Hands-on Homework 1: Making Oscilloscope Measurements

Introduction

Being able to correctly and efficiently use an oscilloscope ("scope") is an indispensable skill for an electrical engineer. Initially, scopes seem complicated and can be difficult to use, but with a few hours (yes, hours) of practice and some explanation, they become arguably the most powerful tool for debugging and design in the lab. In skilled hands, the scope can unveil a subtle bug in one glance compared with hours of repeated component substitution, simulation, or printf statements.

The focus of this exercise is to become proficient with making basic measurements with the oscilloscope. Two to three hours should be adequate if you are prepared. The approach will tend more towards “twisting knobs” than reading a tedious operating manual. But, you must twist knobs intelligently, not randomly hoping you can get the right picture. At some point however, you probably will need to consult the manual.

In this exercise, there is a representative scope picture for most of the measurements you make. This way, you will know if you are making the measurement correctly. If your scope picture is not right, figure out why, don’t guess.

This exercise will also make clear the importance of proper probing technique. If probing your circuit changes its behavior or does not faithfully present the signal to the scope, the measurement is worse than worthless. It can lead you on a “wild goose chase” for days or miss a simple malfunction.

As part of this exercise we build a circuit to take measurements on. The crystal oscillator and voltage regulator will be used to provide the transient stimulus and supply voltage for most of our transmission line circuits.

Rapid Prototyping Using Ugly Construction

We will build our circuits using a method called ugly construction. In this method, circuits are built directly on the top of an unetched copper clad board (also called a “PCB”). The copper surface serves as both circuit ground and mechanical mounting point for the components. Parts without ground connections are supported by other parts that do.

There are many advantages to building circuits this way. More importantly, for our experiments the solid copper ground-plane provides a nearly perfect low-impedance ground. The copper plane has so little resistance or inductance that circuits built with care will work to 1 Ghz and beyond. It is not uncommon for ugly prototype circuits to outperform those on a finished printed circuit board due to the lack of parasitic capacitance effected by three-dimensional wiring.
If you doubt the usefulness of this technique, refer to the excellent application note AN-47 written by the late Jim Williams of Linear Technology. Appendix F of that application note gives many excellent examples of prototyping high speed analog circuits. This is probably one of the finest application notes ever written concerning building high-speed analog/digital designs.

Building the oscillator and voltage regulator circuit

A stable 20 Mhz square wave source and a 3.3 volt regulated power supply will be required for future experiments. We will now build these circuits. Before soldering anything on the PCB, you must first clean it to remove oxidation and oils that may be on the copper surface. Using sandpaper or Scotchbrite® pad, scour the board till the copper is clean and free of oxidation. This will make soldering to the board much easier. If you can keep body oils and sweat off the board, it will stay shiny and easy to solder for weeks. Put your name and last 4 digits of your student ID on the back side of the board with an indelible marker.

The schematic diagram of the circuit to build is shown below. Refer to the manufacturers data sheets for package and pin orientation. Be sure to use the voltage regulator and not the JFET. They look the same, but the results will be vastly different!
A good place to begin placing the components would be at one corner of the PCB, so that there will be room for other projects to be placed. There should be plenty of room on the board. Even if you have to move entire circuits on your board, it's quite easy with ugly construction.

The wiring of the voltage regulator is non-critical. When bending leads at any component however, bend them away from the body of the part, else the lead gets bent at a sharp right angle and is easily broken. See the Figure 2 below.

Figure 3: Voltage Regulator Assembly

Careful assembly of the oscillator circuit is required for good results in the lab. In particular, the decoupling capacitor for the oscillator needs to have leads that are as short as practical. Otherwise, inductance in the capacitor leads will lead to excessive digital noise on the oscillator output. Be
sure to bend the leads away from the oscillator’s metallic component body to prevent shorting.

When connecting C4 and R1 to the oscillator, keep the leads as short as is practical, while still allowing room for the oscilloscope probe. R1 is the load for the oscillator’s output. The 0.1uF capacitor is there to form a DC block so that excessive DC current will not be drawn from the oscillator.

Build the voltage regulator circuit first, without connecting it to the oscillator. Make sure that its output is 3.3 volts. If you mis-wire the voltage regulator and connect it to the oscillator, you may blow out both the regulator and the oscillator at the same time. Also, when soldering to the battery pack, solder quickly as the metal tabs will melt the plastic housing quickly.

As a general rule, test subsections of a larger project separately. Confirm that each piece works, then connect them.

**Quick Scope Overview**

Before jumping into taking measurements, let’s take a quick scope refresher. The example scope used here is the Tektronix DPO4034. Other digital oscilloscopes have similar functionality. Before you start, here are a few pointers to help you start twisting knobs.

- **Vertical section, just above the probe connectors**
  - Top knob determines where the ground point is displayed on the screen
  - Middle button toggles the selected channel on or off
  - Bottom button adjusts the vertical sensitivity in volts/division

- **Trigger section, far right**
Menu button brings up the menu that determines how the scope is triggered. There are many possibilities but rising or falling edge will usually suffice. The settings to choose are seen at the bottom of the display for the selected channel.

– The Level button sets the voltage level at which the scope triggers when the event such as rising edge occurs.

• Horizontal section, to left of Run/Stop button

– Scale knob sets the horizontal scale in time/division. The setting of this knob is also seen below the scope display.

• Multipurpose section, top, to right of display

– We use these knobs mostly for moving the cursors. There is one knob for each of two cursors. The Select knob allows you to choose between moving the cursors horizontally (time) or vertically (voltage). The Cursors button turns the cursors on and off.

You can save your waveforms with a USB stick by using the USB port at the bottom left of the scope. See Figure 6. There are nearby buttons to control the file name and directory to save in. When saving scope pictures, be sure to allow the USB write operation to finish before pulling the USB stick out.

Making Measurements on the Oscillator Circuit

To make the first set of measurements, set channel one to display 1 volt per division with rising edge triggering set for 1.0 volt. The horizontal timebase should be set to 10ns per division.

In Figure 5 below, the bottom row of blue informative boxes have a set of corresponding buttons. These buttons toggle between the possible settings for each of the blue boxes. For example, toggling the far left button would change the coupling for channel one between DC, AC, and ground. In the ground position, the scope probe is grounded inside the scope. The second box indicates that the scope will be presenting a 1 megohm input impedance to the probe. The first measurements must be made using DC coupling.

Figure 5: Toggle Buttons for Changing Channel 1 Settings
The probe has an internal impedance of 9 megohm. With the scope input impedance, the voltage divider formed divides the input signal at the scope input by ten. The probe is thus marked as a “10X” probe, which means that the scope compensates by amplifying the input signal by ten. Most modern scope probes identify themselves to the oscilloscope via a serial communication bus.

If the trigger menu button is pushed, a menu at the bottom of the screen appears to allow trigger qualification changes as shown in Figure 6. As before, the bottom row of buttons allows a change to the settings box above.

Triggering information about the trace is also given at the far right side above the time and date box. In this picture, the trigger information box tells us that we are triggering on channel one, on a rising edge, at a voltage of 1.64 volts. This box remains visible even when the trigger menu is not active.

![Figure 6: Trigger Menu](image)

Now with the scope settings in place we can make our measurements.

1. Temporarily disconnect R1 and C4 by unsoldering the connection to the oscillator output. Simply bend R1 and C4 out of the way temporarily.

   Using the “witches hat” and full length ground wire, connect the scope probe tip to the output of the oscillator and the ground lead to the copper plane. Channel one should be displaying a 20Mhz signal with 50ns period. See Figure 7 below.

2. Using the scope cursors, measure:
   
   (a) overshoot
   (b) undershoot
   (c) rise time (10% to 90%)

   Make the measurements **without** using the automated measurement capabilities of the oscilloscope. Capture the scope picture for your lab report.
Below is a scope capture of an overshoot measurement. Overshoot is defined as the amount that the signal exceeds the positive supply voltage when making a rising edge transition. Since the signal peaked at 4.66 volts, the overshoot is $4.66 - 3.3 = 1.36$ volts.

Figure 7: Overshoot Measurement
Below is the undershoot measurement. Undershoot is defined as the amount that the signal exceeds the negative supply voltage (in this case, zero volts) when making a falling edge transition. Since the signal reached -1.1 volts on its negative edge, the undershoot is 1.1 volts. Undershoot is usually considered a positive number.

Figure 8: Undershoot Measurement

Here we see triggering occurring on channel one, on a rising edge, at a voltage of 1.0 volts. Also notice that cursor information is available at the upper right. There you can find absolute and relative voltage or time differences between the cursors.
Shown in Figure 9 is the risetime measurement. Typically, rise time is measured between the 10% and 90% points of the rising edge. Here we use a higher vertical sensitivity and smaller horizontal timebase to make a more accurate measurement. It is acceptable to allow the waveform to go off the screen for this measurement. If you use the automated measurement tools of the scope, however, this is not true. This measurement was made with a 350Mhz bandwidth scope and 500Mhz probe. If you have a 100Mhz probe, your edges will appear slower.

![Figure 9: Risetime measurement](image)

By using the “Select” button between the multifunction knobs, you can select how you are adjusting either cursor. You can move them in voltage or time dimensions. In this way, you can make accurate time measurements between specific voltage levels. If your cursors are not showing up, turn them on with the “Cursors” button near the multifunction knobs.

3. Repeat the three measurements of part 1 (overshoot, undershoot and rise time) using a short scope ground lead of solid core wire. CAT-5 cable inner conductors make great “quick and dirty” ground probes. Wrap 4-5 turns of wire around the inner barrel of the probe and twist them enough so it will slide on the barrel but not be loose. You will need to remove the “witches hat” and plastic cover on the probe first. The measurements taken with the short ground wire should look significantly different. Make these measurements using DC coupling, **without** using the automated measurement capabilities of the oscilloscope. Capture the scope pictures for your lab report.
Scope probe bandwidth ratings are developed with no ground wire and no "witches hat". The probe is connected directly in to a socket in a test fixture. Anytime you are using the long ground wire, you are making a relatively inaccurate measurement. However, if you are only checking to see if a signal such as a clock is running, there is no problem using the very convenient long lead and "witches hat".

Figure 10: Scope Probe with High Performance Ground Lead

4. Take a BNC breakout "grabber" set (Figure 11) and connect it to the scope input via a 50 ohm cable where the scope probe went before. Attach the grabbers to the output of the oscillator. Be sure to connect the black lead to the PCB board ground. Keep the scope input impedance at 1 Megohm. In your lab report, describe:

(a) Does the waveform shape and amplitude look correct?
(b) Why do you think the waveform looks like it does?

Figure 11: BNC Breakout with "Grabbers"

We are now going to measure the digital noise present on the Vdd pin of the oscillator. This noise is a natural result of the oscillator’s output inverter driving a large load at its output. For each edge driven from the output, the oscillator must either source or sink current to the load. Each time current must be sourced, the current drawn through the Vdd power supply wiring causes a $L \frac{di}{dt}$ voltage drop to occur at the oscillator Vdd pin. Even the presence of the decoupling
capacitor at the Vdd pin is not enough to prevent some voltage droop at the Vdd pin although it helps.

Since the noise is synchronous to the digital output edge, we should trigger the scope on that edge using one channel and use a second channel to observe the voltage at the Vdd pin. The noise on the Vdd pin is small, typically less than 250mV. If we choose a vertical sensitivity big enough to clearly see the noise waveform, it will be off-screen since the DC voltage on pin 14 is 3.3v. If we used a 10mv per division sensitivity, we would need a scope screen about 350 divisions high.

The solution is to use AC coupling to see the digital noise. We can block the DC component of the signal on pin 14 and only allow the AC component (the noise) to be viewed. We thus can then increase the vertical sensitivity to see the AC noise waveform without having the DC component move our trace well off-screen. Using AC coupling is essentially putting a capacitor in series with the tip of our scope probe.

5. Set the scope so that channel 1 triggers off of the oscillator output at 1.65 volts on a rising edge with DC coupling. Channel 2 is set for AC coupling at 10mv per division.

Reconnect R1/C4 back to the oscillator. Borrowing a scope probe, connect channel 1 to the output of the oscillator. Using the “witches hat” and long ground wire are fine as we are only using channel 1 for a trigger. Then, using the scope probe with the short ground lead you built for Step #2, probe pin 14 (Vdd) of the oscillator with channel 2.

With this setup, when channel 1 triggers, the scope will sample both channels simultaneously, and a clear correlation between the output rising edge on channel 1 and a “droop” in the voltage at the Vdd pin via channel 2 should be visible.

Make a measurement of Vdd noise and capture the picture. You will probably see more noise than the figure below this, depending on how short your decoupling capacitor leads are. The lead length of the decoupling capacitor used in the following scope picture is less than 0.1 inches.
You will often read that keeping short connections between digital integrated circuits and their decoupling capacitors is of primary importance. When decoupling capacitor lead length increases, noise on the power supply lines increases quickly. Here we see the noise on the oscillator Vdd pin with decoupling capacitors that have leads lengths of 0.1 and 0.2 inch.

(a) Decoupling capacitor leads 0.1”
(b) Decoupling capacitor leads 0.2”
Notes

- Keep 0.1uf capacitor leads short. The electrolytic capacitor lead length is not critical.

- Noise resulting from digital switching will be synchronous to the digital circuitry. Thus, noise that you see should show a clear relationship to the 20Mhz oscillator, (i.e., periodic, 50nS period). Otherwise, you are looking at the wrong thing.

- Don’t include the Tek "waveform inspector” window in your pictures.

- Waveform measurements should fill at least one-half the scope screen. Otherwise they are too small to be of use.

- Your schematic diagrams should include enough information that an experienced person would not need to look anywhere else to replicate your circuit. You must include part and pin numbers of ICs, values of all components, etc.

- Schematics use standard symbols, not physical representations of the components. Leave that to hobby magazines.

Grading

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<th>Deliverable</th>
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<tr>
<td>overshoot, undershoot, and rise time (long ground lead)</td>
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Table 1: Grading Metrics