Digital Signal Processing (DSP) in Oscilloscopes

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Summary

The oscilloscope is the primary tool used by hardware design and test engineers. Understanding how DSP is used in modern digital oscilloscopes is key to understanding the performance advantages that can be obtained, and avoiding the pitfalls of poor implementations.

Introduction

The oscilloscope's ability to faithfully and accurately reproduce the electrical signal in a test circuit is the fundamental expectation an engineer has when using one. As oscilloscopes have evolved from early analog phosphor-trace display models to digital storage types with long memory and extensive post-processing capability, the ability to debug and analyze test circuits has greatly increased. In addition, the shift to digital acquisition systems, the increase in available computing power, and the use of DSP techniques provided new opportunities to improve on the signal fidelity performance of the raw oscilloscope hardware, and provided new bandwidth extending capabilities not previously possible. It would currently be impossible to deliver the measurement precision demanded in some of the newer applications without the use of DSP. In fact, all modern, high-bandwidth oscilloscopes designed today employ DSP in one form or another.

Uses of DSP

The use of DSP is now so pervasive in electrical design that it is often taken for granted. It is widely used in the following applications:

- Audio signal processing providing sound equalization, noise detection and elimination, effect creation, or speech processing/recognition.
- Audio and video signal compression.
- Digital image processing and enhancement for medical imaging, computer-generated animations, and image restoration.
- Radar, lidar, sonar and other narrow-band or microwave frequency range detection or communication systems for noise reduction, image enhancement, and other effects.

Many engineers have come of age in an era where a world without digital acquisition systems and DSP, and all the improvements and benefits these technologies provide, is unimaginable. For instance, consider the evolution of musical recording, storage and playback over the last 25 years. In this period of time, the long-playing vinyl record (LP) has been replaced by the digital compact disc (CD) format, and now the CD is being replaced by digital files or streaming music delivered over the internet. The recording and storage into digital format evolved to playback and transmission in digital format, which then evolved to serial transmission of audio and video between audio components, with the next logical step being full digital amplification and transmission to speakers. It is easy to imagine the last step in the audio reproduction process - the creation of an analog audio signal for the human ear - is the only remaining analog step. Purists might argue, with merit, that the sound amplification through an old vacuum tube amplifier is superior to today's transistor and IC-based amplifiers. However, the vast majority of consumers enjoy better, smaller, less expensive, and more convenient audio devices with more "features" today than previously possible and manufacturers of this equipment are better able to consistently produce high quality and highly reliable products than otherwise capable. The conversion from analog to digital acquisition and transmission and the attendant use of DSP for audio signal equalization and enhancement has made this possible. In fact, it is easy to imagine the day when a true digital amplifier uses DSP to faithfully and accurately reproduce the sound of a vacuum tube amplifier at much less cost, weight, size, and heat generation, just to name a few benefits.

So what does this have to do with oscilloscopes? Nearly all oscilloscopes sold today have digital acquisition systems, and those with higher price points have powerful on-board processing capabilities. This combination has created an opportunity to use DSP in oscilloscopes improving on front end signal fidelity and, more importantly, providing new features and capabilities. The use of DSP in high-end oscilloscopes is now pervasive; all major oscilloscope manufacturers use DSP in some ways, and the more advanced and capable manufacturers use it in the most efficient, novel and productive ways bringing new test capabilities to market faster than ever.

DSP Implementations In Oscilloscopes

The use of DSP in oscilloscopes has been a huge benefit for engineers and implementations in oscilloscopes have been continuously improving. Ideally, DSP implementations in the oscilloscope should be transparent to the user and have no processing or acquisition time tradeoffs – the enhancements and capabilities of DSP should be "always on" so the user is always obtaining DSP signal fidelity benefits. Features made possible by DSP should be exposed to the user in a way that is clearly recognized and understood. Lastly, the limitations of DSP should be recognized by the oscilloscope supplier and inappropriate usage should be avoided.

LeCroy has implemented DSP in the processing-efficient X-Stream software architecture. This software architecture utilizes variable waveform segment lengths to improve CPU-cache memory efficiency. CPU-cache memory transfers are very fast and if each waveform segment can be size optimized to match the cache memory size, then the processing steps, including DSP filter operations, can be processed very quickly and efficiently. Furthermore, the addition of the DSP filter operation does not degrade the oscilloscope processing rate since there is little inefficiency in performing one additional processing step while the waveform segment already resides in CPU-cache memory. LeCroy's approach differs from traditional oscilloscope software architectures which are inattentive to CPU-cache architectures and process acquired waveforms in a single segment (often many megapoints) length. In this case, there is a significant processing speed penalty with enabled DSP, and for this reason, DSP is often allowed to be turned off in order to achieve reasonable processing update rates.

In addition to efficient software architecture, LeCroy also provides multi-core central processing units (CPUs) for most of their oscilloscopes. These multi-core CPUs fully leverage the efficiency of the X-Stream architecture and provide orders of magnitude better processing speeds and responsiveness compared to traditional software architectures paired with single-core CPUs, even with DSP enabled.

When the oscilloscope with DSP enabled has better signal fidelity, is incredibly responsive, and quickly processes long records with extensive processing, there is no reason to ever disable the DSP function.

LeCroy has utilized DSP allowing users to fine-tune the step response of their oscilloscope. This is done with an "optimization mode" with "pulse", "eye diagram" or "flatness" response selections. Choices are made separately for each channel and allows the user to optimize the oscilloscope when reproducing their specific signal most accurately since the need for serial data eye diagram testing may be significantly different from the need for pulsed RF testing, for example. The user selection of an optimization mode is simply a selection of a different DSP filter providing the specific capability.

The true test of the quality of an oscilloscope is how faithfully the instrument reproduces the input signal when compared to a golden reference, typically a high-bandwidth sampling oscilloscope. Good hardware design combined with appropriate DSP software implementations can produce oscilloscope signal fidelity superior to what is possible with hardware alone, especially at the highest bandwidths.

Uses of DSP in Digital Oscilloscopes

DSP is may be employed in digital oscilloscopes to perform the following functions. Each is subsequently explained in detail. Note that all manufacturers make some use of the following techniques:

- Signal Fidelity Enhancements
  - Front End Response Bandwidth Roll off
  - Front End Response Smoothing
  - Front End Response Matching
  - Front End Group Delay Adjustment
  - Probe Compensation
- Bandwidth Adjustment
  - Front End Response Bandwidth Limit Filters
  - Front End Response "Boosting"
  - Digital Bandwidth Interleaving
- Application Enhancements
  - Response Optimizations
  - Adding/Removing Pre- or De-emphasis
  - Cable and Fixture Embedding/De-Embedding
  - Serial Data Channel Emulation
  - Serial Data Receiver Equalization
  - Virtual Probing

Signal Fidelity Enhancements

The oscilloscope should contain the best technologies available, such as DSP, to faithfully and accurately reproduce the electrical signal existing in the device under test (DUT). DSP techniques are applied to modern oscilloscopes to significantly enhance already high signal fidelity. In addition, the highly accurate reproduction of fast edges, such as found in high-speed serial data signals, requires pristine signal fidelity and low distortion. DSP enhancements are an important reason why these high-speed signals can be so faithfully and accurately reproduced. These enhancements usually involve correcting for small chip-to-chip or component-to-component variations in the response that can have an impact on signal fidelity. If uncorrected, this can make it more difficult for the oscilloscope measurement device to maintain significantly better signal fidelity than the device being measured. The benefit to the oscilloscope user is that each channel on the oscilloscope has nearly identical step response and bandwidth roll off characteristics, with minimal signal distortion. This makes the oscilloscope a much more reliable tool for debug and characterization, providing benefits when measuring and comparing nearly identical signals or when performing a math subtraction of a differential signal pair (in lieu of using a differential probe), and makes possible the display of high-speed serial data eye patterns with a signal fidelity otherwise unattainable.

More detailed descriptions of how DSP may be used to enhance different aspects of oscilloscope signal fidelity are listed here:

Front End Bandwidth Roll off Matching

High frequency analog front ends have a nominal bandwidth by design. However, it is likely that different front ends have slightly different responses or a roll off profile that is not matched below the maximum bandwidth rating. Even small variations (±0.5 dB) can have significant (±5%) impact on the amplitude. By analyzing normal component-to-component and lot-to-lot variations, it is possible to choose a conservative "nominal" profile for the analog front end and use DSP filters to modify the response of that component to exactly fit the nominal profile. Therefore, every front end can have the exact same bandwidth profile with variations between channels so small that the bandwidth response of each channel is nearly indistinguishable.

Front End Response Smoothing

It is desired that the analog front end have as smooth a response as possible without significant peaks and valleys in the response that can impact the signal fidelity. Even good analog front ends can have response variations of 1 dB or more, which can cause 10% amplitude variations at specific frequencies, and can impact the step response characteristics of the oscilloscope. Therefore, "smoothing" the response as much as possible is advantageous, and DSP makes it possible to achieve smoothed responses better than ±0.5 dB.

Front End Response Matching

Once the front ends exhibit the defined bandwidth roll off profile, and have a sufficiently smooth response, it is important to ensure that each front end (i.e. oscilloscope channel) match every other front end at every oscilloscope gain range. DSP makes it possible to achieve this stringent requirement.

Front End Group Delay Adjustment

Group delay refers the variation in propagation speed of different frequencies along a transmission line. Since a typical signal is complex and composed of many different frequencies, it stands to reason that a high group delay in a transmission line results in worse signal fidelity, which usually manifests itself as a slower rise time and a non-ideal step response shape. As signals have surpassed 1 GHz, group delay has become a major contributor to signal fidelity.

Since an oscilloscope should faithfully and accurately reproduce the signal, the oscilloscope should not affect the signal's inherent group delay while input to the oscilloscope. The additive effects of the oscilloscope to the signal's group delay can be measured and adjusted while using DSP to ensure the highest signal fidelity is maintained.

Ten years ago, if you asked a engineer to describe a pristine oscilloscope front end response, he would have said "a perfectly smooth, well-defined bandwidth roll off with few peaks and valleys, providing a rise time equal to 0.375/BW, and making every channel and every gain range perform exactly the same." Today, through the use of DSP, this is not only possible, but is commonly available, with the exception that the highest bandwidth oscilloscopes in any product line typically only exhibit a rise time equal to 0.45/BW given that bandwidth is inherently hardware limited at some point.

Bandwidth Adjustment

As previously described, DSP can be used to modify the inherent hardware frequency response to a conservative "nominal" profile and then fit a prescribed roll off shape.   This opens the door to flexibility for tailored bandwidth reduction, providing significant benefits to the user. It also permits bandwidth "boosting", which may result in significant signal fidelity issues.

Bandwidth Limit Filters

If a DSP filter is applied to fit a conservative "nominal" profile that roughly equates to the raw hardware performance, then similar filters can be applied to reduce the bandwidth even further with no penalty to signal fidelity (with the exception that rise times are reduced with the lower bandwidth). Oftentimes, an engineer doesn't need the full bandwidth rating of the oscilloscope for a particular test, and instead desires a lower noise floor provided by reducing the bandwidth while maintaining the overall signal fidelity. Using a DSP bandwidth limit filter is the preferred method to achieve these goals.

Bandwidth Boosting

The bandwidth available in a given front end amplifier is often less than what engineers at the leading edge of technology desire in their oscilloscope. This tempts oscilloscope suppliers to boost the bandwidth of the oscilloscope by increasing the gain of the front end amplifier using a DSP filter at higher frequencies counteracting the natural hardware roll off.   When the boost is moderate, the side-effects are small. However, modern IC processes in the microwave frequency range tend to have rather steep roll offs at their limits. Therefore, any DSP filter used to boost the bandwidth often has a very high gain. This high gain results in a faster rise time (commensurate with the bandwidth) but also potentially degraded signal fidelity, higher overshoot, higher electrical noise, and other artifacts. This is generally not the preferable use of DSP.

Digital Bandwidth Interleaving (DBI)

The technologies and IC design processes used to design the front end amplifiers in real-time oscilloscopes are the same as those that customers at the leading edge of technology want to test. The resulting paradox is that the oscilloscope never has enough bandwidth to maintain the pace of innovation required by the leading-edge technology the engineer wants to use. Traditionally, this meant the engineer had to make compromises in the test process by substituting other equipment for a real-time oscilloscope, delay the implementation of new technologies until the oscilloscope gained the capability, or cede the market to competitors. None of these alternatives were desirable.

With the invention of DBI technology by LeCroy in 2005, a method was found to use low-noise microwave hardware technology in conjunction with DSP to double the inherent hardware bandwidth. With DBI, a single high frequency broadband signal is input to the oscilloscope and split into two paths with the resulting highest frequency half of the signal down converted. The two signals are then each input into their own front-end amplifier and ADC path, digitized, and then re-assembled using DSP, into a single high-frequency broadband signal. Reference figure 1 for a block diagram. The benefits to this approach are that no front end amplifiers are ever boosted to achieve higher bandwidth – the front ends are always comfortably operated within their stated range, so signal fidelity performance of the oscilloscope at the doubled bandwidth remains high. However, it should be realized that, at the higher (doubled) bandwidth, the number of channels is halved.

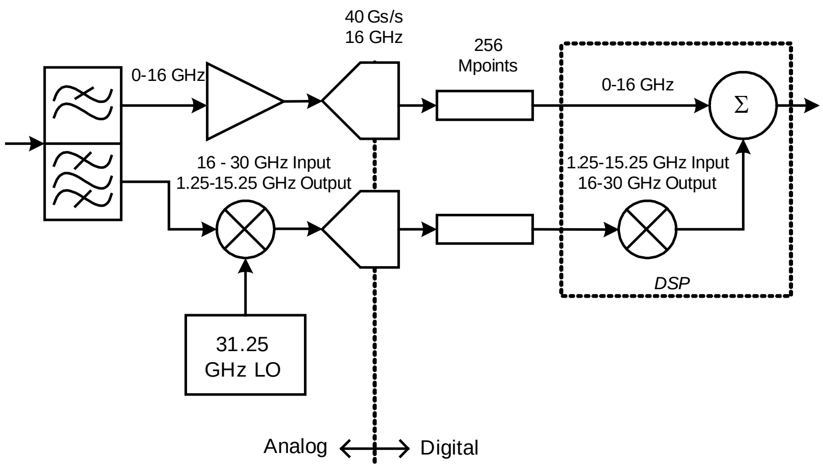

Figure 1: Block diagram of Digital Bandwidth Interleave (DBI) technology as used in a WaveMaster 830Zi oscilloscope. In addition to doubling the bandwidth, it also doubles the memory and sampling rate.

Application Enhancements

Just as when DSP is used in consumer electronics, application enhancements can be added when DSP is used in oscilloscopes. A few examples LeCroy provides in their higher bandwidth oscilloscopes include:

Response Optimization

Once DSP is used for bandwidth roll off and group delay adjustment, it is possible to tailor the response of the oscilloscope for different applications. LeCroy provides three different response optimization modes, each selectable from the channel menu, to provide different step responses. Since these are post-processing DSP adjustments, the user can capture a signal once and view the result with any of the response optimizations. The different modes are described here:

- **Pulse Response** – this response uses the standard 4th order Bessel roll off and allows a minor amount of group delay at the highest frequencies to provide a step response closely resembling the performance of analog hardware (which has some non-zero amount of group delay at the highest frequencies). A step response captured using this mode would show very little to zero pre-shoot, some overshoot, and a slightly slower rise time (due to the group delay). This mode is the default response for LeCroy oscilloscopes since it provides the preferred step response for general purpose use and represents the historical performance of non-digital oscilloscopes.

- **Eye Diagram Response** – this response also uses a 4th order Bessel roll off, with zero group delay at any frequency. The result is equalized pre-shoot and overshoot, which is preferable for serial data eye diagram measurements. The rise time with this response is slightly faster than the Pulse response.

- **Flatness Response** – this response maintains a flat frequency response out to rated bandwidth, also with zero group delay. Since there is additional high-frequency content in this mode, the fastest oscilloscope rise times are possible with this response. The only tradeoff is slightly more pre-shoot and overshoot compared to Eye Diagram response. This response is preferred for measurements of narrow band frequencies where flat response is preferred or for situations where fastest rise time is most critical.

Cable & Fixture Embedding/De-Embedding

Cables or test fixtures connected between the device under test (DUT) and the oscilloscope have frequency responses which typically result in attenuation of the input signal at higher frequencies. DSP filters are used in the oscilloscope to compensate for this attenuation and provide a view of the signal as if the fixture and/or cables were not attached.

Adding/Removing Pre- or De-emphasis

Serial data channels have losses, so transmitter designers sometime employ the use of emphasis to pre-compensate for these effects. DSP filters are used in the oscilloscope to compensate for this, or to simulate the amount necessary to compensate for specific serial data channels.

Serial Data Channel Response Emulation

Engineers may want to refer their measurement to the far side of a particular serial data channel instead of at the probing point. DSP filters are used in the oscilloscope to simulate the response of the serial data channel and eliminate the need to use a physical channel to perform the same test.

Virtual Probing

The signal transmission path may be physically complex and preclude probing in the desired location. If the S-parameters for a signal path are known, then DSP can be used to “virtually probe” and view the signal at any point in the signal path, even if that point is physically inaccessible.

Serial Data Receiver Emulation

Serial data receivers often incorporate equalization to compensate for losses associated with the serial data channel. DSP filters are used in the oscilloscope to simulate the receiver equalization and provide a view of the oscilloscope acquisition from the perspective of the receiver.

Summary

Engineers are constantly challenged to integrate new technology and bring innovative new products to market faster, and the pace of innovation is accelerating. In the consumer marketplace, the types and range of products has dramatically changed in the last 10 or 20 years. The companies most successful in surviving in this challenging marketplace are those that quickly adopt and integrate new technologies. Likewise, their suppliers must do the same; especially ones relied upon for design testing, validation, debug, and analysis. Digital signal processing of digitally acquired data is a universally accepted method to improve and enhance digital system performance, especially in oscilloscopes, and provides clear benefits to the user. Understanding the types of DSP implementations in oscilloscopes and the benefits they provide is the key to making smart test equipment choices.

References:

“Digital Bandwidth Interleaving” By Peter J. Pupalaikis, http://www.lecroy.com/wp/dbi/