TUTORIAL AND
LAB GUIDE

DSOXBODE Bode Plot Training Kit

Using Keysight InfiniiVision X-Series Oscilloscopes

Creating gain and phase Bode plots based on the frequency response of electrical circuits — both theoretical and measured in the lab — is typically a key part of the electrical engineering (EE) curriculum in undergraduate studies. Many of Keysight Technologies' InfiniiVision X-Series oscilloscopes support automatic Bode plot measurements. Keysight also provides an optional Bode plot training kit (DSOXBODE) to help EE students learn about frequency response analysis measurements. This training guide begins with background information on Bode plots, and then provides step-by-step instructions on how to perform manual, as well as automatic Bode plot measurements using a Keysight InfiniiVision X-Series oscilloscope along with the Bode plot training kit. If the Bode plot training kit is not available in your EE teaching lab, you can easily create your own based on three passive devices (resistor, capacitor, and inductor).





KEYSIGHT TECHNOLOGIES

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System requirements and prerequisites

The lab instructions in this document are based on the following Keysight InfiniiVision oscilloscopes and required options.

- InfiniiVision 1000G X-Series oscilloscope (The “G” suffix in the model number indicates the scope is preconfigured with the built-in waveform generator, which is required.) Frequency response analysis (FRA) is standard in all “G” models.
- InfiniiVision 3000T, 4000, or 6000 X-Series oscilloscope configured with the WaveGen option along with one of the following optional software packages that includes FRA.
    - Embedded software package (D3000GENA, D4000GENA, D6000GENA)
    - Automotive software package (D3000AUTA, D4000AUTA, D6000GENA)
    - Aero software package (D3000AERA, D4000AERA, D6000AERA)
    - Power software package (D3000PWRA, D4000PWRA, D6000PWRA)
    - USB software package (D4000USBA, D6000USBA)
    - Ultimate bundle software package (D3000BDLA, D4000BDLA, D6000BDLA)

The above oscilloscopes are available in a variety of bandwidth and number-of-channel configurations, all of which are compatible with the lab instructions in this document. If your EE circuits lab is not equipped with any of the above oscilloscopes, the tutorial section, as well as Labs 1 and 2 can be completed using any vendor’s oscilloscope along with a standalone function generator, although some specific set up and measurement instructions may differ. Although the Bode Plot Training Kit (DSOXBODE) is suggested for these labs, you can also create your own using readily available passive components.

As a prerequisite for completing the labs, the EE student following this lab guide should already be familiar with the graphical user-interface of Keysight InfiniiVision oscilloscopes and know how to set up the scope (vertical scaling, horizontal scaling, and triggering) to view repetitive sine waves. The student should also know how to perform basic measurements on these oscilloscopes using cursors and automatic parametric measurements, as well as how to save screen images to a USB drive. This document does not include every keystroke required to set up and perform the required measurements.

Prior to going into the EE circuits lab to perform the measurements outlined in labs 1 through 4, the student should read/study the tutorial section of this guide (pages 1 through 5) and answer the questions on page 5.

Frequency response analysis tutorial

Bode plots are theoretical straight-line approximations of gain and phase versus frequency of a system's output relative to the input (i.e. frequency response) based on poles and zeros of the circuit's transfer function. The result of a frequency response analysis test is a measured plot (not a straight-line approximation) of gain and phase versus frequency. Frequency response analysis testing is often equated with and called Bode plots.

For both Bode plot straight-line approximations, as well as frequency response analysis test results, the magnitude of gain (A) of a circuit (V_{OUT}/V_{IN}) is typically converted into logarithmic units of dB.

$$A(dB) = 20Log\frac{Vout}{Vin}$$

Gain is plotted on the vertical axis versus frequency on a logarithmic horizontal axis. Units of frequency can either be in radians/sec or Hertz.

$$1\frac{radian}{second} = \frac{1}{2\pi}Hz$$

Phase is also plotted on the vertical axis versus frequency on a logarithmic horizontal axis and is usually plotted in units of degrees but can also be plotted in units of radians.

$$1\ degree = \frac{radians\ x\ \pi}{180}$$

Sometimes gain and phase are plotted on separate graphs but gain and phase can also be plotted on the same graph with units of gain and phase labeled on opposite sides of the plot. This the way Keysight's InfiniiVision oscilloscopes plot the measured results of a frequency response analysis test with gain in units of dB, phase in units of degrees, and frequency in units of Hertz.

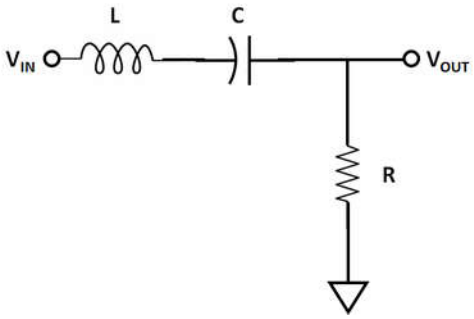


Figure 1. Series R-L-C bandpass filter.

Let's now consider the example of a series R-L-C circuit (Figure 1) that forms a bandpass filter (output attenuated at lower frequencies and higher frequencies but passes/transfers the input to the output at mid-band frequencies). This is the circuit design of Keysight's DSOXBODE Bode plot training kit board you will be testing. The transfer function, ***T(jω)***, of this series R-L-C passive circuit will have two poles and one zero (at 0 Hz) based on the following formulas:

$$T(j\omega) = \frac{V_{OUT}(j\omega)}{V_{IN}(j\omega)} = \left(\frac{R}{L}\right)\frac{j\omega}{\left[(j\omega)^2 + \left(\frac{R}{L}\right)j\omega + \frac{1}{LC}\right]}$$

$$f_{Pole1\ (Hz)} = \frac{1}{2\pi}\left(-\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}\right)$$

$$f_{Pole2\ (Hz)} = \frac{1}{2\pi}\left(\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}\right)$$

$$For\ R \gg \sqrt{\frac{L}{C}}\ ,\quad f_{Pole1\ (Hz)} \cong \frac{1}{2\pi RC}\ ,\quad f_{Pole2\ (Hz)} \cong \frac{R}{2\pi L}$$

Figure 2 shows the Bode plot of gain and phase of a bandpass filter based on a sine wave input at various frequencies. Bode plots, as well the frequency response analysis tests, are always based on sine wave inputs. The solid lines represent the straight-line approximated Bode plot of gain and phase while the dashed line represents the actual/theoretical gain which can be verified by testing.

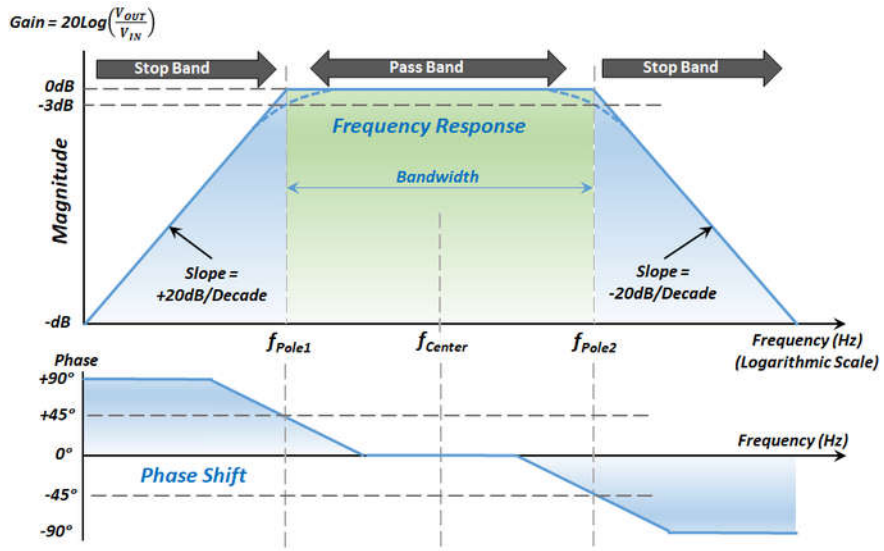


Figure 2. Gain & phase Bode plots of a series R-L-C bandpass filter.

Before we perform any measurements, let's consider the extreme limits of this series R-L-C circuit based on the schematic of Figure 1. This quick analysis may provide you with a more intuitive understanding of why bandpass filters behave the way they do.

Case 1: Frequency = 0 Hz

$$Z_C = -j\frac{1}{2\pi f C}$$, @ f = 0 Hz, $|Z_C|$ = Infinite Ohms (∞ Ω)

$$Z_L = +j2\pi fL$$, @ f = 0 Hz, $|Z_L|$ = Zero Ohms (0 Ω)

In this case all the input voltage (V_{IN}) will be dropped across the series capacitor since the reactance of the capacitor dominates the impedance of the entire series circuit. The output voltage (V_{OUT}) across R will then be 0 V and the absolute gain (V_{OUT}/V_{IN}) will also be zero. The logarithmic gain ($20\text{Log}(V_{OUT}/V_{IN})$) will be negative infinite dB. Don't punch it into your calculator. It may explode!



Hendrik Wade Bode (1905 – 1982)

Hendrik Wade Bode was born in Madison, Wisconsin (USA) on December 24, 1905. Soon after graduating from Ohio State University where he received his B.A and M.A. degree in 1926 in Mathematics, Bode began an illustrious engineering and scientific research career at Bell Labs. While at Bell Labs, Bode successfully completed his PhD in physics at Columbia in 1935. In 1938, Dr. Bode invented what is famously known today by engineering students as "Bode plots" for his namesake. But that's not what he called them. He simply called them "asymptotic frequency-domain magnitude and phase plots". During his time at Bell Labs, Dr. Bode received numerous academic medals and awards and held 25 patents in various areas of electrical and communications engineering. He also collaborated closely with other well-known scientists and researchers at Bell Labs including Claude Shannon and Harry Nyquist.

Case 2: Frequency = Infinite Hz

$Z_C = -j\frac{1}{2\pi fC}$, @ f = Infinite Hz, $|Z_C|$ = Zero Ohms (0 Ω)

$Z_L = +j2\pi fL$, @ f = Infinite Hz, $|Z_L|$ = Infinite Ohms (∞ Ω)

For this case all the input voltage (V_{IN}) will be dropped across the series inductor providing the same output results as Case 1, which is an absolute gain (V_{OUT}/V_{IN}) of 0.0 and logarithmic gain of negative infinite dB.

Case 3: Frequency where $|Z_C| = |Z_L|$

$$If \frac{1}{2\pi fC} = 2\pi fL, then f = \frac{1}{2\pi\sqrt{LC}}$$

At the frequency where the absolute value of the impedance of the capacitor is equal to the absolute value of the impedance of the inductor, the net impedance of the sum of these two series components is 0 Ω. This is because the phase angles of each component's impedance (+*j* and -*j*) are 180° out of phase with respect to each other. In this case all of V_{IN} is dropped across the remaining component, R, which makes $V_{OUT} = V_{IN}$ for an absolute gain (V_{OUT}/V_{IN}) of 1 which equates to 0 dB. The frequency where this occurs is called the center frequency (f_{Center}) of the bandpass filter.

From this quick analysis of this circuit, based on these three data points, we can see that a series R-L-C circuit has very low gain at low frequencies, very low gain at high frequencies, and a gain of 1 (0 dB) at a mid-band frequency. Let's now plug in real numbers based on the actual component values of Keysight's DSOXBODE Bode plot demo kit, which are:

C = 1 µF
L = 10 µF
R = 50 Ω

Using the equations provided on the preceding pages and from what you've learned so far, now determine the following for Keysight's DSOXBODE Bode training kit board:

f_{Pole1} = _____

f_{Pole2} = _____

f_{Center} = _____

f_{Pole1} and f_{Pole2} are the frequencies where the ±20 dB/decade straight-line approximations intersect 0 dB of the straight-line approximated Bode gain plot (refer back to Figure 2). But if you tested this passive circuit, you would discover that the actual gain and phase traces would not be perfect straight lines, especially near these pole frequencies. You would discover that the gain would be down approximately 3 dB at each of the two pole frequencies. Let's now make some measurements.

Lab 1: Quick verification test of a bandpass filter

During this lab we will setup the oscilloscope to capture and display the input (V_{IN}) and output (V_{OUT}) of a bandpass filter (DSOXBODE Bode Training Kit) while manually varying the frequency of an input sine wave (using the scope's built-in generator) to observe and compare the relative amplitudes of the input and output across a range of frequencies. Note that your passive probes should be properly compensated/calibrated before proceeding with the lab. Refer to the "Oscilloscope Probe Loading" tutorial and lab guide listed at the end of this document to learn more about probe compensation.

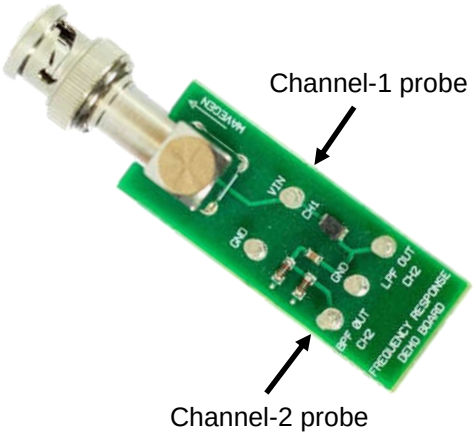


Figure 3. DSOXBODE Bode Training Board.

1. Connect the DSOXBODE training board directly to the InfiniiVision oscilloscope's **Gen Out** BNC.
   If using a Keysight 4000 or 6000 X-Series oscilloscope, connect the training board to the **Gen Out 1** output BNC.
2. Connect a passive probe between the channel-1 input BNC of your scope to the training board's **VIN CH1** test pin. Connect the probe's ground lead to one the test pins labeled **GND**.
3. Connect a passive probe between the channel-2 input BNC of your scope to the training board's **BPF OUT CH2** test pin. Connect this probe's ground lead to the other test pin labeled **GND**.
4. If you are using a Keysight 1000 X-Series oscilloscope and using the original probes that were supplied with this scope (black probes), these probes have selectable attenuation settings (10X or 1X). Make sure the switch on each probe is set to the **10X** setting (not 1X). Also, make sure to set the probe attenuation factor to **10.0:1** for each channel of the scope in the channel-1 and channel-2 probe menus.
   a. Press the channel number key
   b. Select the **Probe** menu
   c. Set units to **Volts**
   d. Set probe attenuation ratio to **10.0:1**
5. If you are using a Keysight 3000T, 4000A, or 6000A X-Series oscilloscope, these scopes were originally supplied with non-selectable 10X probes (gray probes) with automatic detection of the attenuation factor by the scope.
6. Press the front panel **[Default Setup]** key on your oscilloscope (Note that a Default Setup does *not* reset the probe attenuation factor).
7. Press the front panel **[WaveGen]** key (or **[WaveGen1]** key on the 4000 or 6000 X-Series oscilloscope), and then establish the following initial generator settings to use as a test input source:
   a. Waveform: Sine
   b. Frequency: 100 Hz
   c. Output Load (under Settings submenu): 50 Ω
   d. Amplitude: 500 mVpp (note that the expected output load impedance must to established before setting the amplitude)

8. Turn on the displays of channel-1 (yellow trace) and channel-2 (green trace) of your oscilloscope and then establish the following oscilloscope settings:
    a. Channel-1 vertical scaling: 200 mV/div
    b. Channel-2 vertical scaling: 200 mV/div
    c. Timebase/Horizontal: 2.000 ms/div
    d. Vertical Position: Using the vertical position knob(s), position the channel-1 waveform (V_{IN}, yellow trace) near the top of the scope's display (-200 mV offset) and position the channel-2 waveform (V_{OUT}, green trace) near the bottom of the scope's display (+500 mV offset).
    e. Triggering should already be set to rising edge transition on channel-1 at 0.0 V which was establish by the Default Setup (step #6).

At these settings your scope's display should look like Figure 4. At an input frequency of 100 Hz you can see that the amplitude of V_{OUT} (channel-2, green trace) is much lower than the amplitude of V_{IN} (channel-1, yellow trace) which means that the gain is very low at this frequency (100 Hz). We'll measure the actual gain in Lab 2 and Lab 3.

We will now setup the scope to manually "sweep" to higher frequencies. "Sweep" is the term most often used when an input variable is changed during a test from a lower initial setting to incrementally higher settings.

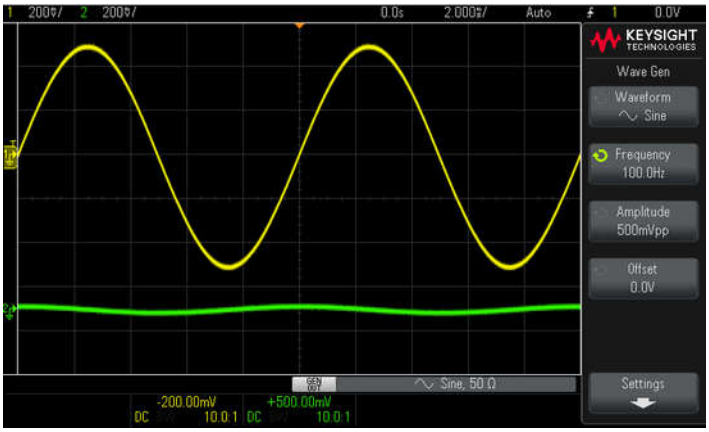


Figure 4. Initial oscilloscope setup condition at 100 Hz.

9. Press the front panel **[WaveGen]** key (or **[WaveGen1]**) again to activate the WaveGen settings menu, and then press the **Frequency** menu key to activate this variable.
10. Using the entry knob, slowly increase the frequency setting from 100 Hz up to 10 MHz while observing the relative amplitudes of the V_{IN} and V_{OUT} traces.

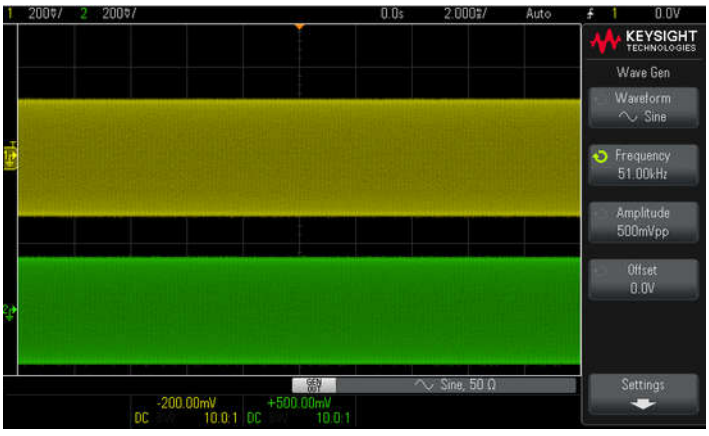


Figure 5. V_{IN} and VOUT near f_{Center}.

As you initially increase the frequency you should observe the amplitude of V_{OUT} getting larger. V_{OUT} will eventually have the same approximate amplitude as V_{IN} (between ~8 kHz to ~300 kHz) as shown in Figure 5. But as you increase the frequency further you should observe the amplitude of V_{OUT} getting smaller again relative to V_{IN}. Note that although you could change the timebase setting in order to view individual cycles of these signals as frequency is increased, even if you leave the timebase set at 2 ms/div, you can still easily see the peak-to-peak extremes of these signals. But of course, if we wanted to measure phase, we would need to rescale the timebase to view just a few cycles.

You may have also noticed that as frequency changed, the amplitude of V_{IN} appeared to change as well — but not as much as V_{OUT}. But since V_{IN} is being probed at the output of the generator, which is also the input to the test circuit, shouldn't V_{IN} have a fixed amplitude since we originally set the generator's amplitude to 500 mVpp (Step 7d)?

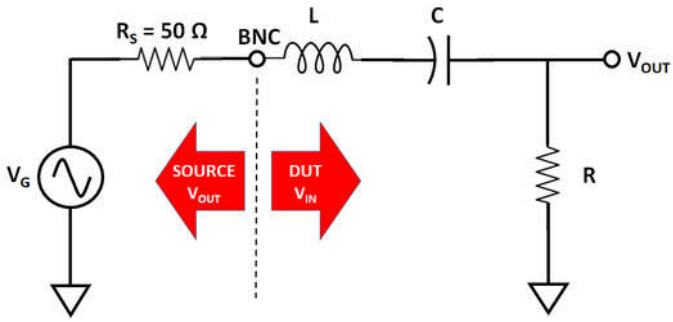


Figure 6. Test circuit including function generator equivalent circuit.

Function generators have a series source resistance (R_S) of 50 Ω as shown in Figure 6. The amplitude of the output of generator at the BNC is relative to a fixed load impedance. In step 7c of this lab, we set the expected fixed load impedance of the device-under-test (DUT) to 50 Ω. Our only choices were 50 Ω or High-Z. Some higher performance function generators, such as Keysight's 33500/600 Series function/arbitrary waveform generators, allow you to enter any specific fixed value for load impedance. But the load impedance of our test circuit is not fixed. It varies based on frequency because the reactance of the series capacitor and inductor vary as a function of frequency. Only near f_{Center} is the impedance of this test circuit approximately 50 Ω. At very low frequencies, such as 100 Hz, the impedance of our circuit is very high, and at very high frequencies, such as 10 MHz, the impedance is again very high. This is why V_{IN} is changing by an approximate factor of 2 to 1 across the range of input test frequencies (100 Hz to 10 MHz).

For a linear system, such as our passive bandpass filter, relatively small variations in the amplitude of V_{IN} theoretically shouldn't matter since we are measuring gain — not absolute amplitudes. If a linear circuit has an absolute gain of 2 at a particular frequency, and if V_{IN} = 1 Vpp, then V_{OUT} = 2 Vpp. If V_{IN} = 2 Vpp, then V_{OUT} = 4 Vpp. The gain should be the same regardless of the value of the input voltage.

Lab 2: Frequency response testing using traditional oscilloscope test methodology

Before performing an automatic frequency response analysis test, we will perform this test manually — the same way EE students have been doing it for years, and probably the way Dr. Hendrik Bode did it nearly a century ago. This is the method that most EE students are still using today because very few oscilloscopes can perform automatic frequency response analysis testing. Although testing the frequency response of our bandpass filter manually will be a somewhat tedious exercise, it will help you to better understand the fundamentals of frequency response analysis testing.

Note that if you just completed Lab 1, the DSOXBODE Bode plot training board should still be connected to the scope's WaveGen output BNC and probed by channel-1 and channel-2 using 10X passive probes. If not, repeat steps 1 through 4 of Lab 1 before proceeding.

1. Press the scope's **[Default Setup]** front panel key.
2. Press the **[WaveGen]** (or **[WaveGen1]**) front panel key, then establish the following generator settings:
    a. Waveform: Sine
    b. Frequency: 100 Hz
    c. Output Load (under Settings submenu): 50 Ω
    d. Amplitude: 500 mVpp
3. Turn on the displays of channel-1 (yellow trace) and channel-2 (green trace) of your oscilloscope and then establish the following oscilloscope settings:
    a. Channel-1 vertical scaling: 200 mV/div
    b. Channel-2 vertical scaling: 10 mV/div
    c. Timebase/Horizontal: 2.000 ms/div
    d. Vertical Position: The channel-1 waveform (yellow trace) and the channel-2 waveform (green trace) should be vertically centered on-screen (0.0 V offset). It's okay during this lab for the waveforms to be overlaid. This will help us to better visualize the phase shift at each test frequency.
    e. Triggering should already be set to rising edge transition on channel-1 at 0.0 V which was establish by the Default Setup action of step #1 above.

Although the peak-to-peak amplitudes of the channel-1 and channel-2 waveforms may appear to some to be similar as shown in Figure 7, note that the channel-1 waveform is scaled at 200 mV/div while the channel-2 waveform is scaled at 10 mV/div. The channel-1 amplitude (V_{IN}) is much larger than the channel-2 (V_{OUT}) amplitude at this initial 100 Hz input frequency. Also notice that the channel-2 waveform (V_{OUT}) appears very noisy. Let's now "clean it up" before attempting to make accurate gain and phase measurements.

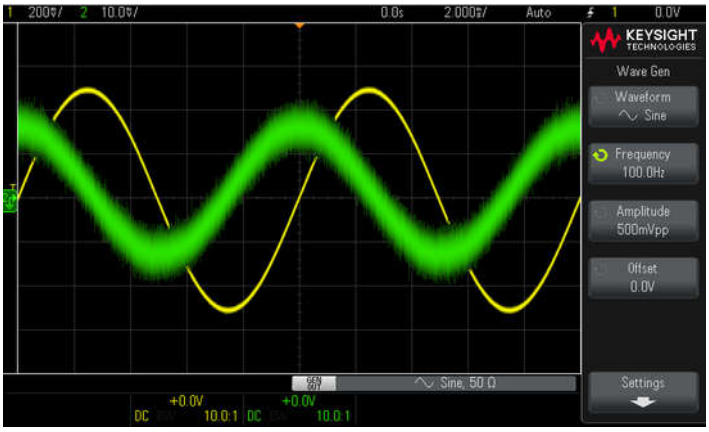


Figure 7. V_{IN} and V_{OUT} at 100 Hz.

4. Select the **[Acquire]** front panel key, and then change the **AcqMode** from **Normal** to **Averaging**. Averaging repetitive acquisitions of the waveforms will help to eliminate random noise and improve measurement accuracy.
5. Using either the scope's manually-placed voltage cursors (*Y1 and Y2*) or automatic measurements, measure the peak-to-peak voltage of V_{IN} (channel-1) and V_{OUT} (channel-1).

   V_{IN} = _____

   V_{OUT} = _____

   $A_{(LINEAER)}$ (V_{OUT}/V_{IN}) = _____

   $A_{(LOGRITHMIC)}$ ($20Log(V_{OUT}/V_{IN})$) = _____

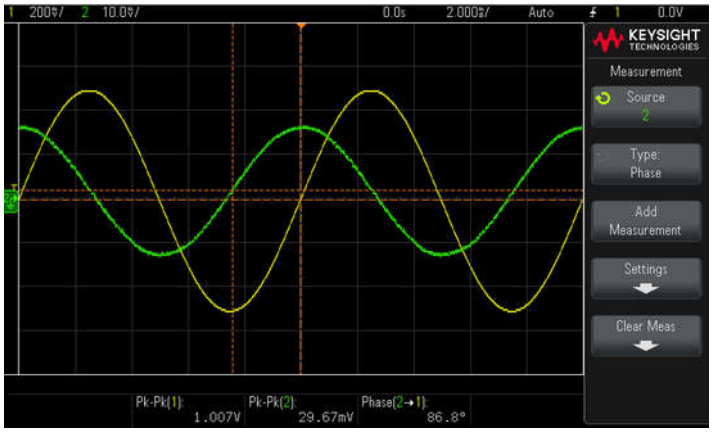


Figure 8. Measuring V_{IN}, V_{OUT}, and phase at 100 Hz using the scope's automatic parametric measurements.

6. Using either the scope's manually-placed timing cursors (*X1 and X2*) or automatic measurements, measure the phase shift of V_{IN} (channel-1) relative to V_{OUT} (channel-2). Hint: If you use the scope's automatic phase measurement capability, **Source1** should be assigned as channel-2 and **Source2** should be assigned as channel-1 before pressing **Add Measurement**.

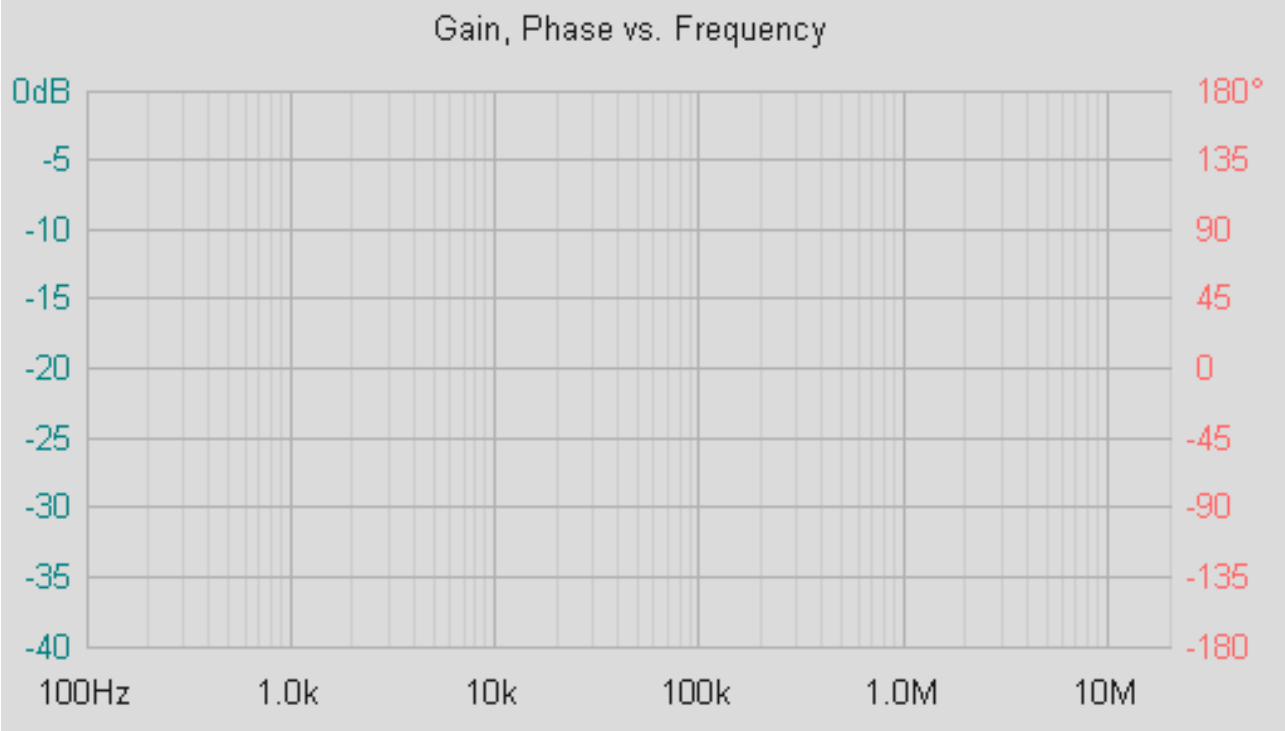
   Phase (Ch-2 to Ch-1) = _____

7. Enter the results of the above measurements and calculations from step #5 and step #6 into Table 1 on the next page of this lab guide.
8. Select the **[WaveGen]** front panel key and then change the frequency setting to **200 Hz**.
9. If necessary, rescale vertical settings (V/div) to ensure that both waveforms are fully on-screen.
10. Rescale the timebase (sec/div) such that approximately 2 to 3 cycles of the waveform are displayed on-screen. Note that if less than 1 cycle is displayed across screen, the scope will not be able to measure phase.
11. Repeat the measurements performed in step #5 and step #6 above, and then enter the results into Table 1 on the next page. Note that if you are using the scope's automatic Vpp and phase measurements, you do not need to re-select these measurements. But if you are using the manually-places cursors for these voltage and timing (phase) measurements, then you will have to re-position the cursors for each different frequency tested.
12. Repeat all measurements and scaling changes (V/div and sec/div) for *ƒ = 500 Hz, 1 kHz, 2 kHz*, etc., up to 10 MHz.

Table 1: Amplitude (Vpp), Gain (A), and Phase Measurement Results

Frequency	V_{IN} (Vpp)	V_{OUT} (Vpp)	$A_{(LINEAR)}$ (V_{OUT}/V_{IN})	$A_{(LOGARITHMIC)}$ ($20Log(V_{OUT}/V_{IN})$)	Phase (Degrees)
100 Hz					
200 Hz					
500 Hz					
1k Hz					
2k Hz					
5k Hz					
10k Hz					
20 kHz					
50k Hz					
100k Hz					
200 kHz					
500 kHz					
1 MHz					
2 MHz					
5 MHz					
10 MHz					

13. Plot the results documented in Table 1 above onto the semi-logarithmic graph provided below or enter the values into a Mac or PC/laptop software application such as MatLab or an Excel spreadsheet for plotting. Suggestion: If plotting manually, use different color pens for gain and phase.



Lab 3: Automatic frequency response analysis of a bandpass filter

Now that you have done it the hard way during Lab 2 — and hopefully learned a few things during the process — we will now perform the same measurements automatically and with significantly higher resolution and accuracy.

Although there have been specialized instruments on the market for years — typically called frequency response analyzers (FRA) or vector network analyzers (VNA) — that provide automatic gain and phase measurements across a frequency spectrum, rarely have these types of instruments been found in the undergraduate EE circuits lab due to cost. Keysight Technologies was the first test equipment vendor to introduce this capability into low-cost oscilloscopes that are commonly used in university undergraduate EE circuits labs.

Note that if you just completed Lab 1 and Lab 2, the DSOXBODE Bode plot training board should still be connected the scope's WaveGen output BNC and probed by channel-1 and channel-2 using 10X passive probes. If not, repeat steps 1 through 4 of Lab 1 before proceeding.

1. Press the **[Default Setup]** front panel key.
2. Press the **[Analyze]** front panel key.
3. Select the **Features** menu key, and then select **Frequency Response Analysis**.
4. If using a Keysight 1000 X-Series oscilloscope, select the **Setup** menu key (Figure 9).
   If using a Keysight 3000T, 4000, or 6000 X-Series oscilloscope, select the **Open Dialog…** menu key (Figure 10).

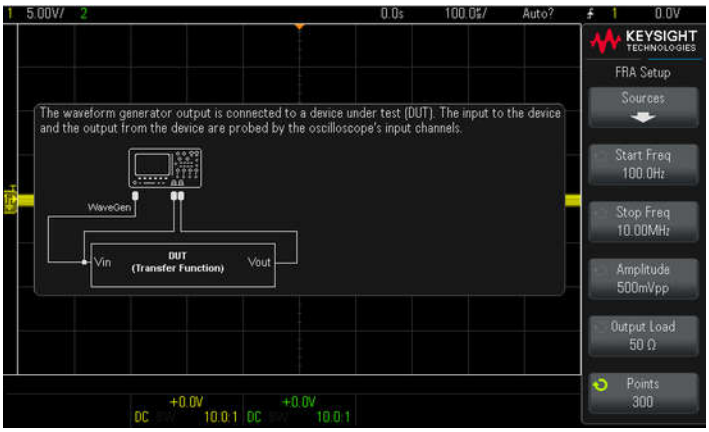


Figure 9. InfiniiVision 1000 X-Series oscilloscope frequency response analysis (FRA) setup menu.

We will perform a "sweep" from 100 Hz (Start Freq) to 10 MHz (Stop Freq) on our bandpass filter based on a 500 mVpp input into a 50 Ω load impedance. This is the same criteria as the manual testing that was just accomplished during Lab 2. However, due to the tedious nature of performing gain and phase measurements manually, we performed tests at just 16 different frequencies during Lab 2. In this lab, we will setup the scope to perform 300 gain and phase measurements across the 100 Hz to 10 MHz frequency span.

5. Change the **Stop Freq** setting from 20 MHz to 10 MHz.
6. Change the **Points** setting (number of different frequencies to test) from 60 to 300.
7. Change the **Amplitude** from 200 mVpp to 500 mVpp.
8. If using a 1000 X-Series oscilloscope, press the **Back** key, and then select **Run Analysis**.

   If using a 3000T, 4000, or 6000 X-Series oscilloscope, select **Run Analysis**.



Figure 10. InfiniiVision 4000 X-Series oscilloscope frequency response analysis (FRA) setup menu.

Figure 11 shows the test results after the 100 Hz to 10 MHz sweep. The scope automatically optimizes the gain (dB) and phase scaling during and at the completion of the sweep. However, you can manually alter chart scaling after the completion of a test if desired.

The blue trace represents gain with scale factors on the left side of the plot. The orange trace represents phase measurement results with scale factors on the right side of the plot.

Let's now measure the gain at the center frequency (f_{Center}) and then determine the actual/measured pole frequencies (f_{Pole1} and f_{Pole2}).

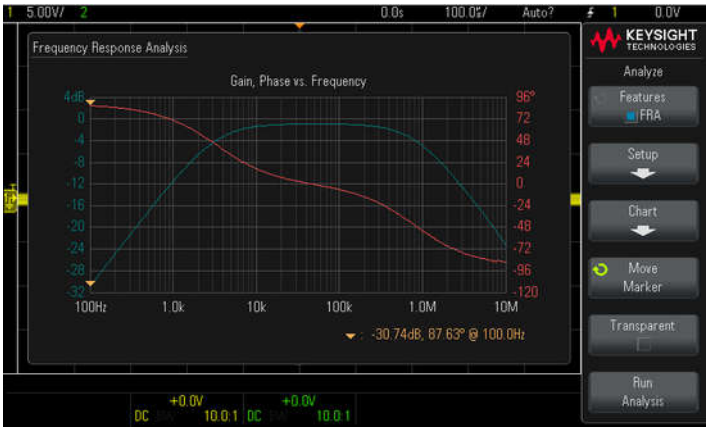


Figure 11. Gain and phase measurement results from an automatic frequency response analysis test.

9. Rotate the entry knob to move the pair of tracking markers (yellow triangles that ride along the gain and phase traces at the same frequency) to the center frequency ($f_{Center} = \frac{1}{2\pi\sqrt{LC}}$) that was previously calculated in the introductory section of this tutorial/lab guide on page 4. The gain, phase, and frequency readout for this pair of markers is below the plot on the right. Note that the Keysight 3000T, 4000, and 6000 X-Series have two pair of tracking markers, but for now we are just using Marker1 if using one of these higher performance scopes.

   Gain ($A_{Measured}$ in dB) @ f_{Center} = _____

   Why do you think that gain (A) is not exactly 0 dB at f_{Center} as theoretically predicted? _____

   _____

10. Rotate the entry knob to move the pair of markers to the approximate f_{Pole1} frequency ($f_{Pole1} \cong \frac{1}{2\pi RC}$) as determined in the introductory section of this tutorial/lab guide on page 4. Now position these markers (as close as possible) to the frequency where the gain is 3 dB below the actual center frequency gain ($A_{Measured}$ @ f_{Center} – 3 dB) as measured in step #9 above. For example, if $A_{Measured}$ at f_{Center} = -0.3 dB, then position the markers at the frequency where A(dB) = -3.3 dB. Note that for a more precise placement of the markers, we could have performed this sweep based on 1000 points across the frequency sweep span, but at the cost of throughput, or we could have limited our span of the sweep to smaller ranges around each pole frequency.

    $f_{Pole1\text{-}measured}$ = _____

11. If using a Keysight 1000 X-Series oscilloscope, now perform the same measurement for $f_{Pole2\text{-}measured}$. Note that $f_{Pole2-Theoretical} \cong \frac{R}{2\pi L}$.

    If using a Keysight 3000T, 4000, or 6000 X-Series oscilloscope, select the **Scroll Marker2** menu key, then rotate the entry to knob to determine $f_{Pole2\text{-}measured}$ using the second pair of tracking markers that are available on these scopes using the same measurement technique as step #10 above.

    $f_{Pole2\text{-}measured}$ = _____

    What is the bandwidth of this bandpass filter ($f_{Pole2\text{-}measured} - f_{Pole1\text{-}measured}$)? _____

12. Save a screen image (.png, .bmp, etc.) of your frequency response analysis test to a USB memory device and attach a printout to your lab test results if required by your professor/lab instructor. Note that the .png format is the most efficient.

    If using a Keysight InfiniiVision 3000T, 4000, or 6000 X-Series oscilloscope, you can also view the measured gain and phase data in a scrollable tabular format as shown in Figure 12 by clicking on (touching) the “table” icon.

    You can also export the measured data in a .csv format using any InfiniiVision oscilloscope, including the 1000G Series, and then upload into an Excel spreadsheet or Matlab for additional processing.



Figure 12. Displaying gain and phase data in a tabular format using a Keysight InfiniiVision 3000T, 4000, or 6000 X-Series oscilloscope.

Lab 4: Characterizing a low-pass filter

Refer back to Figure 1 on page 3 of this training guide and note that if you probe the output (channel-2) of our R-L-C circuit at the node between the capacitor and the inductor, even though this series R-L-C circuit is *not* a classic low-pass filter design, it will behave as a low-pass filter (attenuate signals at higher frequencies) when probed at this point.

Answer the following questions based on probing V_{OUT} at this node.

At low frequencies (approaching 0 Hz)…

What is the impedance of C? _____

What is the impedance of L? _____

What would the output voltage be (in terms of V_{IN}) across the combination of the L and R? _____

At high frequencies (approaching ∞Hz)…

What is the impedance of C? _____

What is the impedance of L? _____

What would the output voltage be across the combination of the L and R? _____

1. Move the channel-2 probe from the test pin labeled **BPF CH2** to the test pin labeled **LPF CH2**.
2. Press the **[Default Setup]** front panel key.
3. Perform a frequency response test on this device with this probing configuration based on what you learned from Lab 3. The results should look similar to Figure 13.
4. Measure the -3 dB cutoff frequency of this low-pass filter.

   -3 dB cutoff frequency = _____

   Bandwidth of the filter = _____

   If you measured the amplitude of the V_{OUT} at the cutoff frequency, what would the approximate error be (in %) relative to V_{IN}? _____

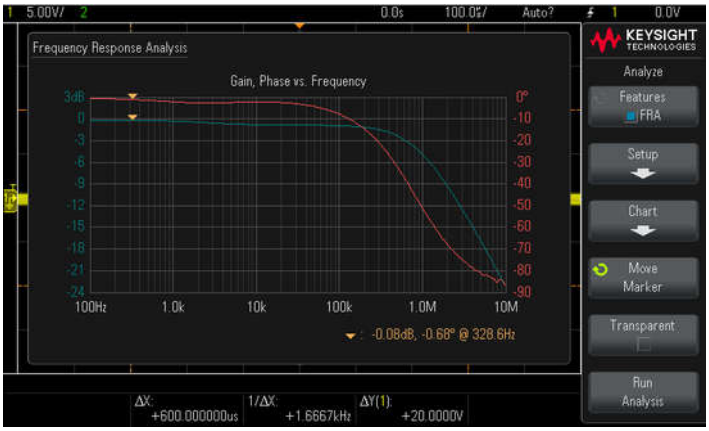


Figure 13. Displaying gain and phase data in a tabular format using a Keysight InfiniiVision 3000T, 4000, or 6000 X-Series oscilloscope.

5. Save a screen image (.png, .bmp, etc.) of this frequency response analysis test to a USB memory device and attach a printout to your lab test results if required by your professor/lab instructor.

The frequency response of oscilloscopes is basically a low-pass filter response similar to what you just tested, except that the cutoff frequency would be much higher for most of today's benchtop oscilloscopes. The cutoff frequency of a 100 MHz bandwidth scope would be approximately 100 MHz (but typically slightly higher to ensure that the scope meets warranted specifications under all environmental conditions). The cutoff frequency of a 1 GHz bandwidth scope would be approximately 1 GHz (or slightly higher). Keysight uses vector network analyzers (VNA) to test the frequency response performance of their scopes. VNAs can test to higher frequencies than a typical entry-level FRA.

Since a signal's amplitude is down approximately 30% at the -3 dB cutoff frequency based on a sine wave input, Keysight recommends that the scope's bandwidth be at least 3X higher than the highest sine wave frequency anticipated to be tested. For example, if you anticipate the need to test analog signals up to 100 MHz in frequency, you should use a scope with a specified bandwidth of 300 MHz or higher. But for digital signals that contain multiple odd and even harmonics higher than the actual clock rate, Keysight recommends using scopes that have a specified bandwidth that are at least 5X higher than the highest digital clock rate in order to capture up to the 5th harmonic with reasonable accuracy. For example, if you need to test digital signals in a system based on a 200 MHz clock, Keysight recommends using a scope with a specified bandwidth of 1 GHz or higher. If you used a 200 MHz bandwidth scope to capture and display and 200 MHz digital clock signal, it would appear more as a sine wave as opposed to the square wave.

Summary

Frequency response analysis testing (measured Bode plots) have a broad range of applications. Besides being used to characterize passive filters for audio applications or front-end system signal conditioning, frequency response analysis can be used to characterize active circuitry such as op amp circuits, as well for power supply characterization including power supply rejection ratio (PSRR) and control loop response analysis to test the stability and response timing of negative feedback amplifiers that regulate output voltage of DC-to-DC converters during load changes. And as we just discussed, frequency response analysis is used to test the bandwidth performance of a broad range test equipment, including oscilloscopes.

To learn more about frequency response analysis and oscilloscope specifications and theory, download Keysight's application notes listed in the table below.

About the Author



Johnnie L. Hancock

Johnnie Hancock is an oscilloscope product manager at Keysight Technologies. He began his career with Hewlett-Packard in 1979 as an R&D hardware designer and holds a patent for digital oscilloscope trigger-path amplifier calibration. Johnnie regularly speaks at technical conferences on a variety of topics related to oscilloscope measurements including automotive serial bus applications, power supply characterization, and frequency response testing. He is also the author of many articles, white papers, and application notes. Johnnie graduated from the University of South Florida with a degree in electrical engineering, and he has a passion for helping EE students learn how to more effectively use test equipment. In his spare time, he enjoys fishing, kayaking, and spending time with his four grandchildren.

Related Literature

Publication Title	Publication Type	Publication Number
Frequency Response Analysis (Bode plots)	Application note	5992-4010EN
Control Loop Response Testing	Application note	5992-0593EN
Power Supply Rejection Ratio (PSRR) Testing	Application note	5992-0594EN
Understanding Oscilloscope Frequency Response and Its Effect on Rise-Time Accuracy	Application note	5988-8080EN
Evaluating Oscilloscope Bandwidth	Application note	5989-5733EN
Evaluating Oscilloscope Sample Rates	Application note	5989-5732EN
How to Select Your Next Oscilloscope: 12 Tips on What to Consider	Application note	5991-2714EN
Oscilloscope Fundamentals	Application note	5989-8064EN
Oscilloscope Probe Loading Experiment	Tutorial and Lab Guide	5990-9175EN

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