not important, and

- The signals are large enough that introduction of noise into the circuit via a long ground lead is not a problem, and

- The signal magnitude is not too large to display on the scope.

9 Grounding the Scope Probe

The oscilloscope measurement circuit must be complete: there must be a return path to the circuit common (aka *ground*).

There are a variety of ways that the ground may be connected. In order of increasing effectiveness:

1. **Power Line Ground** In this case, the operator has thrown away the probe ground lead as an unnecessary nuisance. The scope probe is connected into the circuit at the measurement point without a ground lead. The circuit common is somehow connected to the power-line ground. Perhaps the circuit power supply has a third (green) terminal (the power-line ground) and the circuit common is connected to that. The oscilloscope also connects to the power-line ground, and that completes the measurement circuit.

   This is a terrible measurement setup, for several reasons:

   (a) The measurement circuit is a large loop (sometimes referred to as a *ground loop*) and this will tend to act as an inductive pickup for noise

   (b) The large measurement loop and its inductance result in terrible transient response so square waves are badly distorted, showing spurious overshoot and ringing.

   (c) Power-line currents, in the power ground connection in the length of wire between the power supply ground and oscilloscope ground, create a noise voltage that is superimposed on the measurement.

2. **Separate Ground Wire to Scope** The circuit common is connected by a separate wire to the oscilloscope. This might go from the common terminal on the power supply to the ground terminal on the oscilloscope.

   Again, this is a very poor measurement setup. It eliminates the problem of noise due to power-line currents, but it retains the disadvantages of poor transient response and serious inductive noise pickup because of the large area in the measurement loop.

3. **Probe Ground Clip** The probe ground clip can be seen in the photo of figure 1 as a short wire with an alligator clip at the end. In this ground arrangement, the clip is attached to a ground point in the vicinity of the measurement point. Now the measurement circuit loop is reduced to a small area which includes the scope probe and the ground clip wire.

   This measurement setup is adequate for many applications. However, if you notice that moving the ground clip wire changes the shape of the scope waveform or has some effect on the amount of noise pickup, then the measurement loop is having an effect.

4. **Probe Ground Ring** In the photo of a scope probe in figure 1 can be seen a silver ring in the vicinity of the probe tip. This ring is at ground potential and the ultimate ground connection is at this point. This arrangement is not the most convenient, but it can be accomplised by wrapping stiff wire around the ground ring and then connecting that ground wire into the circuit with the shortest possible wire length. Some authors suggest using a knife blade to connect the scope ground ring to a circuit ground. For a permanent test point, there are sockets that receive the scope probe and simultaneously connect the ring to a circuit ground.

It helps to have a strong suspicion of all measurements. Ask the question: is this waveform what is really happening in the circuit or is some or all of it an artifact of the measurement setup?

10 Resources

Syscomp DSO-101 PC-Based Oscilloscope
`www.syscompdesign.com`

Measurement Concepts: Probe Measurements
Walter E.McAbel, Tektronix, 1969
A definitive work on oscilloscope probes.

11 Appendix: Compensation Analysis

The x10 probe of figure 5 on page 3 has the equivalent circuit shown in figure 7.

The upper part, which we'll call Z_1, represents the x10 probe and is composed of $R_1 \parallel C_c$. (C_c is the adjustable *compensation* capacitance).

The lower part Z_2 represents the input circuit of the oscilloscope and is composed of $R_2 \parallel C_l$. We'll use the shorthand symbol s to represent $j\omega$, where $\omega = 2\pi f$ and f is the frequency.

Then the voltage division ratio K (the ratio of output to input signal) is equal to

Figure 7: The Compensated Divider

$$K = \frac{Z_2}{Z_1 + Z_2} \qquad (1)$$

where

$$
\begin{aligned}
Z_1 &= R_1 \parallel 1/sC_c \\
&= \frac{R_1}{1 + sR_1C_c}
\end{aligned}
\qquad
\begin{aligned}
(2) \\
(3)
\end{aligned}
$$

and

$$
\begin{aligned}
Z_2 &= R_2 \parallel 1/sC_l \\
&= \frac{R_2}{1 + sR_2C_l}
\end{aligned}
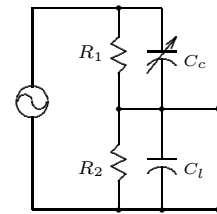\qquad (4)
$$

Substitute for Z_1 and Z_2 in equation 1:

$$
\begin{aligned}
K &= \frac{\dfrac{R_2}{1 + sR_2C_l}}{\dfrac{R_1}{1 + sR_1C_c} + \dfrac{R_2}{1 + sR_2C_l}} \\
&= \frac{R_2(1 + sR_1C_c)}{R_1(1 + sR_2C_l) + R_2(1 + sR_1C_c)}
\end{aligned}
\tag{5}
$$

If we make adjust the compensation capacitance C_c so that

$$
R_1 C_c = R_2 C_l \tag{6}
$$

(that is, the divider is *compensated* correctly) then equation 5 simplifies to

$$
K = \frac{R_2}{R_1 + R_2} \tag{7}
$$

which is independent of frequency, since it contains no s terms.

Put another way, the compensated divider has a flat frequency response and it will reproduce a waveform without distortion.

12   Appendix: Oscilloscope Input Capacitance

If oscilloscope input capacitance is a problem, why don't scope manufacturers design lower capacitance input circuits? One issue is noise.

The voltage noise generated in a resistor due to thermal agitation is given by

$$
e_n = \sqrt{4kTBR} \tag{8}
$$

where the quantities are:

e_n voltage noise, rms volts
k Boltzmann's constant, 1.38×10^{-3}
T absolute temperature, kelvins (293 for $20°$)
B measurement bandwidth, Hz
R resistance, ohms

For a 1MΩ resistor connected into an amplifier with 20MHz bandwidth, the voltage noise e_n is about 0.5mV. This sets a lower limit to the measurement sensitivity of the scope.

Now consider the effect of a capacitor of 20pF across this 1MΩ resistor. The capacitor acts as path for noise current at high frequencies, reducing the effective noise bandwidth to 8kHz.Then the voltage noise at the input of the amplifier drops to 11μV.

The tradeoff is the low impedance of the capacitor presented to the measurement circuit.

Acknowledgement