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Fast Frequency Measurement Analyzes Modulation and Oscillators

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The oscilloscope and spectrum analyzer are standard equipment on any RF designer's bench. Oscilloscopes are time domain instruments. Both analog oscilloscopes and digital storage oscilloscopes perform the same basic function of displaying signal voltage versus time. Spectrum analyzers operate in the frequency domain, measuring the spectral components of signals in amplitude versus frequency form, typically using a swept narrow band receiver technique. Both the oscilloscope and the spectrum analyzer continue to serve us well for most applications. However, another measurement technology, based in the modulation domain, may soon take its place beside these two.

In Figure 1, the axes of time, frequency, and amplitude illustrate the close relationship between the time domain, frequency domain, and the modulation domain. The signal shown is the output of a 50 MHz oscillator which can be looked at in any of the three domains. The significance of choosing one domain over another is really a matter of choosing the best measurement technology for your task. Suppose our task is to analyze the performance of this 50 MHz oscillator. The oscilloscope is the ideal general purpose tool that can provide amplitude, frequency, and time information for the signal. The oscilloscope, using cursor functions to measure a few periods of the waveform, tells us the frequency is 50.0 MHz, its amplitude is 1 Vpp, and that, visually, the wave-shape looks like a "pretty good" sine wave. For detailed spectral information on the signal, such as its harmonic distortion, the spectrum analyzer is the right choice. The spectrum analyzer can also tell us that the frequency is 50.0 MHz, the amplitude of the fundamental carrier is +4 dBm, and that the second harmonic is −45 dBc, a more precise indicator of the sine wave purity. The spectrum analyzer may not be able to provide a real-time picture of rapidly changing signals because of limitations in sweep speed and resolution bandwidth. To more clearly understand the frequency behavior of the oscillator, either in terms of short-term jitter or long term stability, the frequency counter is the right choice. What has made the frequency counter a more powerful option is the vastly increased measurement speed, resolution and analysis power unavailable in a cost-effective product until recently.

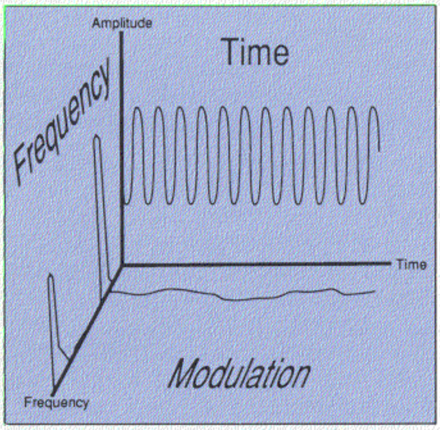

Figure 1. Time, frequency, and modulation domains.

Frequency counters have gotten a lot faster and more capable, creating a whole new range of measurement possibilities for the traditional frequency counter. Measurement speeds in thousands or even millions of readings per second are now possible. Equally important is improved frequency resolution, now at 10 digits of resolution per second of measuring time. New analysis tools, either built into the instrument or in software, provide quick access to frequency versus time plots, histogram plots, and mean, standard deviation, and min/max calculations.

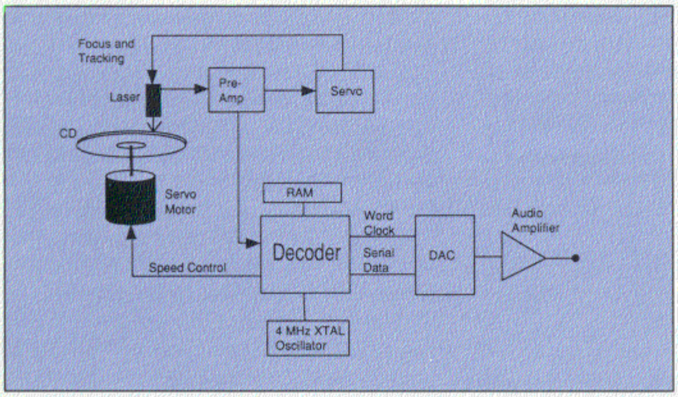

Figure 2. Block diagram of a typical compact disk player.

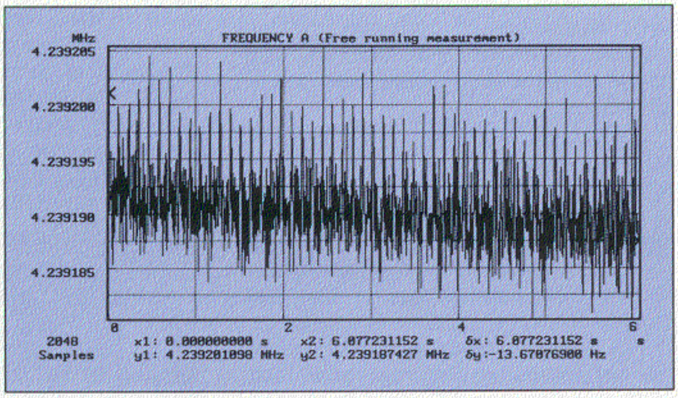

Figure 3. Frequency versus time plot of CD player oscillator.

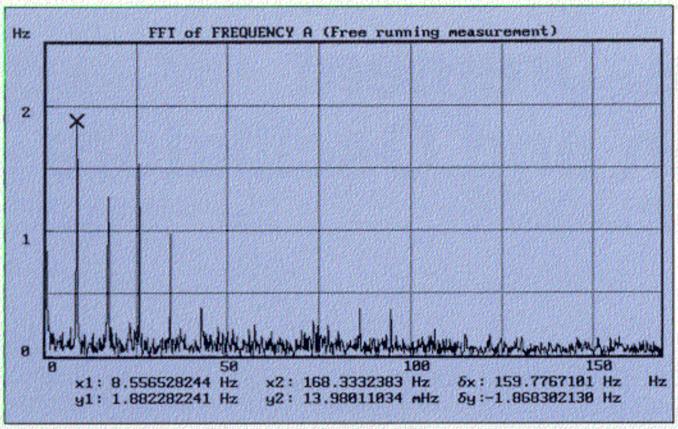

Figure 4. Frequency versus offset frequency of 4.239 MHz oscillator.

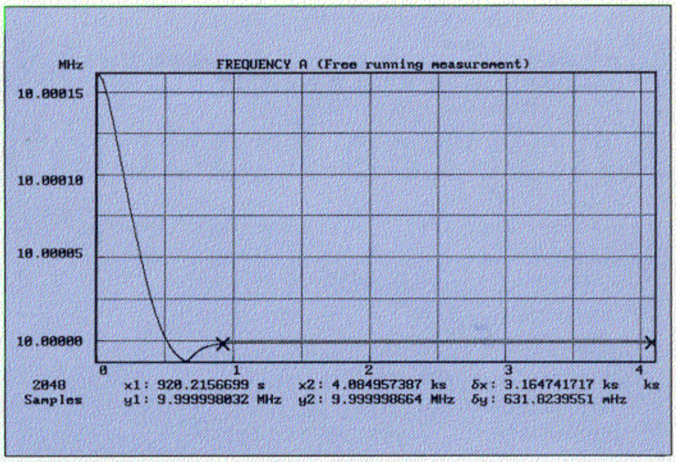

Figure 5. Oven oscillator warm up curve.

This new class of measurements has been dubbed the modulation domain. Modulation domain analysis was previously available only in analyzers costing $20,000 and over. The Philips PM 6680 frequency counter/timer and TimeView software now provide this capability for less than $3,000. TimeView is a PC-based software package for analyzing time and frequency data from the PM 6680. The best way to illustrate the power of modulation domain analysis is with some real measurement examples.

Analyzing Clock Jitter in a CD Player

Compact disk players are complex systems containing electro-mechanical servo loops to rotate the disk and position the laser, digital filters and decoders to handle the digital data, and an analog audio chain down-stream from the D/A convertor for the right/left audio channels. Figure 2 shows a typical block diagram of a CD player.

CD players depend on crystal oscillators, typically using low-cost AT crystal strip resonators to maintain system stability. All major clock functions and sampling rates are derived from this 4 MHz clock.

Looking at only a few samples of the 4 MHz crystal oscillator output with an oscilloscope showed a visible amount of jitter on the signal. Other than knowing that short term stability does not look good, there is no further analysis we can do with the oscilloscope. A fast frequency counter is just the right tool.

The frequency counter was set up for 2.5 ms measuring time per point and 2048 samples (about 5 seconds of data) were collected and displayed (Figure 3) using the TimeView software package and the Philips PM 6680 counter. Although this plot may look a lot like a conventional oscilloscope plot, the information being displayed is quite different. Instead of sampled voltages, this plot displays calculated frequencies, which are averaged over the measuring time between successive points. Measuring times and sample intervals can be independently set.

From the data in Figure 3, the oscillator appears to be frequency modulated at a periodic rate by an impulse waveform. The average height of the spikes is approximately 6 Hz off the main carrier of 4.239 MHz. We can analyze this behavior in greater detail using the Fast Fourier Transform function.

A Fourier transform of a frequency versus time plot produces an entirely new plot called a frequency versus offset frequency plot. This transform is not difficult to deal with when you realize that a Fourier transform just operates on waveforms, whether it is voltage versus time or frequency versus time. Assigning meaning to the new axes is the tricky part. Taking the Fourier transform of frequency versus time signal results in a direct demodulation of a signal. The vertical axis represents frequency deviation in Hz. The horizontal axis is the frequency offset from 0 Hz. There is no need to convert the signal down to baseband in order to see the modulation products.

In Figure 4, the carrier component, at 0 Hz offset with 4.239 MHz "deviation", is clipped in order to zoom in on the modulation components which happen to be down in the Hz range. The modulation is highly periodic over the 5 second time record, since there is very little spreading in the sidebands. The fundamental frequency is 8.56 Hz. The modulation waveform is mainly an impulse as we can see that it is rich in both even and odd harmonics.

Checking this frequency against other system elements in the CD player to find the source of the modulation, the 8.56 Hz frequency exactly matched the rotation frequency of the compact disk (513 rpm). Note that a CD player is a constant-velocity mechanism and the disk rotation speed can vary between 400 and 800 rpm depending on the track. The drive motor draws current in spikes using pulse width modulation control, apparently modulating the oscillator frequency through the power supply.

Remember that this technique of direct demodulation does have the natural limitation present in any sampled system: the Nyquist rate. The maximum sampling speed of the PM 6680 is 2,000 readings/second. Modulation components greater 1 kHz offset may alias and "wrap-around" into the base band spectrum. Unlike its voltage-sampling cousin the DSO, a frequency sampled system cannot easily be fitted with an anti-alias filter. In the case of our CD player clock oscillator, we would need a bandpass filter centered around the 4.239 MHz carrier, rejecting modulation components further than 1 kHz from the carrier.

Oven Oscillator Warm-Up Time

Oven oscillators operate at a closely regulated internal operating temperature, typically 75 degrees C depending on the turn-over point of the oscillator crystal, to obtain high stability and immunity to ambient temperature vari-

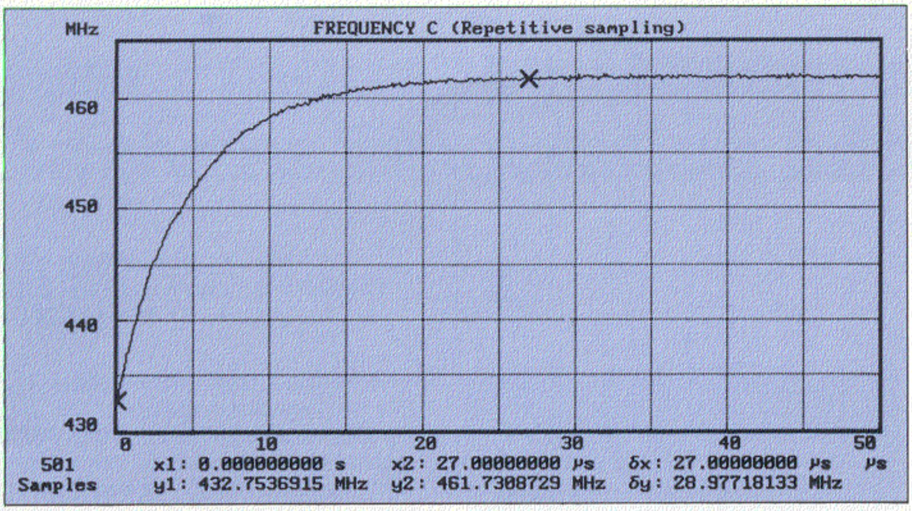

Figure 6. Step response of a 450 MHz VCO.

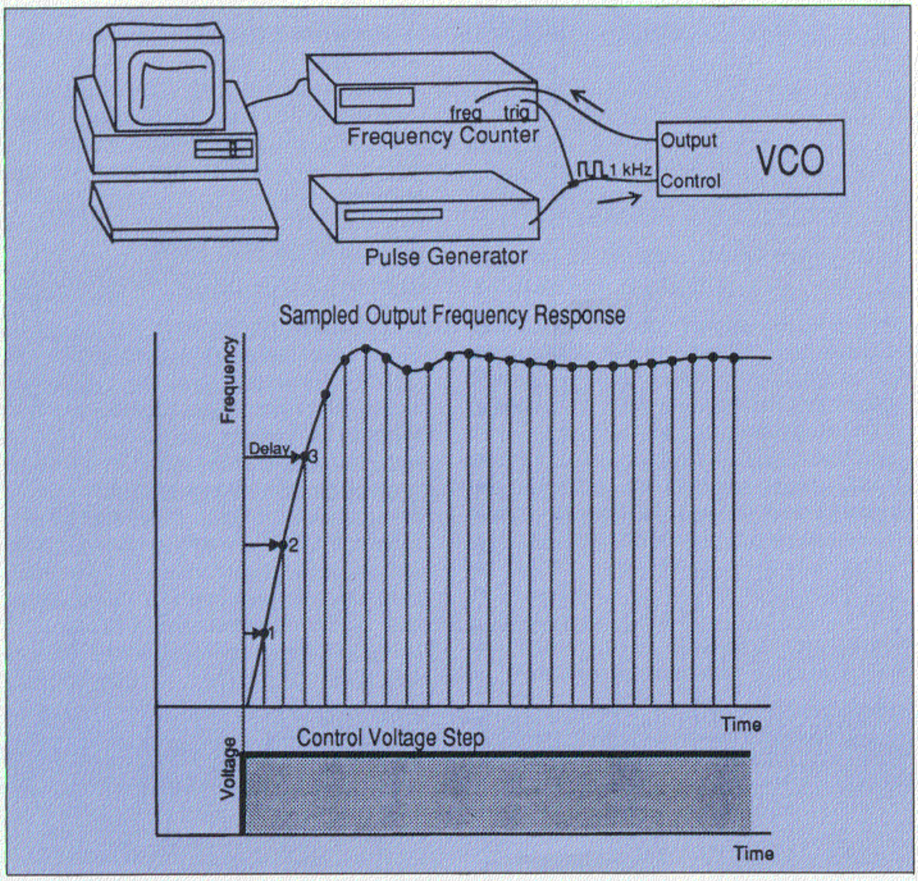

Figure 7. VCO step response test set-up.

ations. In powering up from a cold start of 25 degrees C ambient temperature, an oven oscillator requires time to warm up and stabilize. This warm-up time is primarily determined by the thermal mass of the oscillator, the heating power of the oven, and the amount of overshoot that occurs in the thermal control mechanism. Warm-up time is an important parameter because it determines how long the user must wait after power-up for his system to meet specifications.

A 10 MHz oven oscillator was tested for warm-up time by powering it up from cold start and measuring its output frequency over 2 second intervals.

The data in Figure 5 was gathered over a time period of 4000 seconds beginning at oscillator cold-start. The oven warms up very rapidly in the beginning, over-shoots the final operating temperature, and slowly ramps back in. The warm up curve has three main points of interest, including the cold-start frequency, the length and time of the frequency overshoot, and the time required for the oscillator to be within tolerance of its final frequency:

Cold Start: The cold operating frequency is +160 Hz from the final 10 MHz operating frequency.

Over Shoot: An over-shoot in oven temperature occurs 11 minutes after start-up, causing the output frequency to dip to −11 Hz from the operating frequency. The oscillator then gradually moves up toward the stable operating frequency of 10.000 MHz.

Within Tolerance: At 20 minutes, the oscillator is within 100 mHz (0.01 ppm) of the 10 MHz operating frequency.

VCO Step Response Characterization

Voltage controlled oscillators are usually characterized by plotting output frequency versus DC control voltage. Such plots are useful and easy to do. Often overlooked, however, is the dynamic response of the VCO to fast-changing AC control voltages which are often encountered in real systems. Measuring step response is a standard measure of the dynamic behavior of the VCO. From the step response, parameters such as frequency slew rate (how fast the VCO can change frequency) and damping (overshoot or undershoot) can be measured.

From the curve in Figure 6, we can see that the VCO is under-damped and requires approximately 27 us to slew from 432.7 MHz to 461.7 MHz. This curve was created with an equivalent sampling rate of 10 MS/s using the Philips PM 6680 and TimeView software in repetitive sampling mode. Measuring this step response at 10 MS/s requires a little extra effort. The TimeView software package has a repetitive sampling mode that automates the measurement process. The test set up is shown in Figure 7. As with digital storage oscilloscopes, the waveform being measured must be repetitive and the counter must have a stable trigger point. A pulse generator, with 2 ns rise time,

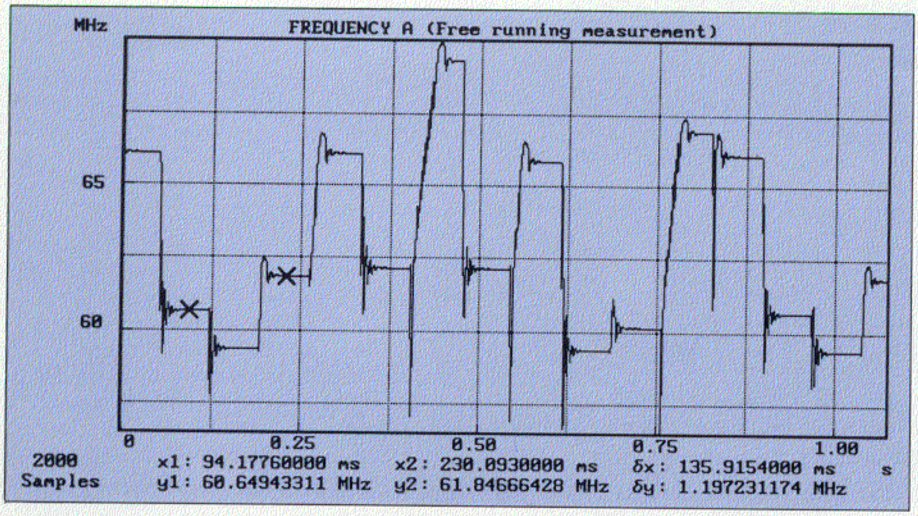

Figure 8. Frequency versus time plot of frequency agile local oscillator.

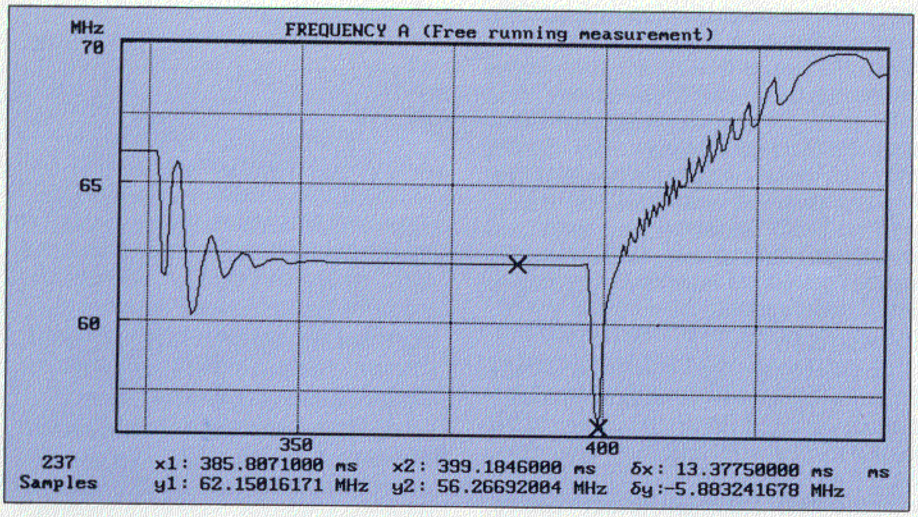

Figure 9. Zoom-in view of oscillator "drop-out."

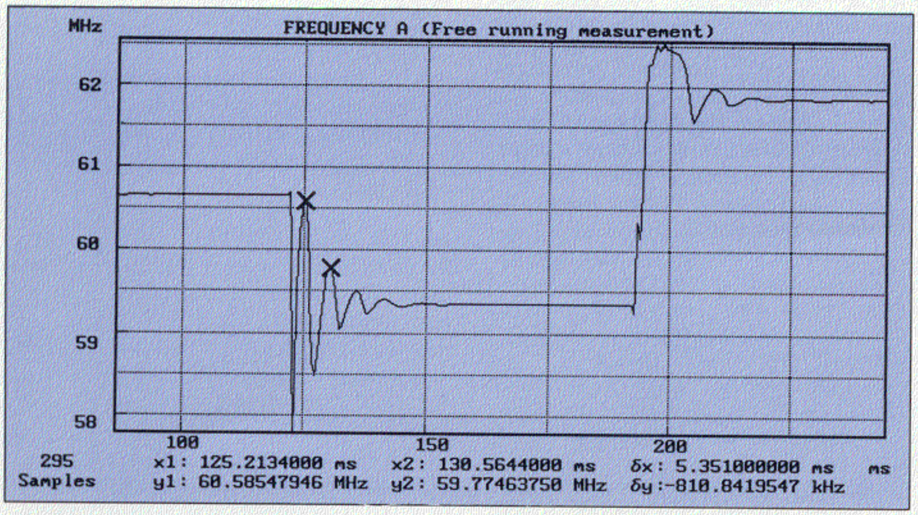

Figure 10. Close-up view of the overshoot and ringing.

was used to generate the step waveform.

The step waveform created by the pulse generator is actually a 1 kHz square wave. The frequency counter triggers off the positive edge of the pulse and measures the instantaneous frequency of the VCO at varying delays off that edge. By successively delaying the measuring further and further from the trigger point, the step response is reconstructed from the repetitive series of measurements. The maximum resolution of this programmable time delay is 100 ns, which gives a maximum equivalent sampling rate of 10 MS/s.

Frequency-Agile Local Oscillator Performance

The local oscillator is one of the key subsystems in a frequency agile receiver. Such a subsystem might consist of a programmable frequency synthesizer phased locked to a voltage controlled oscillator. As new frequencies are sent to the synthesizer, the VCO must follow and maintain phase lock. By rapidly sampling the output of the VCO using a frequency counter, the real performance of the local oscillator subsystem can be determined.

The receiver being tested had a local oscillator that ranged between 56 and 70 MHz. Figure 8 shows a 1 second time record of the local oscillator as it switches from channel to channel. From this plot, we can make a number of observations regarding its performance:

Slew Rate: The slew rate of the local oscillator is significant in that it can significantly reduce the amount of time the receiver spends on channel if the VCO has to move a long way to get there. During small frequency transitions with negligible slew time, on-channel time is around 60 ms. During large frequency transitions involving a significant amount of slew time, on-channel time drops to 27 ms. The upward slew rate of the oscillator is 227 MHz/ms. The worst case slew time is from the lowest channel (59.35 MHz) to the highest channel (69.35 MHz) is 44 ms. The down-ward slew rate of the VCO is nearly 10 times faster.

Drop-Outs: The plot also shows several frequency "drop-outs" as indicated by the sharp down-ward spikes where the local oscillator appears to lose its loop error voltage. A quick zoom-in shows these spikes are real, with 5 - 10 frequency samples that give a shape to

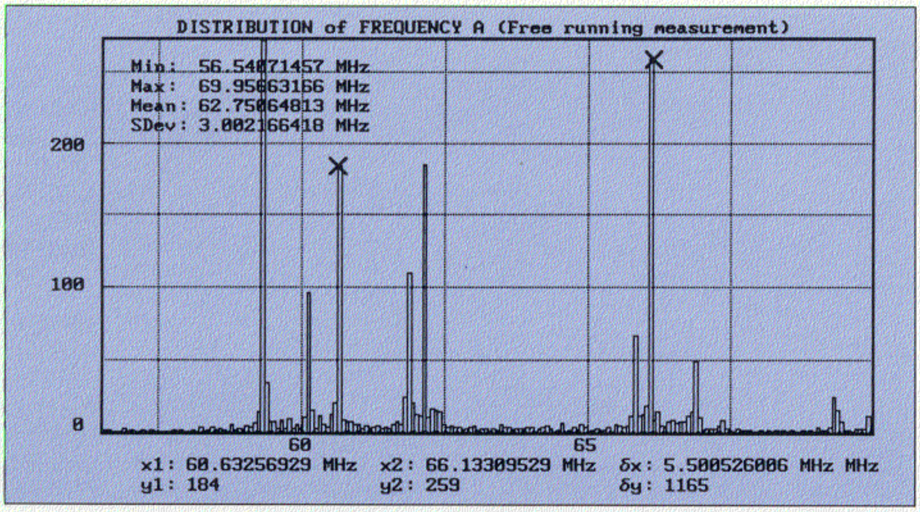

Figure 11. Histogram of frequency counts.

the drop-out. The oscillator appears to lose the loop error signal altogether, regaining it after about 4 ms. The depth of the drop-out is around 5 MHz. The reason for these drop-outs is unclear but may be related to delays in setting up the divider chain during a frequency change.

Ringing and Overshoot: There is a significant amount of overshoot (moving up toward phase lock) and ringing (moving down toward phase lock). Using the Zoom feature of TimeView, we can take a closer look at the over-shoot and ringing.

The ringing occurs during the down-transitions in frequency from one channel to another. In our picture, the ringing has a period of 5.3 ms, as shown by the cursors on the crests of the waveform, a ringing frequency of about 190 Hz. The ringing dies out after 25 ms, leaving 47 ms of usable on-channel time.

Over-shoot occurs during the up-transitions in frequency. Over-shoot levels of 0.53 MHz and durations of 20 ms were typical for all channels.

On-channel versus Off-channel Time: The histogram capability built into TimeView makes it easy to statistically characterize the relative amount of time the local oscillator spends on-channel and off-channel. The off-channel bins show graphically the amount of time the local oscillator spends moving between channels or out of lock. An ideal local oscillator would maximize the time spent on-channel, expressed as bin counts, and minimize the time spent off-channel.

Compiled from the frequency versus time plot of Figure 8, the histogram of Figure 11 shows the relative amount of time the local oscillator spends at each frequency, recorded as bin counts. The tallest 9 bins are the on-channel bins. The off-channel bins show the results of ringing and overshoot in the bins surrounding the on-channel bins. Slew-rate limitations increase the counts between widely spaced channels. The highest channel, at 69.35 MHz, clearly suffers from oscillator slew rate and overshoot deficiencies which significantly reduce the ratio of on-channel to off-channel counts.

Conclusion

The examples covered illustrate the wide variety of measurements that cannot otherwise be done with conventional oscilloscopes and spectrum analyzers. Better analysis tools help create better designs and minimize design cycles. The modulation domain, thanks to faster, higher resolution counters like the Philips PM 6680 and TimeView software, is a powerful and affordable new tool for understanding the frequency behavior of signals. *RF*

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Doug Barker is a product manager with the John Fluke Manufacturing Company, Philips Test and Measurement Group. Before joining Fluke, Doug worked for 5 years as a manufacturing development engineer with the Hewlett-Packard Company. He holds BSEE and MSEE degrees from The University of Michigan and an MBA from The University of Washington. He can be reached at John Fluke Mfg. Co., Inc., PO Box 9090, M/S 213A, Everett, WA 98206-9090. Tel: (206) 347-6100.

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