Understanding and measuring an oscilloscope’s frequency response

This vital performance parameter impacts measurement accuracy and credibility.

By Brig Asay, Agilent Technologies

Frequency response is defined as:

A measure of the effectiveness with which a circuit, device, or system transmits the different frequencies applied to it. It is a phasor whose magnitude is the ratio of the magnitude of the output signal to that of a sine-wave input, and whose phase is that of the output with respect to the input.

Frequency response curves are used as a measure of an oscilloscope’s performance or quality. An oscilloscope’s frequency response is important and should be understood when purchasing one because the flatter the frequency response, the more accurate the oscilloscope will represent the signal it is measuring, Figure 1.

Figure 1a and 1b: An example of measurement differences caused by different frequency responses, notice that the rise time is faster on the image on the right and the measurement twice as repeatable (difference between min/max)

This means greater measurement repeatability and accuracy. As a result, oscilloscopes strive to achieve a “flat” response, with vendors often using digital signal processing (DSP) to improve the flatness of their hardware response. Typically, oscilloscope vendors do not specify their
frequency response characteristics, but the response can be measured or you can ask the oscilloscope vendor for this data (they will frequently satisfy such requests).

The frequency response of an oscilloscope is usually characterized by the magnitude of the system's response (measured in decibels) and the phase (measured in radians) versus frequency. There are several different methods used for measuring the frequency response of a system. For the purpose of this paper, we will focus on the method oscilloscope vendors use to specify their measurement - simply sweep a constant-amplitude pure tone through the entire frequency range of the oscilloscope and measure the output level and phase shift relative to the input.

In addition to the multiple methods used to measure the response, there are two ways to plot the frequency response (the Bode plot or the Nyquist plot). This paper will focus on the Bode plot. A flat frequency response (ideal for oscilloscopes) means the plot stays near 0 (either dB or rads) until the high frequency of the oscilloscope. Any variation from zero means less accuracy, Figure 2.

Oscilloscope vendors measure the frequency response using a swept sine wave technique. This system splits the output of a Vector Signal Generator (VSG) into a power meter and the oscilloscope under test (DUT).

For example, to measure Agilent’s 33 GHz Infiniium DSAX93204A oscilloscope, it is recommended that you use Agilent’s E8257D with option 540 (allowing for 40 GHz of bandwidth). It is also important to ensure that the response of the signal generator is flatter than the response of the oscilloscope (it is important to understand the specifications of the signal generator).
In addition to the signal generator, equipment such as a power splitter, a power meter, power sensor, cabling, and SMA connects are also required. The frequency response measurement is only as good as the cables and external devices being used. Purchasing equipment that is less accurate will add to measurement errors and incorrect frequency response measurements of the oscilloscope. Agilent recommends the following list of equipment for measuring the frequency response of its Infiniium 90000 X-Series oscilloscope:

<table>
<thead>
<tr>
<th>Description</th>
<th>Critical Specification</th>
<th>Recommended Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Generator</td>
<td>Maximum Frequency</td>
<td>E8257D with option 540</td>
</tr>
<tr>
<td>Power Splitter</td>
<td>Maximum Frequency</td>
<td>Agilent 11667D</td>
</tr>
<tr>
<td>Power Meter</td>
<td>Agilent E-Series</td>
<td>Agilent E4419D</td>
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<tr>
<td>Microwave cable</td>
<td>Maximum Frequency</td>
<td>Agilent N2812A</td>
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<tr>
<td>Power Sensor</td>
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<td>Agilent 8487A</td>
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<td>SMA Adaptors</td>
<td>3.5mm (m) to 3.5mm (m)</td>
<td>Agilent E2655-83202</td>
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</tbody>
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Table 1: Recommended equipment to measure the frequency response of the Agilent 90000 X-Series oscilloscope

The equipment is then placed as shown in Figure 3:

Figure 3: Configuration to test the frequency response

To measure the frequency response of an oscilloscope the following procedure should be followed:
1) Preset the power meter.
2) Ensure that the power sensor is disconnected from any source and zero the meter.
3) Connect the power sensor to the power meter's Power Reference connector and calibrate the meter.
4) Make the connections to oscilloscope channel 1 as shown in the connection diagram shown in Image 3.
5) Set up the Power Meter to display measurements in units of Watts.
6) Press Default Setup on the oscilloscope. Then configure the scope as follows:
   a. Ensure Channel 1 is displayed and all other channels are turned off.
   b. Set the vertical sensitivity of channel 1 to 100 mV/div
   c. Set the horizontal scale to 16 ns/div (to display 8 cycles of a 50 MHz waveform).
   d. Pull down the Setup menu, select Acquisition, and then set up the acquisition parameters as follows:
      I. Memory Depth = Automatic
      II. Sampling rate = Maximum (80 GSa/s)
      III. Sin(x)/x Interpolation filter enabled
      IV. Averaging = Disabled
   e. Pull down the Measure menu, select Voltage and then select Vrms,
      Figure 4.

   Figure 4: Selecting Vrms from measurement menu

7) Set the generator to apply a 50 MHz sine wave with a peak-to-peak amplitude of about 4 divisions.
8) Measure the input power to the scope channel and convert this measurement to Volts RMS using the expression: 
   \[ V_{in} = \sqrt{P_{meas} \times 50\Omega} \]
9) Press the Clear Display key on the scope and record the scope V\text{rms} reading. For all scope readings in this procedure, use the mean value in the Measurements display area at the bottom of the screen.

10) Calculate the reference gain as follows:

\[ Gain_{50 \text{MHz}} = \frac{V_{\text{out @ 50 MHz}}}{V_{\text{in @ 50 MHz}}} \]

11) Change the generator frequency to 100MHz

12) Repeat steps 8 and 9

13) Calculate the gain at this frequency with the following expression (New frequency)

\[ Gain_{\text{New frequency}} = 20\log_{10} \left( \frac{V_{\text{out new frequency}}}{V_{\text{in new frequency}}} \right) \]

14) \[ Gain_{\text{New frequency}} \]

15) Record this value as the Calculated Gain @100MHz Freq (we now have two points - one at 50MHz and another at 100MHz).

16) Repeat steps 12 to 14 at 50MHz steps (or your chosen increment) until you reach the full bandwidth of the oscilloscope.

Notice that a flat frequency response will give a value of “0” dB because \( V_{\text{out}} \) and \( V_{\text{in}} \) will be equal to the “Gain at 50 MHz” value. By sweeping the signal generator over a range of frequencies, we are able to very accurately characterize the frequency response of the oscilloscope and now have an accurate depiction of the magnitude response. Unfortunately, the plot measured earlier was only taken on a single channel at 100mV/div. To properly measure an oscilloscope, one must measure every vertical setting on every channel. This can be very time consuming as it means dozens of measurements. Due to this, oscilloscope vendors will usually share their frequency response data if they are asked.

Currently, only one vendor specifies the magnitude flatness of their oscilloscope. The specification is the following:

\[\text{Passband flatness (20, 50, 100 mV/div)} = \pm 0.5 \text{dB to 50\% of nominal bandwidth}\]

The passband flatness specification signifies that the oscilloscope to half the bandwidth will only vary by 0.5dB. For instance, on a 20 GHz oscilloscope, the specification is good to 10 GHz which means the flatness could vary greatly above 10 GHz. Figure 5 highlights Agilent’s 90000 X-Series frequency response. It varies by less than 0.5dB to 30 GHz. Above 30 GHz, you can see a slight gain.
As mentioned in the introduction, oscilloscope vendors now use digital signal processing (DSP) to improve their frequency response. Fifteen years ago it was almost taboo to use DSP to correct the response, but major advances in hardware processing speeds and understanding have led to more acceptance of the DSP correction method. By using DSP, oscilloscope vendors are able to correct their response to look flatter than previously possible with hardware only. DSP also enables oscilloscope vendors to offer more than one frequency response.

For instance, the Agilent 90000 X-Series offers two different frequency responses: the maximally flat / brickwall response and the maximally flat / Gaussian response. The response labeled flat/brickwall is a response that matches the response found in Figure 5. The response stays very flat until it reaches the designated bandwidth and then rolls off very quickly. Notice that the response at 35 GHz is more than 20dB down. The advantage of a flat/brickwall response is that it will track rise times very accurately as long as the rise time remains within the bandwidth of the oscilloscope.

The other advantage is that the response minimizes aliasing. The major disadvantage is that the oscilloscope will appear to “ring” if the rise time exceeds the bandwidth of the oscilloscope (Figure 6).
The Gaussian response rolls off its magnitude very slowly, similar to the response that you would expect to see with a cable (Figure 7). The advantage of the Gaussian response is that you will not see the “ringing” effect for rise times that exceed the oscilloscope bandwidth. However, the Gaussian roll off will not track the rise time as accurately as the brickwall response.

To maximize the accuracy of the oscilloscope through DSP, oscilloscope vendors will measure the hardware frequency response of hundreds of oscilloscopes and then determine the baseline correction. The baseline correction can be only as good as the average of all the
measurements, which means there is potential for oscilloscope-to-oscilloscope variation (see Figure 8).

![Figure 8a and 8b: The blue line represents the frequency response of two sampling oscilloscopes. Notice the variation between the two oscilloscope.](image)

While no oscilloscope vendor has addressed this variation in a real time / single shot oscilloscope, sampling oscilloscopes have a solution. Oscilloscope vendors can develop custom correction based on the response of an individual oscilloscope. Agilent’s System Impulse Response Correction is one such example of this software and is the only such solution available on the market today. Agilent bases its correction on the exact hardware of the sampling oscilloscope module which limits the errors. This means a flat response for each oscilloscope without any variation and ensures that measurements are exactly the same from oscilloscope to oscilloscope.

Oscilloscope frequency response is largely an unspecified measurement of an oscilloscope. Currently, Tektronix is the only vendor to provide the specification in their real time oscilloscope data sheet, but their specification is incomplete which makes understanding the response difficult. Most vendors will provide this data if they are asked. This is important because the flatter the frequency response of the oscilloscope, the more accurately it will depict the signal it is measuring. A flat frequency response also means more repeatable measurements and less oscilloscope-to-oscilloscope variation. As a result, it is vital that you understand the frequency response of an oscilloscope before you purchase one.

About the author

Brig Asay manages product planning and strategic marketing for Agilent’s high-performance oscilloscope business. He joined Agilent Technologies in 2005 as a Technical Support Engineer. During his five years with Agilent, he has held positions as Marketing Operations Manager, where he oversaw the marketing budget and managed the technical support and learning products teams; and Technical Support Engineer, which he helped solve numerous customer problems. Previously to Agilent, Brig worked at Micron Technologies, Inc. as a Test Engineer. Brig
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