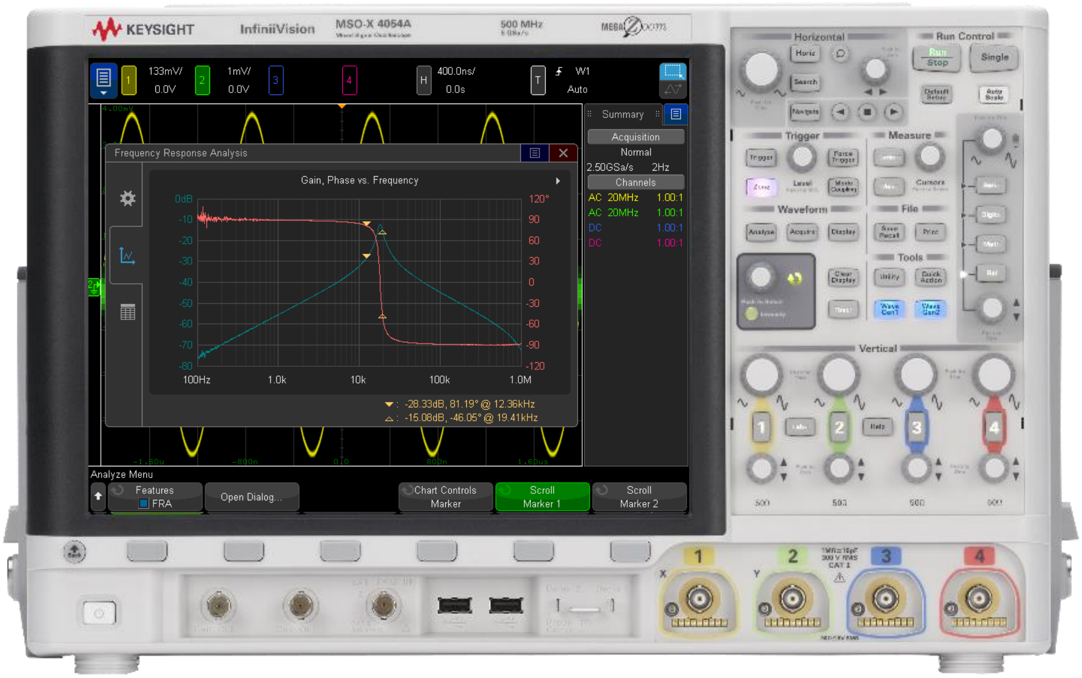
APPLICATION NOTE

Frequency Response Analysis (Bode Plots)

Using Keysight InfiniiVision X-Series Oscilloscopes

With many of today's electronic designs, performing frequency response analysis is often necessary to ensure they meet performance requirements. This domain of signal characterization allows you to observe how the outputs of your circuit designs respond across a broad spectrum of different frequency inputs. Failure to perform such analysis may result in faulty designs and products. Frequency response analysis (FRA) is critical in devices such as passive and active filters, amplifiers, and negative feedback networks of switch mode power supplies (closed-loop response).

In this application note, you will learn about what FRA is and see three different measurement examples illustrating how to use the application.



KEYSIGHT
TECHNOLOGIES

What is Frequency Response Analysis?

If you are not familiar with frequency response measurements, remember back to your electrical engineering college days when you were required to create Bode plots. 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). The plot is based on poles and zeros of the circuit's transfer function. For example, the transfer function, T(jω), of a series R-L-C passive circuit (Figure 1) will have 2 poles and 1 zero (at 0 Hz). This results in a bandpass filter based on the following formula:

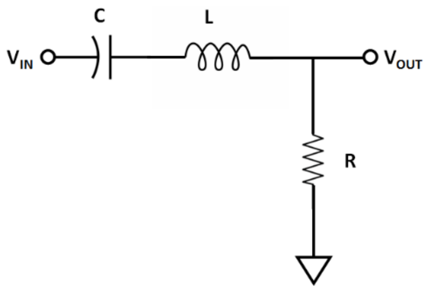


Figure 1. Series R-L-C passive circuit.

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

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

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

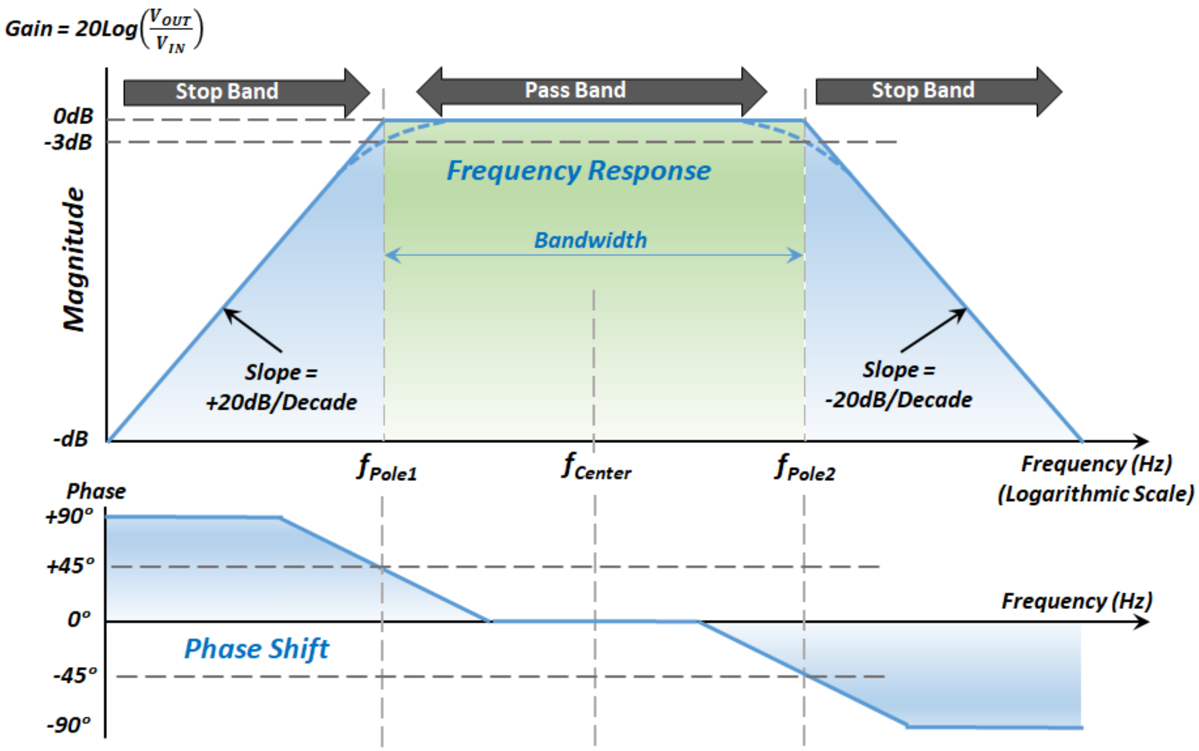


Figure 2. Gain and phase Bode plots of a series R-L-C.

Assuming R = 50 Ω, L = 10 µH, and C = 1 µF, f_{Pole1} theoretically occurs at 3.2 kHz and f_{Pole2} theoretically occurs at 800 kHz. These are the frequencies where the ± 20 dB/decade straight-line approximations intersect 0 dB as shown in 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 find that the gain would be down approximately 3 dB and phase would be approximately ± 45°at each of the two pole frequencies.

So how do you test a design to verify actual performance versus the theoretical?

Automatic Frequency Response Analysis

Unless you are fortunate enough to have access to a dedicated Frequency Response Analyzer (FRA) or Vector Network Analyzer (VNA), this analysis has historically been a very tedious measurement exercise using an oscilloscope along with a function generator as the sinewave input source. It involved lots of manually-performed amplitude and timing measurements to determine gain ($A = 20 \log V_{OUT}/V_{IN}$) and phase at multiple frequency settings. This is the method that most EE students use today. However, the introduction of Keysight's frequency response analysis (FRA) application has completely changed this. For the first time, you can perform automatic frequency response measurements using the scope's built-in waveform generator as a sinewave input source, along with automated in-scope FRA software.

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.

Frequency Response Analysis

Frequency Mode: Sweep

Frequency (Start, Stop): 100.0Hz 20.00MHz

Points: 1000

Source (Input, Output): 1 2

WaveGen (Amp, Imp): 200mVpp 50 Ω

☐ Amplitude Profile

Figure 3. InfiniiVision “Settings” menu used to establish test conditions for a frequency response analysis test.

Before you perform a frequency response test to produce a gain and phase Bode plot, you should have a basic understanding of the test parameters in the InfiniiVision scope’s FRA “Settings” menu shown in Figure 3.

- Frequency Mode:
  - **Sweep –** The scope performs multiple gain and phase measurements at frequencies ranging from the specified Start frequency to the specified Stop frequency. This produces an overlaid logarithmic gain plot and linear phase plot versus frequency. Measurement results can also be viewed in a table.
  - **Single –** The scope performs a gain and phase measurement at just one specified frequency producing numerical gain and phase test results only (no plot).
- Frequency (Start, Stop): The specified **Start** frequency is the initial test point and can be set as low as 10 Hz. The specified **Stop** frequency is the final test point and can be set as high as 20 MHz.
- Points: The specified number of frequencies to test (1 to 1000) across the Start/Stop sweep range. A higher number of test points provides more resolution; however, it will take longer to plot all the data.
- Source (Input, Output): The specified oscilloscope input source (channel-1, channel-2, channel-3, or channel-4) and the specified output source (channel-1, channel-2, channel-3, or channel-4).
- WaveGen (Amp, Imp): The specified test amplitude and load impedance. For linear systems, a higher test amplitude will typically provide measurements with higher dynamic range. But when testing systems that can become saturated and then exhibit non-linearities, such as feedback amplifier circuits, a test amplitude that is set too high can cause waveform distortions and inaccurate test results.
- Amplitude Profile: If turned **ON** the test amplitude can be specified to increase or decrease linearly from decade-to-decade frequencies, as opposed to using a fixed test amplitude across the entire Start/Stop sweep range. This test mode can be useful for optimizing dynamic range when testing systems that can sometimes exhibit non-linearities. Note that amplitude profiling is not available in the 1000 X-Series scopes.

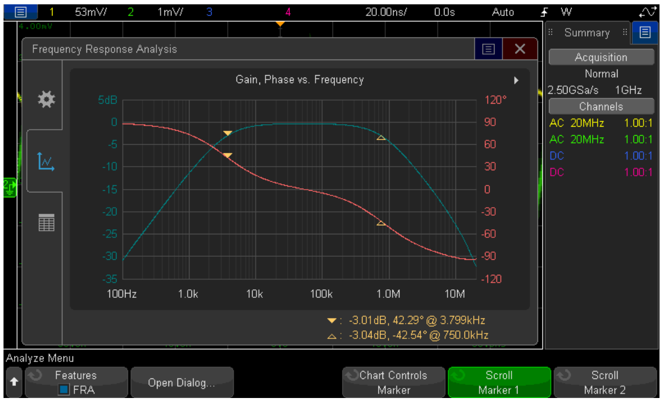


Figure 4. Gain and phase plot of a series R-L-C bandpass filter (gain = blue trace, phase = orange trace).

#	Frequency	Amplitude	Gain	Phase
291	3445.9Hz	0.2000Vpp	-3.44dB	45.18°
292	3488.2Hz	0.2000Vpp	-3.40dB	44.82°
293	3531.0Hz	0.2000Vpp	-3.32dB	44.47°
294	3574.4Hz	0.2000Vpp	-3.25dB	44.26°
295	3618.3Hz	0.2000Vpp	-3.23dB	43.77°
296	3662.7Hz	0.2000Vpp	-3.16dB	43.42°
297	3707.7Hz	0.2000Vpp	-3.13dB	43.07°
298	3753.2Hz	0.2000Vpp	-3.09dB	42.71°
299	3799.3Hz	0.2000Vpp	-3.05dB	42.36°
300	3846.0Hz	0.2000Vpp	-2.97dB	42.08°
301	3893.2Hz	0.2000Vpp	-2.93dB	41.66°
302	3941.0Hz	0.2000Vpp	-2.89dB	41.47°
303	3989.4Hz	0.2000Vpp	-2.84dB	40.96°
304	4038.4Hz	0.2000Vpp	-2.78dB	40.75°

Figure 5. Exportable (.csv format) gain and phase numerical test results of a series R-L-C bandpass filter.

Figures 4 and 5 show the resulting Bode plot and tabular results from a 100 Hz to 20 MHz sweep on the series R-L-C bandpass filter from Figure 1. Using the scope's dual-tracking gain and phase markers, you can see the lower -3 dB cut-off frequency occurs at 3.8 kHz and the upper -3 dB cut-off frequency occurs at 750 kHz. The reason for the difference between the theoretical and the actual cut-off frequencies is due to real-world imperfections such as device tolerances and lead inductances. This further illustrates the importance of performing real testing.

One advantage of Keysight's oscilloscope-based FRA test solution is that you can view the V_{IN} and V_{OUT} time-domain waveforms during the sweep. This is important for two reasons. First, it provides positive visual feedback that your circuit-under-test is operating during the test. Secondly, it allows you to monitor waveform shapes for possible non-linearities due to overdriving an active circuit. This is not possible when using a standalone one-box Frequency Response Analyzer. Figure 6 shows an example of normal sinusoidal wave shapes of V_{IN} and V_{OUT} while using a test amplitude of 200 mV_{PP}. Figure 7 shows an example of distorted/non-sinusoidal wave shapes while testing at 1 Vpp. It is important that V_{IN} and V_{OUT} remain sinusoidal during the entire sweep to avoid gain and phase errors.

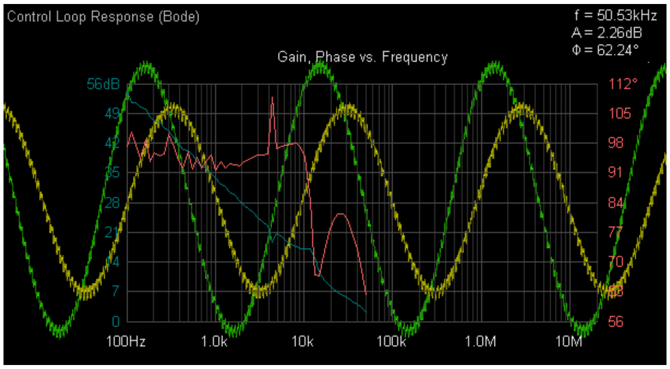


Figure 6. Normal sinusoidal wave shapes of V_{IN} and V_{OUT} during FRA sweep.

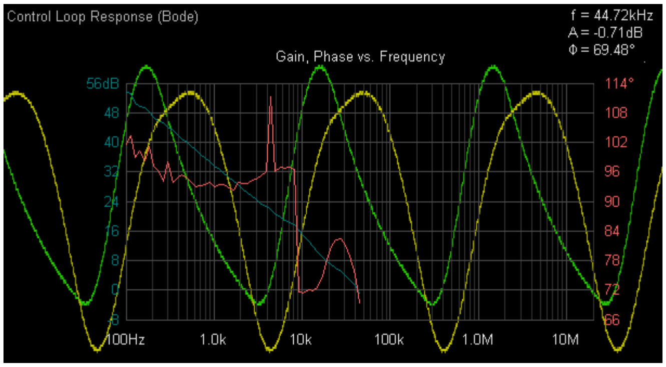


Figure 7. Distorted sinusoidal wave shapes of V_{IN} and V_{OUT} due to overdriven conditions.

Control Loop Response Testing

Frequency response analysis is also important in testing the stability of negative feedback amplifier compensation networks of switch mode power supplies, as shown in Figure 8. With sudden load changes, such as an increased load (load requires more current), output voltage momentarily drops. The negative feedback amplifier should drive the output voltage back up to the intended regulated output voltage level. But if the feedback amplifier network responds too quickly, it could result in an unstable/oscillating output. Responding too slowly could result in failing to keep the load properly powered-up and operating. Performing an in-circuit Control Loop Response test (Bode plot) is important to ensure that these conditions don't occur.

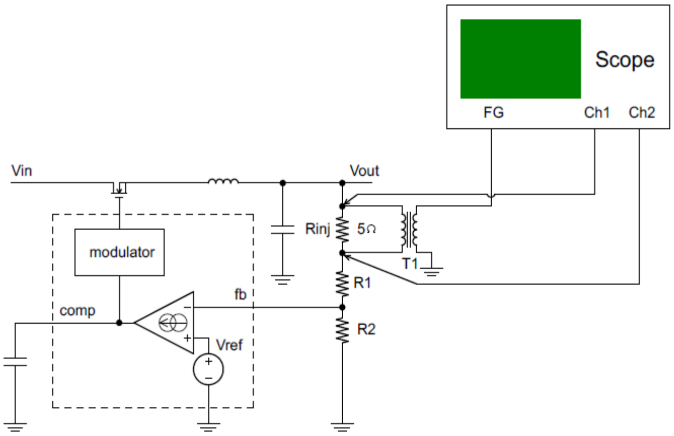
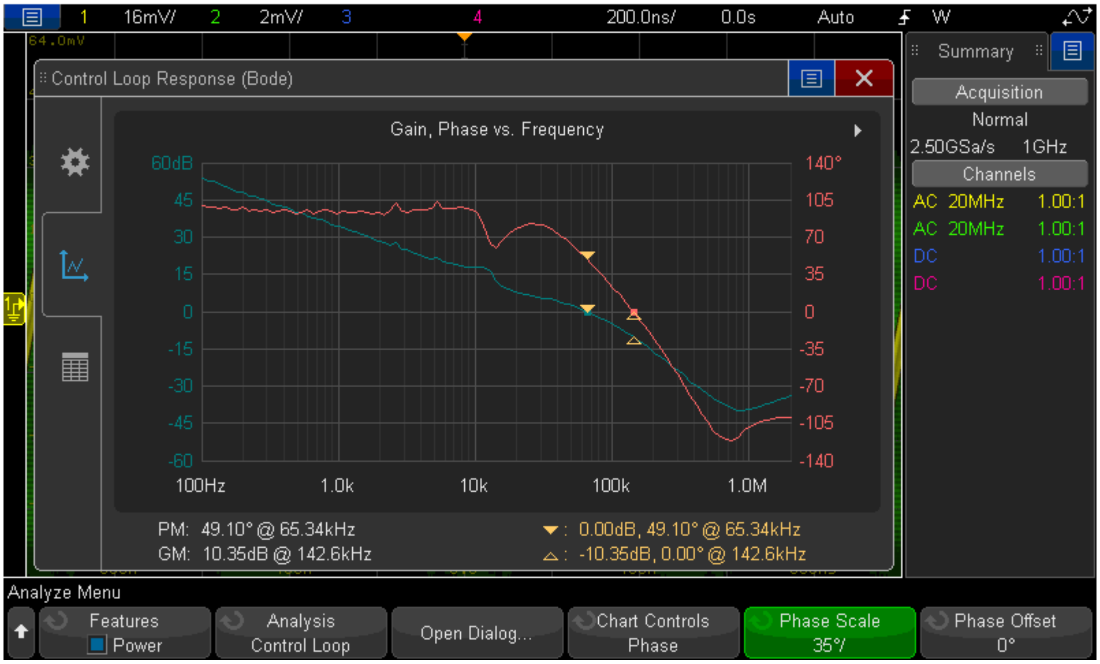


Figure 8. Testing the control loop of a switch mode power supply.

Figure 9 shows the results of an in-circuit control loop response measurement on the feedback network of a switch mode power supply. Critical measurements include phase margin (PM) and gain margin (GM). InfiniiVision oscilloscopes display this automatically at the end of a frequency response test if licensed with the optional Power Measurements software package. In this test, 49° of phase margin at the 0 dB cross-over frequency and 10 dB of gain margin at the 0° cross-over frequency are sufficient to insure stability.



PM: 49.10° @ 65.34kHz
GM: 10.35dB @ 142.6kHz
▼: 0.00dB, 49.10° @ 65.34kHz
△: -10.35dB, 0.00° @ 142.6kHz

Figure 9. Control Loop Response test on the negative feedback network of a switch mode power supply.

To learn more about Control Loop Response testing refer to the application note on this topic listed near the end of this document. This application note also includes a discussion of the required accessories and recommended probes to perform this in-circuit measurement.

Power Supply Rejection Ratio Testing

Power Supply Rejection Ratio (PSRR) is another type of frequency response measurement that is performed primarily on linear dc-to-dc converters such as low-voltage drop-out regulators (LDOs). Linear converters are often used in applications where it is important that the DC output remain extremely flat with minimal noise/ripple. To test the converter's vulnerability to disturbances on the input, the DC input is modulated with a variable frequency AC signal.

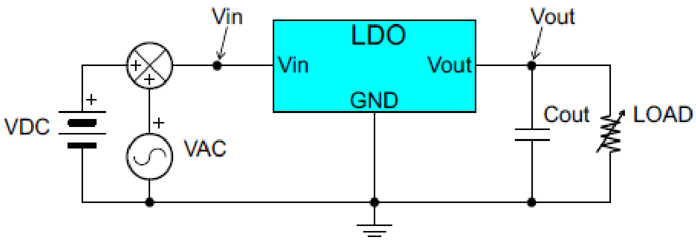
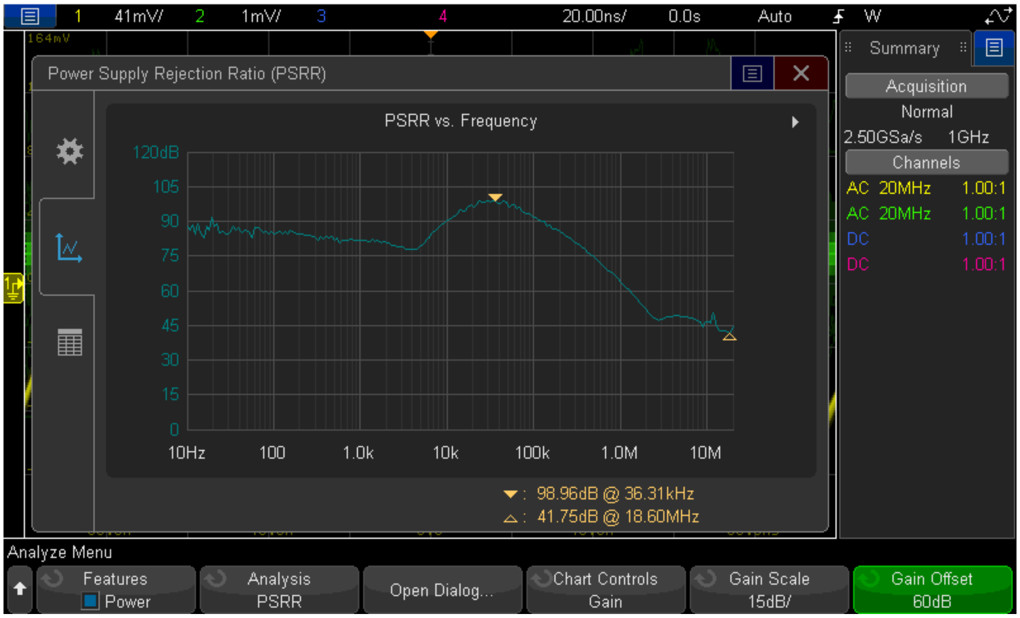


Figure 10. Testing PSRR of a linear voltage regulator.

Figure 10 shows a block diagram of a PSRR measurement test setup. It should be noted however that "rejection" is the inverse of "gain". Where a typical frequency response test plots gain versus frequency based on 20Log(V_{OUT}/V_{IN}), PSSR plots rejection versus frequency based on 20Log(V_{IN}/V_{OUT}).

Figure 11 shows the results of a PSSR test on a linear power supply. In this test the power supply measured a maximum rejection of 99 dB at 36 kHz and a minimum rejection of 42 dB at 19 MHz near the end of the sweep.

To learn more about Power Supply Reject Ratio (PSRR) testing refer to the application note on this topic listed near the end of this document. This application note includes a discussion of the required accessories and recommended probes to perform this in-circuit measurement.



Normal
2.50GSa/s 1GHz
AC 20MHz 1.00:1
AC 20MHz 1.00:1
DC 1.00:1
DC 1.00:1

▼: 98.96dB @ 36.31kHz
△: 41.75dB @ 18.60MHz

Features: Power
Analysis: PSRR
Chart Controls: Gain
Gain Scale: 15dB/
Gain Offset: 60dB

Figure 11. Power Supply Rejection Ratio (PSRR) test on a linear power supply.

System Requirements

Frequency response analysis (FRA) comes standard on all entry-level InfiniiVision 1000 X-Series oscilloscope “G” models, which include a built-in waveform generator. Frequency response analysis is included in the higher-performance InfiniiVision 3000T X-, 4000 X-, and 6000 X-Series oscilloscopes when licensed with the power, embedded, automotive, aero, USB, or ultimate bundle software packages. The datasheets for each software package can be found below with more details. In addition to general-purpose FRA measurements (gain & phase Bode plots), the optional power measurements software package includes the Control Loop Response test with automatic phase margin (PM) and gain margin (GM) measurements, and the Power Supply Rejection Ratio (PSRR) test with automatic gain inversion (rejection) plotting.

Summary

Performing frequency response measurements is often necessary to ensure that circuit designs meet required bandwidth performance specifications and to insure system stability. Performing these measurements manually with a traditional oscilloscope and function generator can be a tedious process with insufficient dynamic range test results. Furthermore, dedicated frequency response analyzers are often either not available or too difficult to use. Keysight’s InfiniiVision oscilloscopes now offer built-in FRA measurements with:

- Built-in waveform generator
- Automated FRA software
- Dual-tracking gain and phase markers
- Monitor time-domain waveforms for possible distortions during test
- Optimize dynamic range with amplitude profiling
- Automatic phase and gain margin measurements

Related Literature

Publication title	Publication type	Publication number
Control Loop Response Testing	Application note	5992-0593EN
Power Supply Rejection Ratio (PSRR) Testing	Application note	5992-0594EN
InfiniiVision 1000 X-Series Oscilloscopes	Data sheet	5992-3484EN
InfiniiVision 3000T X-Series Oscilloscopes	Data sheet	5992-0140EN
InfiniiVision 4000 X-Series Oscilloscopes	Data sheet	5990-1103EN
InfiniiVision 6000 X-Series Oscilloscopes	Data sheet	5991-4087EN
Power Software Package (FRA included)	Data sheet	5992-3925EN
Automotive Software Package (FRA included)	Data sheet	5992-3912EN
Embedded Software Package (FRA included)	Data sheet	5992-3924EN
Aero Software Package (FRA included)	Data sheet	5992-3910EN
USB Software Package (FRA included)	Data sheet	5992-3920EN
Ultimate Bundle Software Package (FRA included)	Data sheet	5992-3918EN

To configure your product and request a quote:
http://www.keysight.com/find/software

Contact your Keysight representative or authorized partner for more information or to place an order:
www.keysight.com/find/contactus

Learn more at: www.keysight.com

For more information on Keysight Technologies' products, applications or services, please contact your local Keysight office. The complete list is available at:
www.keysight.com/find/contactus

KEYSIGHT
TECHNOLOGIES