

# Digital Shaker Vibration Controller --- a Historical View

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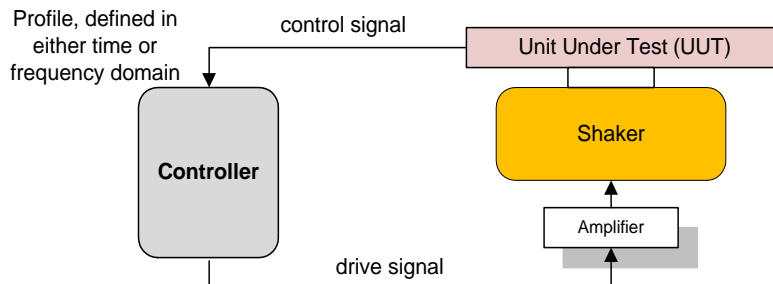
## Introducing Vibration Controller

The digital Vibration Control System (VCS) is a computer system that can conduct close-loop control for vibration shaker table systems. It generates an electronic signal that drives the amplifier which then provides the drive signal to either a hydraulic or electro-dynamic shaker. The vibration response on the UUT (Unit Under Test) is fed back to the VCS as a feedback control signal. In the close-loop control environment, the control signal must follow certain pre-specified characteristics in the time or frequency domain. These have been defined as Sine, Random, Sine-On-Random, Random-on-Random, Classical Shock, SRS, Road Simulation and other forms of control.

Most tests use a single axis shaker to excite the structure. Some sophisticated tests ask for multiple shakers. In the case when multiple exciters are used, the control system will involve MIMO (multiple-input/multiple-output) cross channel calculations. The technique used in the multiple-exciter control is much more sophisticated than the single axis controller. This paper mainly addresses single axis control.

A control signal refers to one or multiple signals measured from the UUT. If the control signal indicates that it is other than the desired testing profile, adjustments are made to the drive signal so that the control signal will converge to the desired profile. The control system continuously, in real-time, corrects for the dynamics of the shaker and UUT dynamics to maintain accurate control. Safety checking is enhanced by a distributed processing architecture that handles the control loop independent of the PC host computer.

The block diagram below shows the process closed-loop control. Sensors such as accelerometers are used to measure the response of the UUT and provide the Control Signal.



A random controller will continuously output a random signal (Drive Signal) so that the power spectral density of the control signal (Measured Signal) has the defined spectrum shape. This defined spectrum shape is called the Profile Spectrum.

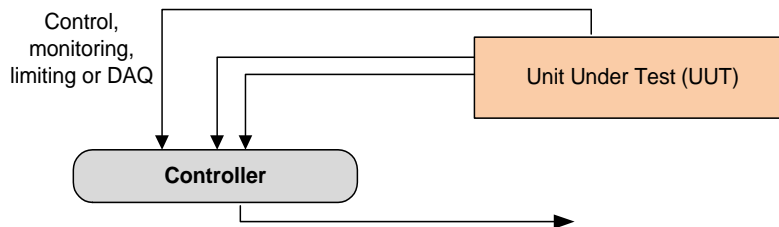
A sine controller will continuously output a swept sine signal at a certain voltage so that the control signal, which is also a sine-like signal, will follow the pre-defined amplitude spectrum.

Classical Shock controllers define their required profile in the time domain. SRS defines it in the SRS spectral domain. Road Simulation controller defines its required profile as a very long time signal.

Sine on Random or Random on Random, which are also called mixed mode control, combine the random controller with other modes of control therefore their testing setup is more complex.

It is estimated that nearly 100% of the controllers in the market ask for Random and Sine control. Roughly 50% ask for Classic Shock control. Mixed mode, SRS, Transient History and Road Simulation are used in less common, specialized applications.

Even with one excitation source, there are reasons to take the measurements for many points on the UUT. These measurement points can be used for several purposes, as shown below:



When multiple inputs are used as control channels, the user will choose Control Strategy, such as Average, Maximum or Minimum. For example, the average-strategy takes account of all the measurement channels as control channels and averages their effect in the frequency domain with different weighting factors.

### ***First Generation VCS ---- Standalone***

The earliest digital vibration shaker controller was developed by a few HP engineers in 1970s. They tested many close-loop control algorithms with the earliest most successful signal analyzer, HP5451. The HP5451 was built based on HP2100 mini-computer with very limited memory and computation resource. The engineers used various clever methods in trying to tackle the physical world that in nature requires a few kilohertz real-time bandwidth. Ron Potter and Peter Moseley made the greatest contribution to the early generation controllers.



**Figure 1 HP 5451 Dynamic Analysis System**

After HP successfully tested the algorithms with HP5451, HP5427, a dedicated VCS was commercially produced in the early 80s. It consisted of a few stacked boxes, with dedicated display screens and control panels. HP5427 was a very successful product. However, HP quickly abandoned this product line due to their company strategy.



In the early 70s, two inventors, Edwin Sloane and Charles Heizman working for a company named Time Data, were granted a patent for random vibration control. Time Data was later purchased by GenRad that released their standalone control system. The GR25xx was probably the most successful controller sold in the late 80s. A picture of GenRad VCS is shown below:



**Figure 2 GenRad 2506**

The vibration control department of GenRad later became part of Spectral Dynamics. Dr. Marcos Underwood was the chief engineer for the GenRad controller. In the algorithms he invented, he focused more on the “error” control instead of the proportional control which was used by HP. Tony Keller also made great contribution to the controller development in the early days. The PDP-series mini-computers from DEC were the hardware platforms of VCS.

In early 80s, LMS worked together with HP to provide all the vibration control software to HP’s new hardware (Paragon). LMS’s relationship to HP was similar to Microsoft’s relationship to IBM’s PC. Eventually LMS and Microsoft profited more by selling software compared to IBM and HP who provided only the hardware.

Other players of earlier generation VCS were Ling Electronics, MB Dynamics, Schlumberger, etc. Based on dedicated hardware, the first generation VCS was usually sold in the range of \$80k to \$200k. They were very sophisticated to operate. However, capitalizing on the vast demand in the structural testing of aerospace, automotive and military in the 1980s, an industry was born. Most of the control algorithms used today were originated at that time. The MIL810 standard, which sets the most comprehensive procedure of environmental testing including vibration test, was also established in this period.

## Second Generation VCS ---- PC-Based

In the early 90s, the IBM-PC gained popularity in industry. Many companies started to use PC as the platform for data acquisition and dynamic signal analysis. Sri Welaratna and Dave Snyder, two ex-veterans from HP, founded Data Physics. The Lansmont Corporation initiated a developmental program in collaboration with Data Physics for the development of the first PC-based digital VCS which resulted in the production of the Lansmont TTVI controller and the DP540. These early DOS based controllers had impressive and flexible graphic user interfaces for that time. The DP540 used multiple ISA plug in DSP cards. Each card had several DSPs and A/D or D/A converters. Dr. James Zhuge was a key member of the Data Physics development team at that time. The product was a huge success.



Figure 3 Data Physics DP540

Along the same line of DP540 and later DP550 (the Windows version of DP540) several other vendors released their own PC-based VCS, such as Puma from SD, DVC from UniDyn, VWin from Unholtz-Dickie.

The second generation of VCS took advantage of the PC and dedicated DSPs. The usability and the performance of the products were greatly improved and the cost was reduced. With the PC, the display, reporting capability, connectivity, and system performance was greatly improved.

The continuous price drop made VCS more feasible for commercial applications such as electronics and packaging testing. While the unit price was declining, the total market size of VCS was in fact increasing moderately year by year.

The shortcoming of the second generation VCS was that the system was heavily dependent on the PC performance. This was because the control loop went through the PC CPU and the PC plug-in cards were housed by the PC. Many controllers mentioned above used the ISA bus which restricted the loop-time of the controller by the interrupt and the traffic bandwidth of PC. Even the PCI bus was used, the PC CPU still played a very important role in the control process. In addition, the analog performance was limited due to interference by the PC's physical and electrical environment.

Aside from the PC architecture, LMS and  $m+p$  continued to build their software around HP hardware using the UNIX operating system, including Paragon and VXI systems. They mainly targeted high-end customers where simultaneous data acquisition was critical during the test.

### ***Third Generation VCS ---- PC-Tethered***

In 1996 Dactron Inc., founded by Joseph Driscoll (the Lansmont CEO) and Dr. James Zhuge, decided to pursue the next generation VCS. Dr. Zhuge believed that there existed technical shortcomings in the existing technology and he identified opportunities for improvement. The Dactron LASER series products turned out to be a great success. While the PC was still used, it was viewed as a peripheral of the system. In the new controller, the control loop did not go through the PC. With this strategy a much faster loop-time could be achieved. Many new algorithms were realized in the controller by taking advantage of floating point DSP. Justin Tang, the hardware manager, designed the controller hardware. George Ma, the senior software engineer, designed the Windows software. Dave Galyardt was the marketing manager of Dactron Inc..

The LASER was the first VCS product that used multiple floating point DSP processors, 24-bit delta/sigma A/D converters and the PCI, USB technology. The original application software was built based on native Microsoft MFC. The new architecture and the new technology allowed the system to offer many more functions while still maintaining its ease-of-use. Thousands of Dactron's LASER controllers have been installed all over the world. In 2001 Dactron was acquired by LDS, the world largest ED shaker manufacturer at that time. Now LDS is part of B&K.



**Figure 4 LDS-Dactron LASER**

After Dactron released the LASER and the Comet, many other companies including VRC and DP introduced new generations of VCS with the control loop independent of the PC.

### ***Fourth Generation VCS ---- Networked***

In 2010 Crystal Instruments announced the release of Spider-81, the next generation of vibration control systems. The Spider-81 fully takes the advantage of modern hardware, signal processing algorithms and new software technology.



Spider-81 is the first network-based vibration control system that integrates the IEEE 1588 time synchronization technology. The base module can be configured with 4 or 8 input channels. Additional channels can be expanded to 1024 channels. It features very high reliability, high accuracy of measurement, high control performance and ease-of use. Spider-81 is equipped with a drive output channel, bright LCD, digital I/O interface, internal backup battery and on board RUN/Stop button. Spider-81 uses an Ethernet connection.

Spider-81 is viewed as the fourth generation of controller because it features the following:

#### **DSP Centralized Architecture**

Unlike traditional controllers that rely heavily on an external computer for real-time operation, Spider is the first controller that directly integrates the time-synchronized Ethernet connectivity with embedded DSP technology. This strategy greatly increases the control performance, system reliability and failure protection of the controller. It also allows a large number of channels to be configured without sacrificing system performance.

#### **Latest Hardware Design**

Spider-81 modules have voltage, charge and IEPE inputs which are ideal for shock, vibration and acoustic measurement or general purpose voltage measurement. The internal flash memory stores test configuration data for controlling up to hundreds of channels simultaneously and stores real-time analysis data. Multiple output channels provide various signal output waveforms that are synchronized with the input sampling rate. A bright LCD displays testing status info. Ten monitoring connections on each unit can be used to read the signals of analog inputs and outputs. The front panel has a dozen function buttons. There are built-in isolated digital I/O and RS485 serial ports to interface with other hardware. Emergency contact switch can be installed to control the immediate shutdown.

#### **Simple Network Connection**

Ethernet connectivity allows the Spider-81 to be physically located far from the host PC. This distributed structure greatly reduces the noise and electrical interference in the system. One PC can monitor and control multiple controllers over the network. Since all the control processing and data recording are executed locally inside the controller, the network connection won't affect the control reliability. With wireless network routers, the PC can easily connect to the Spider remotely via Wi-Fi.

**Time Synchronization between Multiple Modules**

The Spider-81 is built on IEEE 1588 time synchronization technology. Spider modules on the same network can be synchronized with up to 100 ns accuracy, which guarantees  $\pm 1$  degree cross-channel phase match up to 20 kHz. With such unique technology and high-speed Ethernet data transfer, the distributed components on the network truly act as one integrated system.

**Black-Box Mode: Run without PC**

The Spider-81 can be executed in Black Box Mode which allows it to operate without a PC. In this mode, a PC is used only to configure the control system before the system starts operation and to download data after the test is complete. During the test, the controller can be operated according to a preset schedule or from a variety of external devices, such a control pendant, a Wi-Fi enabled PDA, or an iPad.

**On-Board LCD Display**

Each Spider-81 is equipped with a bright front-panel LCD that displays system status and test information. Real-time status such as control RMS or sweeping frequency can be instantly viewed.

**Designed for High Reliability**

Spider-81 is the very first vibration control system designed for fail-safe operation even in the event of network or power loss. A backup battery allows the controller to continue to function and save status information if it loses power. Advanced safety routines allow sensor failures to be detected within milliseconds. The Spider-81 hardware passed strict environmental tests including EMI, temperature, drop shock, sine and random vibration. The system was built tough to withstand the rigors of the testing environment and for long-lasting durability. The unique floating ground design reduces the ground loop problems in the installation.

**Designed for High Accuracy**

Using a patented technology, Spider-81 is the first vibration control system that achieves 130 dB input dynamic range. Each measurement channel can detect signals as small as 6  $\mu$ V and as large as 20 V. This completely eliminates the need for the input range or gain settings found on traditional controllers.

**Designed for High Control Performance**

By using enhanced control algorithms and a simplified DSP architecture, the feedback loop time of Sine and Random control are all greatly reduced. A reduced control loop time gives much better capability of resonance search and dwell or control for a structure with high Q resonances. It also provides faster responses for better safety protection.

**Ease of Use**

The Spider-81 software is further improved at the user interface level. More graphic guidance, wizards, and tools are added to make setup a snap. The interface has been rearranged to make it more logical and more useful. Event-Action Rules, Abort-Sensitivity, and numerous other new concepts are introduced in the software to simplify operation. Searching through a large number of tests is easy with keywords.

**ASAM-ODS Data and File Model**

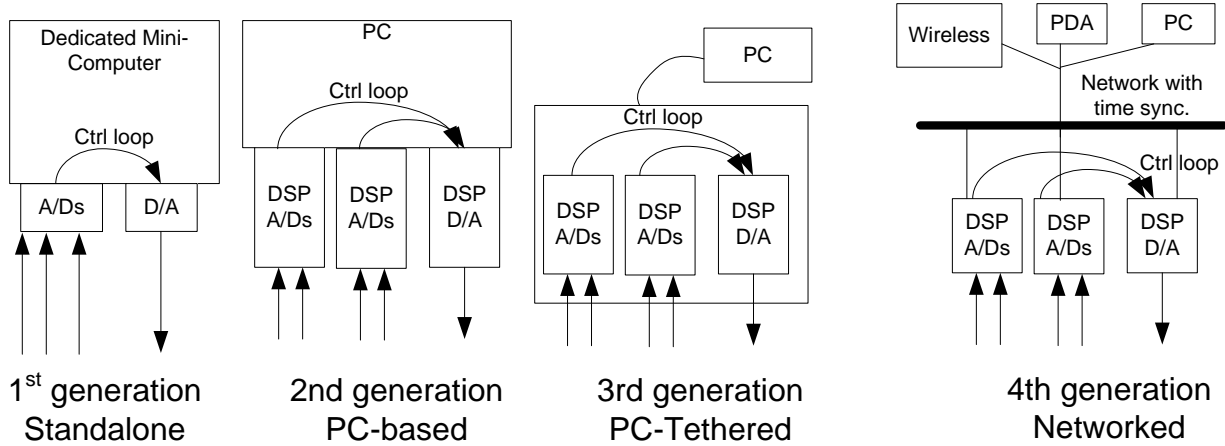
ASAM is an international organization that is supported by more than 150 companies in the testing and measurement industry. Spider-81 is fully compliant with the ASAM-ODS data and file model. With ASAM-ODS, the engineering unit, user control, testing article description and data exchange of Spider-81 are all governed by the ASAM standard. The Spider-81 data can be read by the software of LMS, B&K, BBM, and many other providers.

**Integrated with Dynamic Signal Analysis**

Spider-81 is integrated with general signal analysis functions including time stream recording, transient capture, FFT, auto-power spectra, and transfer function analysis. Multiple Spider-80 DSA modules can work together with Spider-81 VCS module as one integrated system. Spider-81 is enabled with long waveform recording functions. For mission critical testing, each input channel can acquire time domain data and store the signals into the flash memory onboard.

## Architecture Comparison

The architecture comparison of three generations of VCS is shown below:



**Figure 5 Architecture of four generations of VCS**

### Role of PC

The 1<sup>st</sup> generation controller did not use a PC. They were built based on mini-computer with a dedicated user the PC was gradually moving away from the control loop. In the 2<sup>nd</sup> generation, the PC was part of the controller loop. Data was transferred through the PC bus therefore any disturbance in the PC performance had an impact on the control. In the 3<sup>rd</sup> generation, the PC was more or less viewed as an operator terminal.

In the 4<sup>th</sup> generation, the high speed data communication and accurate time synchronization all happened on the LAN. The PC becomes one of the operator terminals residing on the LAN. The user will have a choice to access the controller through a PC, wireless, handheld pendant, PDA or other means. While some earlier generation controllers did have network capability, they were not originally designed as a high speed network device and suffered from the lack of sub-microsecond time synchronization.

The fully networked controller provides significant advantage over previous generations. A user can place the controller close to the shaker table and operate the controller either near the shaker or in a control room a few hundred meters away. A PC can be used to configure the test setup or operation terminal. But during the test the controller can also be operated by other devices such as a dedicated pendant or PDA.

### Real-Time Performance

The 1<sup>st</sup> generation VCS were not true real-time systems. Real-time means every single point of input samples is used for creating the part of next drive signal. The CPU of mini-computer had to skip input data frames when it computed the system transfer function. The loop-time could be as long as seconds.

The 2<sup>nd</sup> generation VCS were real-time systems. All the input samples were used to compute the drive signals. The loop time could be as short as a fraction of second. Taking advantage of the PC, the user interface was greatly improved and the production cost reduced.

The 3<sup>rd</sup> generation of VCS can be called “over-real-time”. It has the capability of using the same input data for multiple tasks. For example, in the Dactron Random controller, multiple control loops can be running for different frequency bands

simultaneously. In an extreme case of the Sine-on-Random controller, two random control kernels, plus 12 sine control kernels, can all run simultaneously. The control-loop time can be as short as a few milliseconds.

The 1<sup>st</sup> and 2<sup>nd</sup> generation controllers were trying to meet the requirement of mechanical characteristics of the UUT. For some demanding applications, the control system may need 5 kHz real-time control bandwidth and up to 70 dB control dynamic range. The situation changed when the 3<sup>rd</sup> generation VCS was introduced. Thanks to the usage of the floating point processor and the sigma-delta converter, the real-time bandwidth and the control dynamic range of the control system far exceeded the external mechanical requirements. From then on, improving the bandwidth and control dynamic range of a VCS cannot realize any real benefits to the customer. It became more or less a marketing pitch.

## Algorithm Improvement

With better electronics and faster processors, various software algorithms are included in the later generation of the controller. Here are a few examples:

In the Dactron controller, a sophisticated filtering technique was developed so that the random controller can have much higher frequency resolution in the low frequency end. This is called multi-resolution control.

In the VRC controller, Kurtosis control was first incorporated so the random control signal has Non-Gaussian characteristics, which more closely simulates real signals recorded from the road.

In a Spectral Dynamics controller, a better filter shape is implemented in the sine controller. It provides flatter filter pass-band characteristics compared with those using rectangular windows during spectral analysis.

## Summary

In the past four decades, the shaker vibration controller has gone through four generations. These can be referred to Standalone, PC-based, PC-tethered and fully networked. The fourth generation, fully networked, is built based on Ethernet with IEEE 1588 time synchronization. This configuration provides much greater flexibility, reliability, configurability and scalability than before.