The Oscilloscope

Figure 1. The BK Precision 2120 Oscilloscope

Purpose

- Gain an understanding of the basic principles of operation of an oscilloscope and a familiarity with its controls, and

- Learn some fundamental measurement techniques using the oscilloscope.

The Principles of the Oscilloscope

The oscilloscope is one of the most widely used instruments in scientific laboratories of all kinds. It provides a way of visualizing voltage signal whose variations can be shorter than a ms ($10^{-3}$ s). More than a voltmeter that only displays a changing number of whatever voltage it is reading at the moment, the oscilloscope can provide a plot of voltage over time. As you can imagine, this is a great tool to studying alternating current (AC) circuits and also digital and analog signal processing.

Most newer oscilloscopes have a digital display. Fortunately, our labs feature a “classic” model with a cathode-ray tube that features a smart application of electric force to generate the desired graph on a fluorescent screen. (See Figure 2.) At one end of the cathode-ray tube is an electron gun which produces a high velocity, focused beam of electrons directed at the fluorescent screen on the other end. This screen emits visible light when the electron beam strikes it, resulting in a bright spot of light on the screen. This spot can be moved around by deflecting the beam on its way to the screen. For this purpose, two pairs of deflection plates are mounted at right angles to each other just after the electron gun.
If we apply a sawtooth voltage across the horizontal deflection plates, we will essentially make the electron beam scan or sweep from left to right on the screen at a regular period. If, additionally, we apply an input signal voltage we want to measure (the sine wave in this example) across the vertical deflection plates, then the beam will move up and down depending on the input signal, effectively tracing out a voltage vs. time graph of the input signal. Figure 3 shows the sine-wave pattern on the screen produced by a point-by-point plot of a sine-wave voltage on the vertical deflection plates versus a sawtooth voltage of the same frequency on the horizontal deflection plates. We can adjust the period of the sweep to change the time scale of the plot. Also, the oscilloscope can also control when to begin a sweep via the use of "synchronizing circuits" which may be based on the input signal (e.g., the sweep voltage is "triggered" whenever the signal rises to 1V).

Figure 2. Sketch and working principle of a cathode-ray tube in an oscilloscope.

Figure 3. A point-by-point plot of the sweeping sawtooth voltage on the horizontal deflection plates and the input signal voltage on the vertical deflection plates.
Apparatus

- BK Precision 2120 dual-trace oscilloscope
- 2 BK Precision 4011 function generators
- Fluke 73III multimeter
- 20 Ω, 50 Ω and 100 Ω resistors
- 1.5 V DC battery

Activity 1. Basic Controls
Oscilloscopes can look a little intimidating as they have a great number of buttons, switches, and dials. The names of these controls are given in the appendix. The following activities will take you through the basic controls in order of increasing complexity.

Activity 1.1. Connecting to an input signal
1. Turn on and set up the function generator to output a sine wave of 1 kHz. Set the output knob to about halfway.
2. Connect the “output” of the function generator to “CH1(Y)” of the oscilloscope using a “BNC to BNC” wire.
3. Turn on the oscilloscope.
4. Describe briefly what you see on screen:
Activity 1.2. Adjusting the visual
5. Adjust the “INTENSITY” and “FOCUS” knobs. Describe their effects on the graph displayed on screen:
   INTENSITY –

   FOCUS –

Activity 1.3. Graph Adjustment and Scale
6. Look at the channel 1 control. Adjust the following knobs and describe their effects on the graph displayed on the screen:
   ▲ POS –
   ▼
   CH 1 VOLTS/DIV –
   VARIABLE –

7. Look at the horizontal controls. Adjust the following knobs and describe their effects on the graph displayed on the screen:
   ◄► X POSITION –
   TIME/DIV –
   VARIABLE (The upper knob of TIME/DIV) –
Activity 1.4. Calibration and Measurement

8. Now that you have moved the VARIABLE knobs, you have put your oscilloscope out of calibration. This means that the volts/div and time/div no longer corresponds to what they indicate. To re-calibrate your scope, you need to input a known signal and adjust until you see on screen what you expect. Fortunately, a signal of known voltage is provided by the metal tab CAL on the lower right-hand corner of your scope. Switch to a BNC to alligator connector on CH1 and clip the positive to the metal tab (the negative is connected internally). You should see two horizontal lines, solid or alternating. This signal has a $V_{p-p}$ of 0.2 V. Adjust the VARIABLE on your CH1 until what is shown on the screen gives the correct number of divisions. Use the finest scale (VOLTS/DIV) possible for the most accurate calibration. This calibration will be valid for all scales even when you change the VOLTS/DIV as long as you don’t move the VARIABLE knob.

9. To calibrate for time, unfortunately, the calibration signal provided does not hold a consistent time. Instead, we will calibrate the timing of the scope using the function generator. With your function generator still set at 1 kHz, connect it to the CH1 of the scope. Set appropriate scale so you can see at least 1 period of the sine wave. Adjust the VARIABLE knob for time until a period corresponds to $T = 1/f = 1/1000Hz = 0.001$ s = 1 ms. Again, try to use the finest scale possible for your calibration for best results.

10. Now that our scope is fully calibrated, we can use it to measure other signals. Change the output and frequency on your function generator to something different than before. On your scope, adjust the graph appropriately and measure the peak-to-peak voltage ($V_{pp}$) and the period ($T$) of the sine wave from the function generator, using the grids on the screen.

$$V_{pp} \text{ measured from oscilloscope} = \phantom{0}$$

$$T \text{ measured from oscilloscope} = \phantom{0}$$

11. To verify the measurements, use the multimeter (on VAC setting) to measure the $V_{rms}$ of the sine wave from the function generator, and record the frequency ($f$) of the sine wave from the function generator display.

$$V_{rms} \text{ measured from multimeter} = \phantom{0}$$

$$f \text{ shown from function generator} = \phantom{0}$$

Do these numbers agree with what you measured using the oscilloscope? (recall that for a sine wave, $V_{rms} = \left( \int_{0}^{T} (V_{max} \cdot \sin(\omega \cdot t))^2 \right)^{\frac{1}{2}} = \frac{1}{\sqrt{2}} \cdot V_{max} = \frac{1}{2 \cdot \sqrt{2}} \cdot V_{pp}$, and $T = \frac{1}{f}$)

Activity 2. Advanced Concepts

Now that you are familiar with the basic connections and controls of the oscilloscopes, we will introduce a few advanced concepts that will be important for us as we proceed through the term.

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Activity 2.1. Ground and Signal Measurement

As you may be aware, the idea of a “0 V” level of electrical potential is an arbitrary level. Therefore, nearly every electrical device that can be plugged into a wall outlet has one terminal which is called a **Ground**. Ground terminals are at the same electrical potential as the ground on which the building is located and is often electrically connected to a large metal spike literally driven into the ground. The ground is taken as the reference voltage and is defined to have an electric potential of 0 V. On a circuit diagram, the ground can be explicitly indicated (though often not) by:

Symbol is \( \mathbb{G} \)

Of special note, our oscilloscopes are also internally connected to ground. Moreover, the negative side of the inputs are also connected to ground. For our purposes, we have to pay special attention to where we are connecting the negative side of our input, because we may introduce connections that the circuit does not expect (if two different points in the circuit are both connected to the same ground). **Failure to properly connect the grounds will lead to odd (and sometimes dangerous) results, including overheating, electrical fires, and electrical shocks!**

The ground connection can limit where we can measure in a circuit. It also affects our ability to measure two signals at once: both signals must have a common ground.
12. Figure 4 shows a number of circuits containing resistors and an AC sinusoidal source as well as various ways of connecting the oscilloscope to the circuit. Beside each circuit, note down whether or not the ground has been properly connected (DO NOT hook these up, as some of these configuration will damage the oscilloscope):

![Figure 4](image_url)

13. To give us more flexibility of measurement location, there is a technique called **differential voltage**. Connect the circuit shown in Figure 5 below. Set the function generator frequency at 200 Hz and a peak-to-peak voltage of 10 V. Verify that the ground connections are proper. (Remember to calibrate Channel 2 using the CAL signal)
14. To show both signals, the **VERTICAL MODE** must be set to **ALT** or **CHOP**. Now Channel 2 will display $V_{R1} + V_{R2}$ while Channel 1 will display $V_{R2}$. The complication occurs if we wish to know what signal $V_{R1}$ looks like. Ground requirements in this circuit prevent this. Oscilloscope designers, though, have provided a work-around. First they have provided an **INVERT** button for Channel 1. Press it and Channel 1 will display $-V_{R2}$. Second, they have provided an **ADD** selection to **VERTICAL MODE**. When this choice is selected, the signals from Channel 2 and Channel 1 are added together and only the **sum** is displayed. Here we have $CH\ 2 = V_{R1} + V_{R2}$ and $CH\ 1 = -V_{R2}$, the sum will thus be $(V_{R1} + V_{R2}) + (-V_{R2}) = V_{R1}$, the signal we were looking for. A signal obtained in this way is said to be a **differential voltage**.

Measure and record the $V_{pp}$ of $V_{R1}$ and $V_{R2}$. Verify that you get the same results using the multimeter.

<table>
<thead>
<tr>
<th></th>
<th>scope $V_{pp}$</th>
<th>scope $V_{rms} = \frac{V_{pp}}{2\sqrt{2}}$</th>
<th>multimeter $V_{rms}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{R1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{R2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

15. Repeat step 11 and 12 with the circuit shown in Figure 6. Set the function generator frequency at 200 Hz and a peak-to-peak voltage of 10 V.
Activity 2.2. DC Offset and AC-GND-DC coupling

So far we have been using a pure AC signal, one whose average value over one period is zero, as shown in Figure 7a. However, signals can have a non-zero average or **DC Offset** as shown in Figure 7b. Our signal generator can provide a signal with a DC offset by pressing the "DC offset" button and adjusting the “DC offset” knob.

<table>
<thead>
<tr>
<th>Unit</th>
<th>scope $V_{pp}$</th>
<th>scope $V_{rms} = \frac{V_{pp}}{2\sqrt{2}}$</th>
<th>multimeter $V_{rms}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{R3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{R4}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{R5}$</td>
<td></td>
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</tr>
</tbody>
</table>

16. Connect the oscilloscope using the circuit in Figure 4a. Adjust the DC offset on your function generator, describe its effect on the graph (hint: to get a sense of where 0 V is, display CH2 as well by pressing in the mono/duel button. Since CH2 is disconnected, it should read a horizontal line at 0 V):

17. The DC offset can be measured quite simply using the AC-GND-DC switch for the channel you are using. Toggle the AC-GND-DC switch for CH1 and describe what happens to the graph:
   - AC –
   - GND –
   - DC –
18. Now, we can use CH2 and the vertical position knob of CH2 to help us measure the DC offset. Set CH2 to GND (so it is inactive), and place the cursor of CH2 at the bottom of the signal of CH1 (AC coupled) like Figure 8a. Now switch CH1 to DC. The signal moves relative to the inactive cursor. The difference between the bottom of the signal and the inactive cursors is the DC offset (Figure 8b). Figure 8b shows a DC signal higher than the AC signal, so the DC offset was positive.

![Inactive (CH2) and Inactive cursor](image)

Figure 8a After adjusting CH2 position and CH1 still AC coupled  
Figure 8b CH1 DC coupled to measure the DC Offset

19. Set the function generator frequency at 200 Hz and 3 Volts peak-to-peak (with no DC offset). Connect the DC battery in series with the function generator and the 100 Ω resistor. Use CH1 of the scope to measure the voltage over the resistor $V_R$: it has both AC and DC components. Measure the peak to peak AC voltage and the DC offset, record both values in the table below, and compare with $V_R$ measured by the multimeter. Finally, reverse the orientation of the battery and repeat the measurements.

<table>
<thead>
<tr>
<th>AC: $V_{pp}$ (V)</th>
<th>DC offset (V)</th>
<th>Multimeter: $V_{rms}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="AC Source" /></td>
<td><img src="image" alt="100 Ω Resistor" /></td>
<td><img src="image" alt="Multimeter" /></td>
</tr>
</tbody>
</table>

Activity 2.2. Frequency Measurements and Lissajous Figures

An oscilloscope can be used to measure the frequency of an AC voltage applied across a resistor,

(i) from the measurement of its period, and
(ii) by the use of Lissajous figures.
The sawtooth (sweep) generator of the oscilloscope provides a horizontal axis calibrated in time from which the period $T$ of an AC voltage may be read directly. The frequency $f$ of the AC voltage is given by $f = 1/T$.

Another way neat (and pretty) trick to measure frequency is to use these so-called Lissajous figures (Figure 9) to determine the ratio between the frequencies of two periodic signals.

![Lissajous figures for frequency ratios of 2:1 and 5:3](image)

**Figure 9 Examples of Lissajous figures**

Instead of using a standard sawtooth voltage for the horizontal deflection plate, it is also possible to connect a signal at CH2 to the horizontal deflection plate with the X-Y button. If the ratio of their frequencies is some integral fraction such as 1/2, 3/4, etc., the pattern is stationary. The frequency ratio is determined by the number of loops of the pattern touching a vertical line at the edge of the pattern compared with the number of loops touching a horizontal line at the edge of the pattern. The reason for this is that an integral number of cycles of the sine wave on the vertical deflection plates are completed in the same time that an integral number of cycles of the sine wave are completed on the horizontal deflection plates.

If $n_x$ is the number of loops of the pattern touching a horizontal fine at the edge of the pattern, $n_y$ the number of loops of the pattern touching a vertical line at the edge of the pattern, $f_x$ the frequency of the sine wave on the horizontal deflection plates, and $f_y$ the frequency of the sine wave on the vertical deflection plates, then $f_y = \frac{n_x f_x}{n_y}$.

20. Set the oscilloscope to X-Y mode. Use a function generator to input a sinusoidal signal with a frequency around 100 Hz into Channel 1 (Y) of the oscilloscope. Use another function generator to input a sine wave of the same amplitude as the reference signal into Channel 2 (X). Adjust the frequency of the reference signal $f_x$ until a symmetric and stable Lissajous pattern appears on the oscilloscope. Sketch the pattern in the table below. Record the data $f_x$, $n_x$, and $n_y$, where $n_x$ and $n_y$ are the numbers of loops of the Lissajous pattern touching the horizontal (X) and the vertical (Y) edges. Suppose that $f_y$ is unknown, we use the equation given above to calculate $f_y$.

21. Switch to CH 1 mode and measure $f_y$ from the period of Channel 1. Finally, record $f_y$ from the display of the function generator.

22. Repeat for two other frequencies $f_y$. 

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Lissajous method | Direct measurement of $f_y$ | Display of function generator $f_y$
|---|---|---|
| pattern | $f_x$ | $n_x$ | $n_y$ | $f_y$ | period | Frequency $f_y$ | $f_y$

| 23. How do $f_y$ obtained in three different ways compare? |

| 24. What are the strengths and limitations of each of the three ways? |
Appendix: The Full List of Controls of the BK Precision 2120 Oscilloscope

Figure A. Full list of controls of the BK Precision 2120 Oscilloscope, use with Table A1

<table>
<thead>
<tr>
<th>Controls</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 or 6 CH 1 or CH 2 VOLTS/DIV</td>
<td>scales vertical axis CH 1 or CH 2</td>
</tr>
<tr>
<td>2 or 7 VARIABLE</td>
<td>vernier adjusts vertical scale</td>
</tr>
<tr>
<td>3 or 8 ▲ POStion ▼</td>
<td>adjusts trace position vertically</td>
</tr>
<tr>
<td>4 or 9 AC-GND-DC</td>
<td>DC component of input blocked, grounds input, or AC and DC components of input displayed</td>
</tr>
<tr>
<td>5 or 10 CH 1 (Y) or CH 2 (X) input</td>
<td>accepts input signal</td>
</tr>
<tr>
<td>11 NORM/INV1</td>
<td>CH 1 signal polarity is inverted (reversed)</td>
</tr>
<tr>
<td>11 CH1/CH2</td>
<td>out: CH 1 signal displayed; in CH 2 displayed</td>
</tr>
<tr>
<td>11 MONO/DUAL</td>
<td>out: single-trace mode; in: dual-trace displayed</td>
</tr>
<tr>
<td>11 ALT/CHOP/ADD</td>
<td>out: CH 1 &amp; CH 2 alternately displayed in: displays channel selected by CH1/CH2</td>
</tr>
<tr>
<td>12 TRACE ROTATION</td>
<td>adjusts trace to horizontal</td>
</tr>
<tr>
<td>17 CAL</td>
<td>provides square wave signal</td>
</tr>
<tr>
<td>18 Grounding jack</td>
<td>provides a ground</td>
</tr>
<tr>
<td>19 TIME/DIV</td>
<td>adjusts sweep rate; set VAR SWEEP to CAL to calibrate</td>
</tr>
<tr>
<td>20 VAR SWEEP</td>
<td>vernier adjusts sweep rate; set to CAL to calibrate</td>
</tr>
<tr>
<td>21 ◄► X POSITION</td>
<td>adjusts trace horizontally</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
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Table A1. Full list of controls of the BK Precision 2120 Oscilloscope

<p>| | | |</p>
<table>
<thead>
<tr>
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</table>

Table A2. Suggested starting position of oscilloscope controls

<table>
<thead>
<tr>
<th>VERTICAL (CH 1 &amp; CH 2)</th>
<th>HORIZONTAL</th>
<th>TRIGGER</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODE</td>
<td>CH1</td>
<td>SEC/DIV</td>
</tr>
<tr>
<td>POSITION</td>
<td>Midrange</td>
<td>VARiable</td>
</tr>
<tr>
<td>VOLTS/DIV</td>
<td>1 V</td>
<td>POSITION</td>
</tr>
<tr>
<td>AC-GND-DC</td>
<td>DC</td>
<td>Magnifier</td>
</tr>
<tr>
<td>VARiable VOLTS/DIV</td>
<td>CALibrated</td>
<td>ALTernate</td>
</tr>
<tr>
<td>BW Limit</td>
<td>Off</td>
<td></td>
</tr>
</tbody>
</table>