Fourier Theory & Practice, Part II: Practice
Operating the Agilent 54600 Series Scope with Measurement/Storage Module

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Introduction:

This product note provides a brief review of Fourier theory, especially the unique behavior of the FFT. The note also describes some typical applications and provides some tips on how to get the most out of the FFT capability of the Agilent 54600 series scopes with an Agilent 54657A or Agilent 54658A FFT module.

Practice:

Adding the Measurement/ Storage module to the scope adds additional waveform math capability, including FFT. These functions appear in the softkey menu under the ± (math) key. There are two math functions available, F1 and F2. The FFT function is available on Function F2. Function F2 can use function F1 as an operand, allowing an FFT to be performed on the result of F1. By setting function F1 to Channel 1 - Channel 2, and setting F2 to the FFT of F1, the FFT of a differential measurement can be obtained. The Measurement/Storage Module operating manual provides a more detailed discussion of these math functions.

The scope can display the time domain waveform and the frequency domain spectrum simultaneously or individually. Normally, the sample points are not connected. For best frequency domain display, the sample points should be connected with lines (vectors). This can be accomplished by turning off all (time domain) channels and turning on only the FFT function. Alternatively, the Vectors On/Off softkey (on the Display menu) can be turned On and the STOP key pressed. Either of these actions allow the frequency domain samples to be connected by vectors which causes the display to appear more like a spectrum analyzer.

The vertical axis of the FFT display is logarithmic, displayed in dBV (decibels relative to 1 Volt RMS).

$$dB\ V = 20\ log\ (V_{RMS})$$

Thus, a 1 Volt RMS sinewave (2.8 Volts peak-to-peak) will read 0 dBV on the FFT display.

Some instrument users work in terms of dBm (decibels relative to 1 mW). With a 50 Ω termination installed at the input to the scope, dBm is given by

$$dBm = 20\ log\ (V_{RMS}\ /\ 0.223)$$

To obtain dBm from dBV (as displayed by the scope), add 13.01 to the dBV value. (This conversion is valid only if a 50 Ω resistor is supplied at the point the voltage measurement is being made.)

The definition and use of decibels is a lengthy topic all by itself. For more information, see Reference 6.

When the FFT is operating, the cursors can read out the amplitude in dBV and the frequency in Hertz. (The cursor source must be set to F2.) Pressing the FIND PEAKS key provides for easy cursor placement by automatically placing the cursors on the two largest spectral lines.

The frequency span of the FFT is inherently tied to the time/division knob. Under the FFT menu (selected under the ± key), there are additional controls for Center Frequency and Frequency Span. Adjusting the time/division knob modifies the frequency span, but leaves the start frequency (that is, the leftmost frequency on the display) constant. The Center frequency and Frequency Span controls are used for zooming in on particular frequencies of interest.

If the time domain waveform goes off the top or bottom of the scope graticule, the waveform data internal to the scope is clipped (or limited) to the maximum or minimum allowable value. If the waveform is clipped, the FFT operates on a distorted time domain waveform and produces a corresponding distortion in the frequency domain (in the form of erroneous frequency components). To avoid this type of problem, the volts/div controls on the scope must be set so that the entire waveform is on screen.

Scope Bandwidth

Keep in mind that the normal response of the scope rolls off at high frequencies (Figure 13). The scope is guaranteed to be no more than 3 dB below its low frequency response at the specified bandwidth.
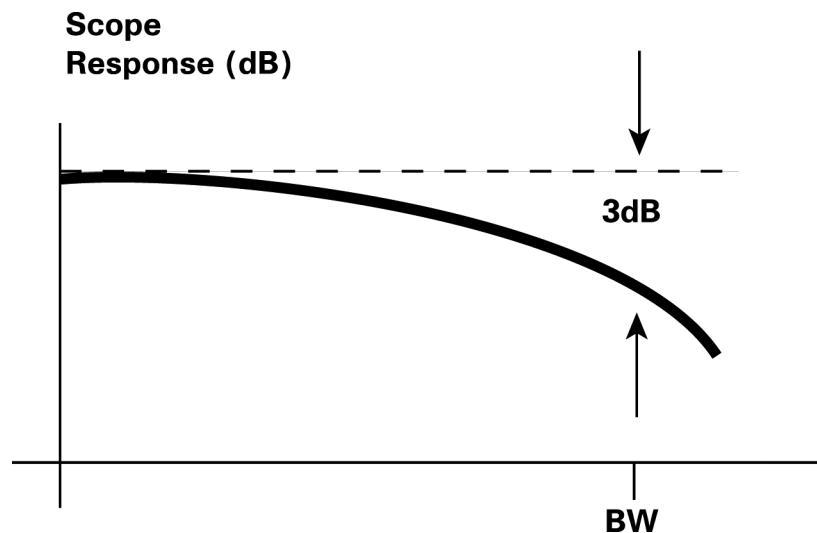

Fig. 13: The frequency response of an oscilloscope rolls off with increasing frequency.

This means that a sine wave with a frequency at the bandwidth of the scope may be measured too low by as much as 30%. Since the FFT operates on the time domain data, this error will exist in both the time domain and the frequency domain.

The FFT computation is capable of displaying frequency spans as high as 20 GHz. Since the bandwidth of the scope's input circuits roll off well below this, the FFT results are not useful out to 20 GHz. However, the scope response does not abruptly end at the specified bandwidth so frequency components above the bandwidth can still be identified.

Dynamic Range

The dynamic range of a frequency domain measurement is the difference (in decibels) between the largest signal and the smallest signal which can be reliably measured at the same time (Figure 14). The largest measurable signal is a full scale (8 division) waveform in the time domain.
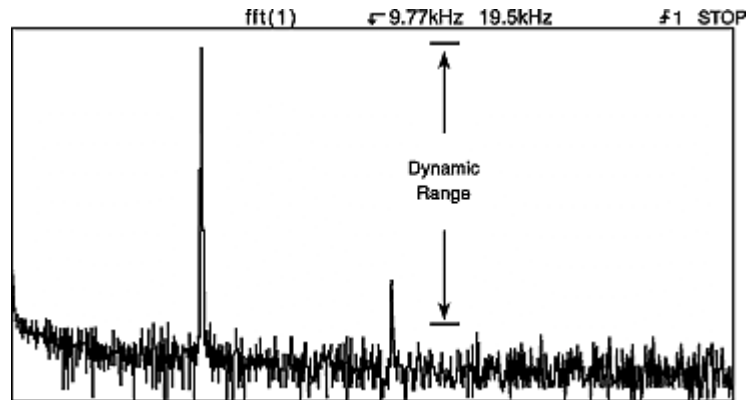
Fig. 14: The dynamic range of a frequency domain measurement is the difference between the largest and smallest signals that can be measured simultaneously.

The noise floor of the measurement determines the smallest signal that can be reliably measured. Any signal below the noise cannot be discerned. Distortion products or sampling artifacts may also limit the dynamic range.

The typical dynamic range of the FFT measurement is 50 dB. On most timebase settings, the dynamic range is limited by the noise floor of the scope. In some cases, spurious responses relating to the sampling process will limit the dynamic range as these spurious responses obscure legitimate signals. The use of averaging generally increases the dynamic range of the measurement by lowering the noise floor and reducing responses due to sampling.

Sampling

The Agilent 54603B scope has a maximum sample rate of 20 MSa/sec. The single-shot bandwidth in the time domain is specified at 1/10 of the sample rate, providing at least 10 sample points per period at the highest frequency. Reliable single-shot operation with the FFT function active occurs with time/div settings of 20 μsec/div or slower. (On faster time/div settings, a full time record may not be acquired on one trigger event, resulting in a poor FFT measurement.) FFT operation on 20 μsec/div results in a maximum frequency display of 5 MHz, which defines the useful single-shot capability of the FFT.

As mentioned earlier, repetitive sampling techniques allow the scope to digitize waveforms much higher in frequency than 5 MHz as long as they are repetitive. The FFT function accurately computes the frequency content of repetitive waveforms up to the bandwidth of the scope.

On time/div settings faster than 20 μsec/div, artifacts of the sampling process, not viewable in the time domain, may show up in the frequency domain. These artifacts may appear as spectral lines at integer harmonics of the sample rate or as intermodulation between the sample clock and the input frequency defined by:

$$f = nf_s \pm f_{in}$$
$$\text{where } f_s = 20 \text{ MHz sample clock}$$
$$f_{in} = \text{frequency of the input signal}$$
$$n = \text{any positive integer}$$

Additionally, the harmonics of the 20 MHz sample clock may appear near full scale during times when the time domain waveform has been only partially acquired (Figure 15). This is

because the waveform has missing sample points which tend to occur at intervals related to the sample rate. Once the waveform is fully acquired, spurious responses due to the sample clock will be much smaller and usually disappear. The intermodulation between the sample clock and the input frequency will typically be more than 5 0 dB below full scale. The use of averaging decreases the level of these responses.
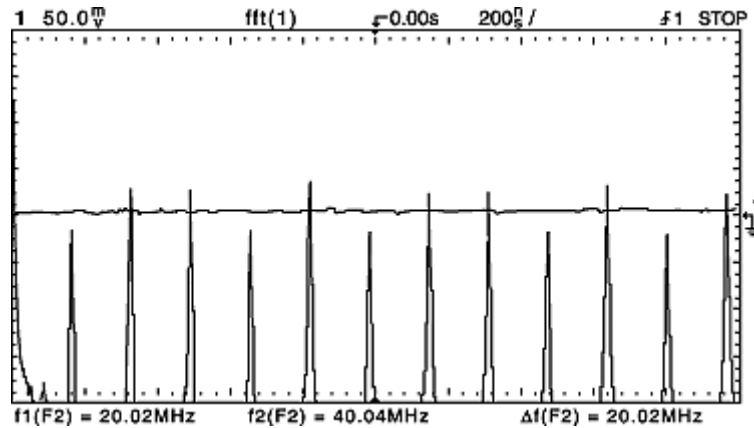

**Fig. 15: On time/div settings faster than 20 µsec/div, the sampling clock
(and its harmonics) can appear until the wave form is completely acquired.**

Application 1:

Harmonic Distortion in a Sine Wave

Sine waves that are not perfectly shaped in the time domain generate harmonics in the frequency domain. This harmonic distortion appears at integer multiples of the sine wave's fundamental frequency. Viewing this distortion in the time domain is usually very difficult, unless the waveform is severely distorted. However, in the frequency domain, these harmonics are very apparent.
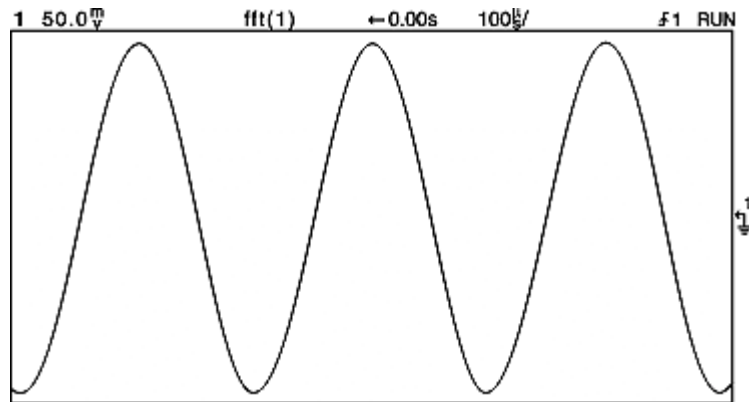

Fig. 16a: The time domain display of a sine wave.

Figure 16 a shows a sine wave which has harmonic distortion which is not visible in the time domain. However, the FFT function can easily determine the amount of harmonic distortion. Figure 16a shows a reasonable time/div setting for viewing the signal in the time domain. If the FFT is applied using this time/div setting, the spectral lines associated with the sine wave will appear in the far left hand side of the frequency domain display. In fact, the sine wave and its harmonics will be so tightly packed that it will be difficult to separate

them. Figure 16b shows a slower time/div setting which will lower the effective FFT sample rate, resulting in better frequency resolution and better separation of the sine wave's fundamental and harmonics. In addition, the center frequency and frequency span controls are used to zoom in on the desired portion of the spectrum as shown in Figure 16c.
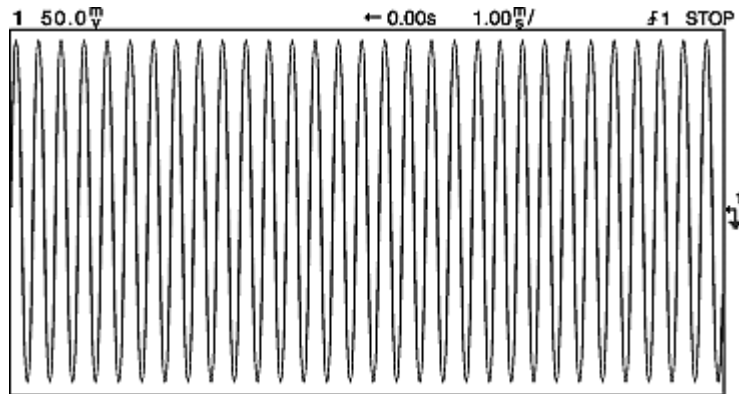

Fig. 16b: Decreasing the time/division setting compresses the time domain waveform and improves the frequency resolution of the FFT.
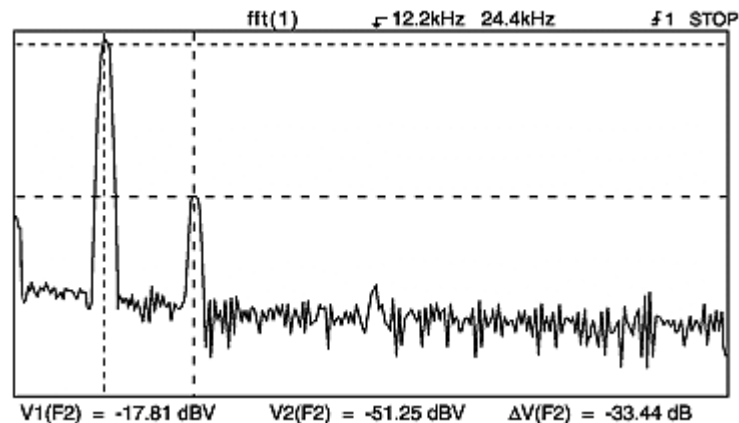

Fig. 16c : The FFT diplay shows the harmonic distortion present in the sine wave.

Note that the flattop window is used in this measurement, resulting in wider spectral lines but more consistent amplitude measurements. The Find Peaks softkey is used to place the cursors on the two largest spectral lines, giving absolute measurements of the fimdamental and the second harmonic. The cursors also read out in a relative manner, indicating that the second harmonic is 33 dB below the fundamental.

Application 2:

Video Colorburst Distortion

A special case of measuring the harmonic distortion in a sine wave is found in video applications. The 3.58 MHz color-subcarrier frequency embedded in an NTSC composite video signal has some amount of harmonic distortion associated with the subcarrier frequency. To measure just this signal, the scope's time/division and delay controls are used to zoom in on the color subcarrier in the time domain (Figure 17a).
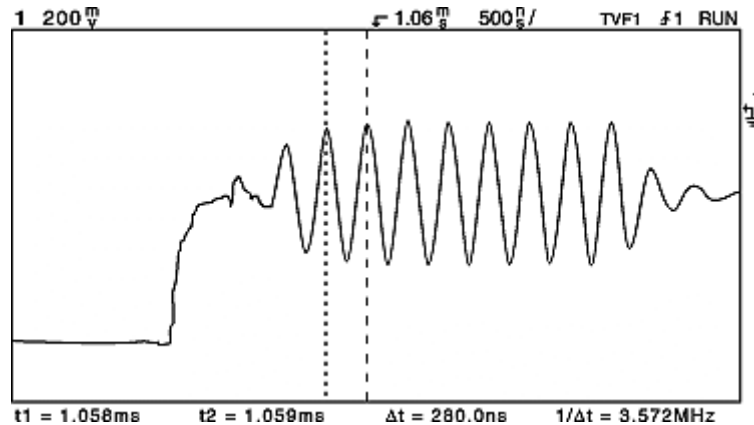
5

1 200 m̄V̄		⌐ 1.06 m̄s̄ 500 n̄s̄/	TVF1 ƒ1 RUN

t1 = 1.058ms   t2 = 1.059ms   Δt = 280.0ns   1/Δt = 3.572MHz

Figure 17a: The scope controls are used to zoom in on the color subcarrier in the time domain.

fft(1)   ⌐ 24.4MHz   48.8MHz   TVF1   1 STOP

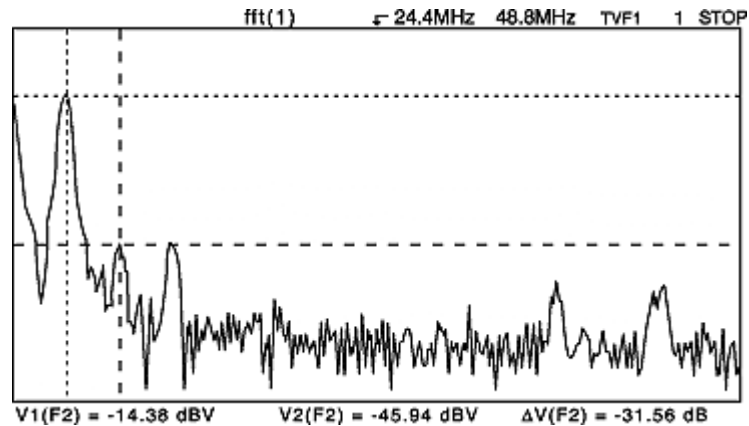V1(F2) = -14.38 dBV   V2(F2) = -45.94 dBV   ΔV(F2) = -31.56 dB

Fig. 17b: The FFT function shows that the harmonic content of the color subcarrier is more than 31 dB below the subcarrier.

The FFT function shows the harmonic content of the subcarrier in Figure 17b. Had the time/division and delay controls not been used to zoom in on the desired subcarrier, the entire video signal (with many frequency components) would have appeared in the frequency domain display. These frequency components would have obscured the color subcarrier and its harmonics. This example illustrates a general technique of using the time domain controls of the scope to select specific time intervals for FFT analysis.

Application 3:

Two-tone Frequency Identification

Another use of the FFT function is to identify frequency components that are difficult to view in the time domain. An example of such a waveform is the two-tone signal shown in Figure 18a. Two non-harmonically related sine waves are unstable when viewed in the time domain so Figure 18a is a single-shot capture of the waveform. Some estimate of the frequency of the tones might be possible but difficult in the time domain. Worse yet, identifying the frequencies of more than two tones is nearly impossible. The FFT function separates the two tones and displays them in the frequency domain (Figure 18b).
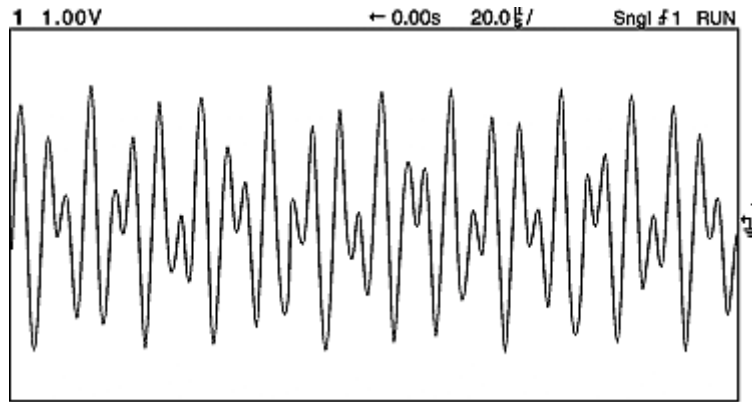
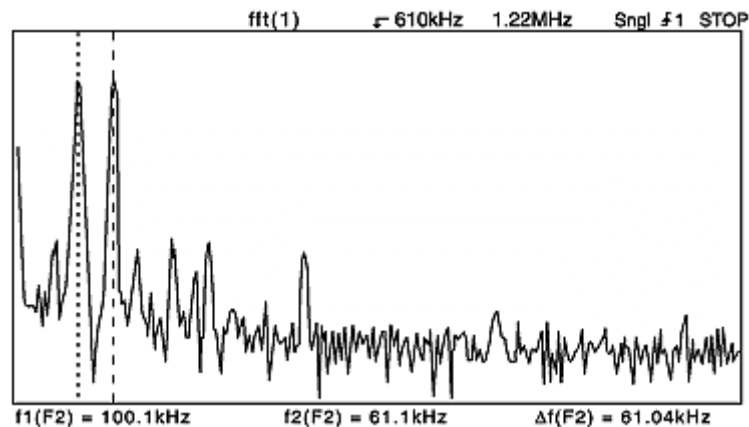**Fig. 18a: A two-tone signal in the time domain.**

Fig. 18b: The FFT display identifies the frequencies of the two tones.

The two largest spectral lines (with the cursors placed on top of them) are easily measured as 100 kHz. Note that the spectral lines are relatively thin due to the use of the Hanning window. This window, which optimizes frequency resolution, is appropriate for this measurement since the frequency content of the signal is being measured. Since two non-harmonically related sine waves are not stable (not repetitive) in the time domain, this measurement must be made in a single acquisition and is valid only on time/div settings of 20 msec or slower.

FFT Operating Hints

1) Keep the FFT effective sample rate greater than twice the signal bandwidth.
2) For best frequency resolution, use the HANNING window.
3) For best amplitude accuracy, use the FLATTOP window.
4) For the best frequency domain display, turn off the channel (time domain display) or press the STOP key.
5) Make sure the time domain waveform is not clipped on the display when using the FFT function.
6) Use time/div settings of 20 msec/div or slower for single-shot measurements.