An overview of Shock Testing into the 21st Century.

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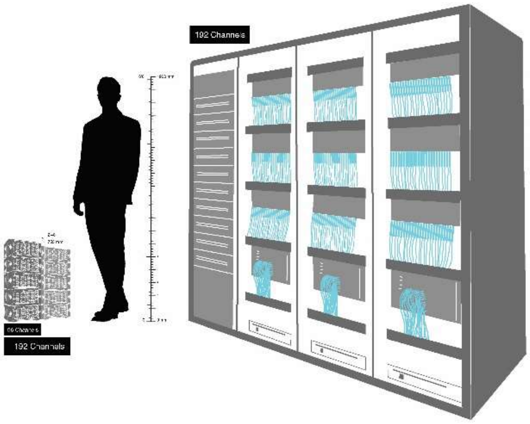
The internet has a great deal of anecdotal and quantitative information about shock testing if you are willing to read and analyze it. I hope that by the end of this presentation you will have a better feel for where we started as a testing industry and most importantly, where we are going. Moore's Law (for computer chips) emphasized the growth and efficiency of computing power over time* The same can be said for the data acquisition world (though it has not advanced as fast as computing power). Still, the speed and accuracy of data collection hardware have grown dramatically, while circuit density has increased, and power dissipation and size have decreased. Your smart phone has more computing power than the early Cray super computers which took up whole rooms and massive cooling. The image below is a large data system from the early 1990's. It was considered a high performance transient measurement system manufactured by DSP Technology, Inc (192 channels, with full WSB signal conditioning, 12 Bit SAR parallel converters w/ S&H at 100kSa/s, and 125k SA of DRAM memory per channel, mounted in 92" tall racks based on the IEEE CAMAC standard utilizing GPIB communications. This system was used for the measurement of rocket launch dynamics). (Image on left)



Today, 192 channels of WSB / ICP signal conditioning, flat to 0.1dB at 1.0 MHz, 5MSa/s @ 24 bits, with 21MSa of memory per channel would fit into just one of the racks shown above. The image on the right is for size comparison.

*Gordon Moore, co-founder of Intel, first described Moore's Law in 1965. Moore's Law is not a scientific law, but rather an empirical observation and projection for the future. It's based on the idea that innovation and technological advancement will continue to allow the number of transistors to double. Moore's Law has been a driving force behind the semiconductor technology revolution.

Topics:

1) **Brief timeline overview of DAS (Data Acquisition System) developments over the last 40 years.**
2) **Technology terms and considerations**
3) **Shock data acquisition and transducers**
4) **Mil Spec 810G Method 517**
5) **RYO (Roll Your Own) Data Systems**
    a. **Traditional approaches and pitfalls associated with the old-school approach to building a DAS.**
6) **COTS (Commercial Off The Shelf) data systems**
    a. **You still need to understand specifications and testing requirements**
7) **Conclusions**

Milestones in High-Speed Data Acquisition

- **1980s**: Emergence of digital systems, accuracy improved to ~8-12 bits, effective sampling rates in the kSa/s range.
- **1984**: IEEE-488 (GPIB) interface, simplified integration of systems but maintained lower sampling speeds.
- **Late 1980s**: PC-based systems introduced, accuracy increased to ~14 bits, sampling rates to 100 kSa/s.
- **1992**: Advancements in sigma-delta ADCs, accuracy improved to ~16 bits, effective sampling rates up to 200 kSa/s.
- **1998**: VXI systems developed, offering modular precision at ~16-bit accuracy and up to 1 MSa/s.
- **Early 2000s**: USB/Ethernet interfaces enhanced portability, with accuracy at ~16 bits and sampling rates up to 10 MSa/s.
- **2010s**: High-speed streaming with SSDs allowed gigabytes per second throughput, accuracy at ~18 bits.
- **Mid-2010s**: IoT integration supported remote monitoring with similar high accuracy and rates.
- **2020s**: AI and ML (MATLAB) enabled real-time analysis, maintaining ~18-24 bit accuracy and GHz sampling rates.

Key Technology Considerations and Terminology

Digitizer Dynamic Range

Dynamic range is one of the critical parameters in shock testing systems as it defines the range of input signals that a digitizer can accurately measure, from the smallest detectable signal to the largest signal it can handle without distortion. It is typically expressed in decibels (dB) and is determined by two main factors: the resolution of the analog-to-digital converter (ADC) and the noise floor of the system.

Resolution and Its Role in Dynamic Range

The resolution of an ADC, expressed in bits, determines the smallest voltage increment it can resolve. For instance:

- A 12-bit ADC provides 212=40962^{12} = 4096212=4096 discrete levels.
- A 16-bit ADC provides 216=65,5362^{16} = 65,536216=65,536 discrete levels.
- A 24-bit ADC provides 224=16,777,2162^{24} = 16,777,216224=16,777,216 discrete levels.

The resolution directly impacts the digitizer's dynamic range. The theoretical dynamic range of an ADC is approximately 6.02·N6.02 \cdot N6.02·N dB, where NNN is the number of bits. For example:

- A 12-bit ADC has a theoretical dynamic range of about 72 dB.
- A 16-bit ADC has a dynamic range of about 96 dB.
- A 24-bit ADC can achieve up to 144 dB.

However, practical dynamic range is often limited by noise introduced by the system, which includes thermal noise, quantization noise, and electronic interference. The use of multiple full scale ranges allows for better use of a given ADC. This means a system using 16-bit converts and 19-full scale ranges can have better dynamic range than a 24-bit system with only 4-ranges.

Noise Floor and Signal Integrity

The noise floor is the level of background noise present in the system. For high-speed shock testing, minimizing the noise floor is essential because it allows the system to detect small-amplitude signals accurately. Engineers must ensure that the system's noise floor does not degrade the effective number of bits (ENOB) of the ADC. ENOB is a measure of the real-world resolution of the ADC after accounting for noise and distortion.

Impact of Dynamic Range on Shock Testing

In shock and transient testing applications, events often generate a wide range of signal amplitudes, from subtle vibrations to high-intensity shock pulses. A digitizer with a limited dynamic range may either lose detail in the low-amplitude signals or clip the high-amplitude signals, leading to inaccurate results. Therefore:

1. **High-resolution ADCs** are preferred for capturing both low-level details and large transients.
2. **Anti-aliasing filters** and proper signal conditioning help maintain the integrity of signals within the digitizer's range.
3. **Oversampling techniques** can improve effective resolution by spreading quantization noise across a broader bandwidth and then filtering it out. When using SAR & Flash converters the rule of thumb has been a minimum of 10x oversampling for the frequency of interest. The Sigma Delts (Delta Sigma) is an oversampling converter by design.

Choosing the Right Dynamic Range

The choice of dynamic range depends on the specific application. For example:

- **Impact testing in aerospace applications** may require a dynamic range exceeding 120 dB to capture fine details of micro-vibrations alongside large shock loads.
- **Automotive crash testing** might prioritize higher bandwidth over dynamic range, though at least 96 dB is often needed to ensure signal fidelity.

Engineers must balance dynamic range with other specifications, such as bandwidth, sample rate, and system cost, to achieve optimal performance.

Shock Data Acquisition & Testing

The physical testing process has not really changed much in the last 50 years. From a simplistic 10,000ft (3km) overview, you need to test something. **You need to identify core testing requirements:** So basic questions must be answered,

1) What type of test are we running?
2) Is this an environmental or vibration test?
3) Is this a Shock test? If it is a shock test, what kind of shock?
4) Is this a destructive test or a long duration multiple shock (durability) test?
5) What is the desired bandwidth of the test data? What is the desired resolution (accuracy) of the data?
6) What types of transducers will be used for the measurement of the physical phenomena?

There are SOP's (Standard Operating Procedures) developed for each type of testing. These procedures are modified as the scope of testing and tools available are expanded.

The days of one size fits all for data acquisition systems (DAS) are gone. A data system designed for monitoring and controlling a shaker system is not appropriate for high-speed, broadband transient shock testing. It is true you can purchase a single high fidelity DAS that can capture fast transients and slow moving signals. However, their inherent operational paradigm makes them inappropriate for vibration control. There are always trade-offs with data systems and special applications. When capturing slow signals with a high-speed DAS you can end up with very large data sets to wade through and process, or in the case of transient recorders (non-streaming) you have many data sets which have time gaps. This is why testing properly requires a deep understanding of both the tools available and the goals of the test.

Mechanical shock categories:

1) Far-Field – Typically Shaker Shock
2) Mid-Field – Shaker Shock using inductor-ring shakers or Drop Tables
3) Near Field -- Classified as Power Shock: Including Resonant Plate, Hopkinson Bar, Bungie Drop Tower, Ballistic and Pyro-Shock (explosive).

Each of these categories comes with their own set of requirements for capturing quality data.

1) Far field shocks would be qualified as gentle shocks when compared to a Pyro event. The transducers and bandwidth requirements for far field events are also far less rigorous than for Pyro. We will generally see PE (Charge Mode) transducers or ICP/IEPE transducers for this type of test. Unless there is some unexpected metal to metal secondary induced shock the bandwidth for these tests usually doesn't exceed 10kHz.
2) Mid-Field shocks require more rugged transducers (higher G ratings) than far field shocks. Straight PE type transducers suffer from charge migration in shock testing environments. The typical transducers for large scale shock testing are ICP or IEPE shock transducers, unless there is a testing requirement for a DC response. ICP & IEPE by their operating nature (AC Coupled) are not good for any measurement which starts & ends at zero. They are also limited in bandwidth, both mechanically and electronically (mostly 10kHz or lower).

   The PR (Piezo Resistive MEMS) transducers are the transducer of choice when DC response and / or broadband response is required. If there is not a broadband requirement, then a Damped PR accel would be a reasonable choice.

3) Near-Field shocks are the most difficult shocks to capture, especially if repeatability is required. These shocks are the most energetic / severe and by their nature the most difficult to measure because of the environmental constraints. Great care must be taken using proper cabling and restraints, clean power and grounding techniques. Today's data systems are far less forgiving than their predecessors because of their increased resolution in both dynamic range and frequency content. Poor techniques can lead to what appears to be a real signal but is actually a measured artifact of environmental noise. The noise

sources, just to name a few, can be caused by EMI / RFI radiation from contactors, CDU's (Capacitive Discharge Unit for setting off high explosives), poor grounding, a tribo-electric effect from cables whipping around. The other thing about near field shocks is they can generate broadband frequency content. This content cand damage or break electronics packages. Use of un-damped PR type transducers increases the likelihood of capturing and later identifying these broadband shocks. Of course, having a data system capable of capturing these broadband events is also a requirement. Mil Spec 810G Method 517 defines 500kSa/s to 1MHz as the minimum effective sample rate of the data system for these type measurements. Ideally, however, the data system should have 1MHz of bandwidth.

Real World Testing

What do I really need? While **Method 517** specifies:

Data Acquisition

- **Sampling Rate**: Minimum of **500 kHz to 1 MHz per channel** to accurately capture transient shock events.
- **Resolution**: **16-bit or higher ADC resolution** to maintain precise data representation.
- **Bandwidth**: At least **50 kHz to 500 kHz** to ensure high-fidelity signal capture.
- **Real-Time Processing**: Ability to perform **Shock Response Spectrum (SRS) analysis** and **Fourier Transform (FFT) calculations** on captured data.

The reality of what is required for the DAS is defined by the choice of transducers, and the actual testing environment and the goals of the test plan. For example, if ICP /IEPE shock transducers are to be used the maximum usable bandwidth will be about 10kHz. For purely mechanical systems 10kHz has been the traditional benchmark. So, the data system in this case can be a less capable system (100 to 200kSa/s @ 24bits).

However, if capturing broadband content is the goal then the use of **PR bridge** type accelerometers would be required. There are other types of high speed transducers, but for this discussion we will be limited to shock accelerometers. Now the data system capabilities are critical. High end integrated data acquisition systems come with end-to-end specifications, taking the guesswork and time intensive, extensive certification testing out of the fielding a system equation. However, when the decision is made to "Roll Your Own" (RYO) data system e.g. buying card level components like NI cards (National Instruments), signal conditioners, amplifiers and digitizers (don't forget AAA Filtering) plus the cabling (if they are streaming cards, timing latencies also play a part) then prior to use / acceptance, the system capabilities certification falls on the integrator.

The instrumentation group fielding the system for a test must validate that the chosen DAS is appropriate for the job. In the case of the high end (COTS) system, you will have a detailed specification sheet of guaranteed capabilities, which are measured using 17025 traceable test equipment. For the RYO system, hopefully the integrator has documented all critical elements.

In real world testing for example, an un-damped PR accelerometer say an Endevco 7270A-200kG accelerometer can have resonances as high as 1.2MHz (the resonant frequency is typically dependent on the max "G" rating of the transducer). So, if you are sampling at a minimum of 2x the resonant frequency, Nyquist says you can capture the signal. These types of transducers typically have a very low output, so now the signal must be amplified to maximize the dynamic range of the measurement. This is where things can get tricky, because stand-alone signal conditioning cards are often specified as max (ideal) bandwidth at unity gain or the -3dB point at gain is specified. However, PR accelerometers need a lot of gain, so an amplifier which may have 1MHz of bandwidth at unity gain, may only have 100kHz of bandwidth at the required gain to maximize the dynamic range of the measurement. Understanding the ramifications of the GBP (Gain Bandwidth Product) of an amplifier will make the difference between taking good data or data which may look good in the time domain (a wiggly line) until it is analyzed.

Common misconceptions when it comes to RYO data acquisition systems:

1) My amplifier is good to a megahertz (as discussed above this is not necessarily the case)
2) I don't need that much bandwidth because I will use an analog filter to limit the bandwidth.
    a. Unfortunately, this assumption can lead to its own set of problems. For example, if the input instrumentation amplifier does not have sufficient bandwidth to present the full broadband (in-band and out of band) input signal to the bandwidth limiting filter (cutoff), you will get slew rate limiting. This will distort the signal presented to the filter, resulting in incorrect measurement.
    b. If you are using programmable filtering, there are intrinsic problems here too.
        i. Over time and temperature programmable filters deteriorate. Filter peaking is an example of this. It will show up as a non-linearity in an otherwise predictable roll off curve (x dB. per octave)
        ii. If the filter is an active filter the same rules about GBP apply. If an amplifier used in a filter does not have sufficient bandwidth to handle the "Out of Band" energy, you will get a DC shift in the output waveform. The magnitude of this shift is proportional to the magnitude of the out of band energy. Again, the result in a bad measurement.
        iii. Programmable analog filters also introduce group delays. In large or small channel count tests, all analog filters should be the same type and set to the same frequency.

    iv. Most importantly, if the programmable filter is to double as the Analog Anti-Alias (AAA) filter for the system, the filter roll off should be sufficient to reduce possible alias energy to a threshold close to the bit density of the digitizer at the Nyquist of the digitizing rate. So, if you have a 16-Bit digitizer running at 500kSa/s, any energy above 250kHz should be ~ 92dB-96dB down. (Note: you will not get the required level of attenuation with a 4, 6 pole filter. Even with an 8 pole analog filter, the filter cutoff must be well below 100kHz)

c. Using a 2-Tone testing process can immediately identify DAS system inadequacies for a given testing regimen. The test uses either a signal generator capable of delivering two discrete Sine tones at different amplitudes combined into one output, or two separate signal generators fed into a summing junction which is then fed into the DAS. Care needs to be taken not to pick Sine Tone frequencies which are even (e.g. 10.000kHz & 1.000MHz) as this will lead to digital artifacts caused by harmonics of the two frequencies and the effective sampling rate of the DAS.
    i. The chosen frequencies should be determined by the desired measurement frequency & magnitude and the max out-of-band frequency & magnitude.
    ii. If we use the case of the 7270A 200kG accelerometer, our mechanical response frequency would be in the 10kHz range ~ 20mV PP. The resonance would be around 1.2MHz ~ 5VPP.
    iii. When these frequencies are combined and fed into and digitized by the DAS, you should be able to extract the two original frequencies from the complex waveform using digital filtering. The key is to verify that there is no distortion of the low frequency small magnitude sine wave. If there is distortion, then the system is likely slew rate limited.

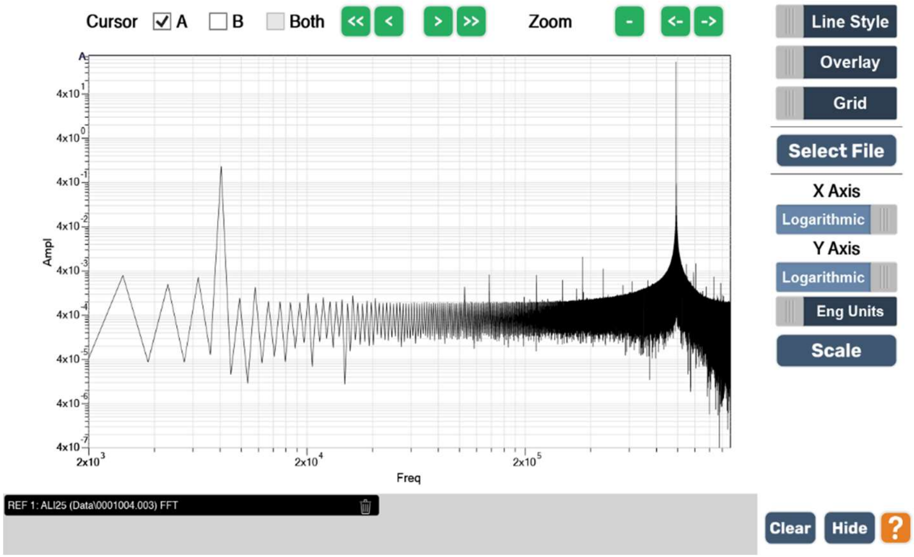
COTS: Why buy a fully integrated turn-key DAS

As mentioned earlier, a “**Designed For Purpose**” DAS system takes the guesswork out of fielding a system which will yield high quality test results. The end-to-end capabilities are specified, using the latest tools and technology. Instead of worrying whether you have a gain limitation issue, you can just look at the data sheet. New systems like the Computer Methods / PhoenixKonnect ALI-25 system, for example specifies effective sample rates, the digitizer bit density, and rather than gain, they specify full scale ranges. The bandwidth is specified in terms of flatness (0.1dB at 1.0 MHz), this flatness is on any full scale range. The ALI-25 system is designed to deliver maximum bandwidth with none of the concerns of early systems using programmable analog filtering. There is one fixed AAA filter set to the base rate of the digitizer, all subsequent filtering is digital FIR, so there are no group delays to worry about, no filter-peaking. Over 20 years ago Spectral Dynamics, Inc introduced their VXI based product which set the bar for a high reliability integrated high speed transient recorder. Until now the VX2805C capabilities remained unequalled in the domestic shock testing arena. Companies made faster digitizers, but there was no signal conditioning. The ALI / PK (PhoenixKonnect) based system meets or exceeds every capability of the SD product augmented by a broader range of transducer support, triggering capabilities, smaller size, field testing ruggedness and distributed acquisition capabilities.

Below are a set of graphs generated from a 2-Tone test performed on a Computer Methods ALI / PK data system. The test input frequencies & magnitudes are:

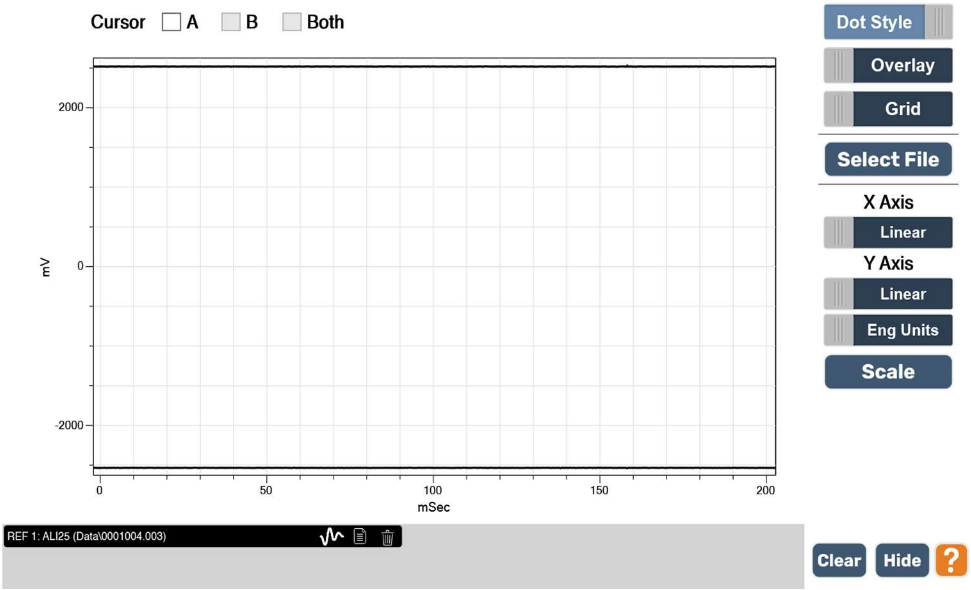
Signal 1: 20 mVpp @ 9.7 kHz Signal 2: 5Vpp @ 1.23 MHz

Image #1 is the FFT of the complex waveform showing the distinct 2-Peaks (nominal 10kHz & 1MHz) in Log x Log format

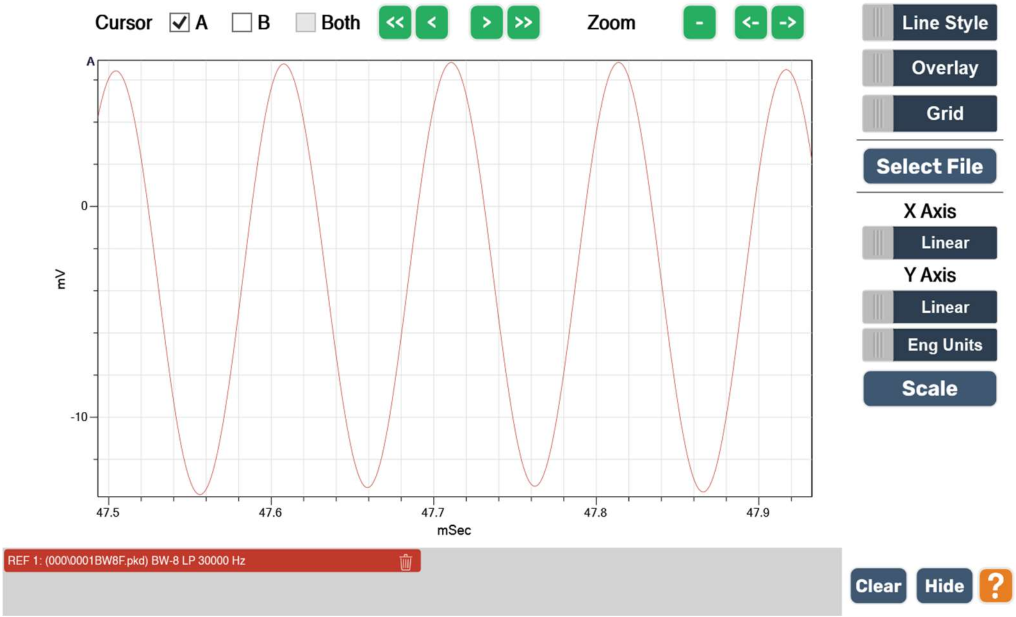


X Axis
Logarithmic
Y Axis
Logarithmic

The second image shows the max Peak to Peak magnitude of the complex signal using DOT mode for clarity. (5V PP)

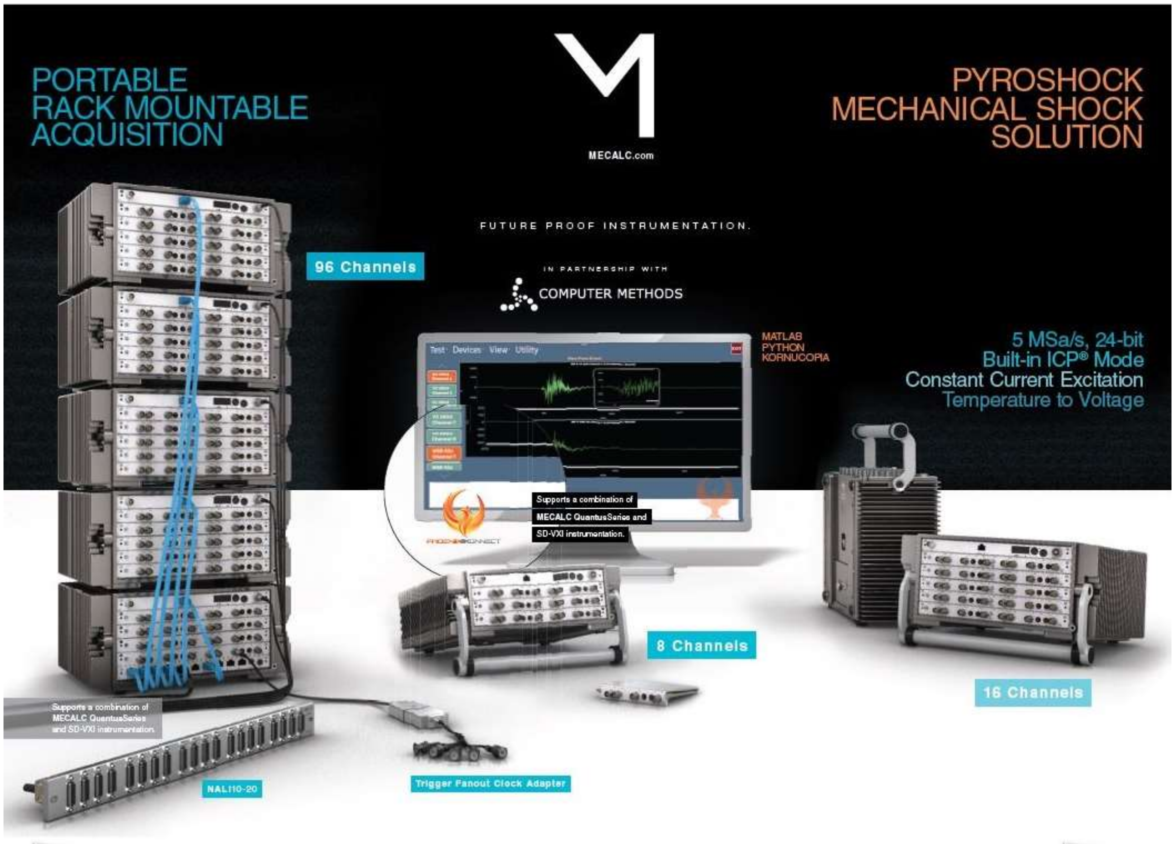


The third image is the low pass filtered (post processed) resulting waveform. Note: that there is no distortion in the Sine Wave.



Conclusions:

Whether you choose to RYO or buy a COTS system, it is up to you to validate that your DAS is up to the task for your testing series. Always make sure that there are applications support options available for your chosen approach. This can be difficult for the RYO approach, whereas the COTS approach is being a DFP (Designed For Purpose) system, so the vendor should have resources available to support you. Remember, in the testing world, it is always what you didn't see or anticipate that will cause unexpected failures. Reach out to your local PK/ALI resource and let us show you what you have been missing.



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