Digital Shaker Vibration Controller --- a Historical View

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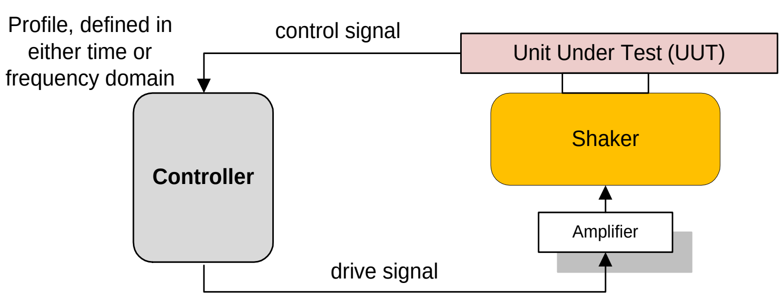
Introducing Vibration Controller

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 (ED) shaker, or an acoustic driver. The response on the UUT (Unit Under Test) is fed back to the VCS as a feedback control signal. The response is usually measured with one or more accelerometers. 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 (shock response spectrum), Road Simulation and other forms of control.

Most tests use a single shaker to excite one axis of the structure. More sophisticated tests use multiple shakers or multiple acoustic drivers to excite the structure in multiple directions. When multiple exciters are used, the control system will involve MIMO (multiple-input/multiple-output) cross channel calculations. Since multiple-exciter control is much more sophisticated than single axis control, this paper addresses mainly single axis control.

The control signal refers to one or multiple signals measured from the UUT. If the control signal is not the desired testing profile, adjustments are made to the drive signal until the control signal converges on 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 closed-loop control process. 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 drive signal so that the power spectral density of the control signal has the pre-defined spectrum shape. A pre-defined spectrum shape is called the profile spectrum. Likewise, a pre-defined time waveform can also be used.

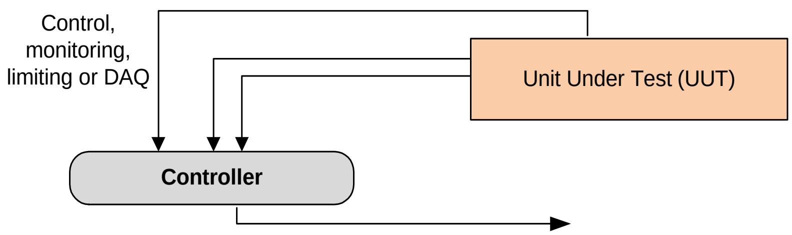
A sine controller will continuously output a swept sine signal at a certain voltage so that the control signal, which is also a sine-like signal, will follow the pre-defined amplitude spectrum.

Classical shock controllers use a pre-defined time domain profile. SRS (shock response spectrum) control uses a pre-defined SRS spectrum. A Road Simulation controller uses a very long pre-defined time signal as the control target.

Sine on Random or Random on Random control are also called mixed mode control. Each combines random control with another mode of control, and therefore their testing setup is more complex.

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

Even with one excitation source, there are reasons to measure the response at many points on the UUT. Multiple measurement points are used for several purposes, as indicated below:



With multiple control channels, the user will choose different control strategies, such as Average, Maximum or Minimum. For example, an average-strategy might average multiple control signals together in the frequency domain with different weighting factors. A typical VCS might also include additional response channels to be used to monitor critical response points or parameters of the UUT.

First Generation VCS Inventors

One of the earliest digital VCS's was developed by a Hewlett Packard engineers in the mid-1970s. HP researched many different close-loop control algorithms, using one of the earliest FFT-based signal analyzer systems, the HP5451. The HP5451 analyzer was based on an HP2100 mini-computer, which had very limited memory and computational resources. The HP engineers used various clever methods in trying to tackle the physical world that in general requires a few kilohertz of real-time bandwidth to control effectively. Two engineers, Ron Potter and Peter Moseley made many of the earliest contributions to the early generation controllers.

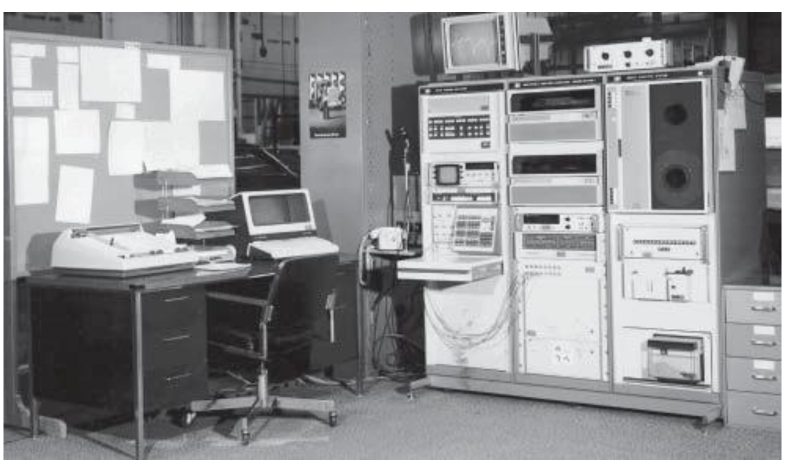


Figure 1 HP 5451 Dynamic Analysis System

After HP successfully tested the control algorithms with the HP5451, a dedicated VCS (the HP5427) was commercially produced in the late 1970's. It utilized the same computer architecture as the HP5451, but was packaged in a single bay of hardware, and dedicated to vibration control alone.

Time Data Corporation, which later became a division of General Radio (GenRad), was also an early developer of a VCS product. In the early 70s, two engineers at Time Data, Edwin Sloane and Charles Heizman, were granted a patent for random vibration control. The GenRad GR25xx standalone control system was probably the most successful controller sold during the late 1980’s. A GenRad VCS is shown below:

Figure 2 GenRad 2506

The vibration control group at the Structural Test Products (STP) Division of GenRad was later sold to the Spectral Dynamics corporation. Dr. Marcos Underwood, chief engineer for the GenRad controller, focused more on “error” control instead of the proportional control which was used by HP. Another Spectral Dynamics engineer, Tony Keller, also made many contributions to controller development in the early days. GenRad used Digital Equipment PDP-series mini-computers are the hardware platforms in their series of VCS’s.

Beginning in the early 1980s, LMS (Leuven Measurement Systems, a Belgian company) worked together with HP to provide the vibration control software for HP’s new Paragon FFT analyzer hardware. LMS’s relationship with HP was similar to Microsoft’s relationship with IBM and the PC. Like Microsoft, LMS profited by selling only software that ran on the HP hardware.

Other players of earlier generation VCS were Ling Electronics, MB Dynamics, and Schlumberger. The first generation VCS’s sold in the range of $80k to $200k, but they were very sophisticated and difficult to operate. However, most of the control algorithms in use today were developed during the 1970’s and early 1980’s. Also, the MIL810 testing standard, which sets the most comprehensive procedure of environmental testing including vibration test, was also established in this period.

Second Generation PC-Based VCS

In the early 1990's, the IBM-PC began to gain popularity in industrial applications. Many companies started to use the PC as the platform for data acquisition and dynamic signal analysis. Sri Welaratna and Dave Snyder, two former HP engineers, founded a company called Data Physics and developed one of the first PC-based VCS's. The Lansmont Corporation initiated a developmental program in collaboration with Data Physics which resulted in the production of the Lansmont TTVI controller and the DP540. This early DOS based controller had an impressive and flexible graphic user interface for that time period. The DP540 used multiple ISA plug-in DSP cards to the PC. 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 very successful in the marketplace.

Figure 3 Data Physics DP540

In the same time frame as the DP540 (and later the Windows-based DP550) several other vendors released their own PC-based VCS; Puma from Spectral Dynamics, DVC from UniDyn, and VWin from Unholtz-Dickie.

The second generation of VCS's took advantage of the low price and graphics of the PC together with the signal processing power of dedicated DSPs. The usability and the performance of these products were greatly enhanced compared to their predecessors.

The continuous drop in price throughout the 1990's made VCS more affordable for commercial applications such as electronics and packaging testing. In addition, the market size for VCS increased moderately year by year.

A shortcoming of second generation VCS's was that they were heavily dependent on the performance of the PC. This was because the control loop relied on both the PC CPU and the PC plug-in cards that were installed in the PC. Many of the controllers mentioned above used the ISA bus which restricted the loop-time of the controller due to interrupts and the bus traffic bandwidth of the PC. Even when a PCI bus was used, the PC CPU still played a significant role in the control process. In addition, the analog performance of the plug-in cards was limited due to interference from the PC's physical and electrical environment.

LMS and another company, *m+p* Corporation, continued to build software only VCS solutions using the HP Paragon or newer VXI hardware, and the UNIX operating system. They targeted mainly high-end customers where simultaneous data acquisition was also required 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. They recognized technical shortcomings in the existing technology and identified opportunities for improvement. The Dactron LASER series was developed as a next generation series of VCS products. The PC was still used, but it was viewed as a peripheral of the VCS instead of the center of it.

In this new controller design, the control loop did not utilize 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 chips. Justin Tang, the hardware manager at Dactron, designed the controller hardware, and George Ma, senior software engineer, designed the Windows software.

The LASER was the first VCS product that used multiple floating point DSP processors, 24-bit delta/sigma A/D converters and the PCI and USB technology. The original software was based on the native Microsoft MFC. This new signal processing technology and architecture allowed the system to perform many more functions while still maintaining its ease-of-use. In 2001 Dactron was acquired by LDS (Ling Data Systems), the world’s largest ED shaker manufacturer at that time. LDS has subsequently been merged with B&K (Bruel & Kjaer), a leading noise and vibration equipment vendor.

Figure 4 LDS-Dactron LASER

After Dactron released the LASER and the Comet, other companies including VRC (Vibration Research Corporation) and DP introduced new generations of VCS’s using this same architecture with the control loop independent of the PC.

Fourth Generation VCS ---- Networked

In 2010 Crystal Instruments, founded by Dr. James Zhuge, announced the release of Spider-81, the next generation of vibration control systems. The Spider-81 takes full advantage of the most modern signal processing algorithms and hardware plus the latest in software technology.

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

Spider-81 is considered a fourth generation of controller because of the following new features;

DSP Centralized Architecture

Spider is the first controller that directly integrates time-synchronized Ethernet connectivity with embedded DSP technology. This strategy greatly increases the control loop performance, system reliability and failure protection. It also allows a large number of channels to be configured without sacrificing system performance.

Latest Hardware Design

The Spider modules have voltage, charge and IEPE inputs which are ideal for shock, vibration and acoustic measurement, or for general purpose voltage measurement. The internal flash memory stores test configuration data for controlling up to hundreds of channels simultaneously, and also stores real-time analysis and time history 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. An emergency contact switch can be installed to control the immediate controlled shutdown of the test.

Simple Network Connection

Ethernet connectivity allows the Spider-81 to be physically located far from the host PC. This distributed structure greatly reduces noise and electrical interference. One PC can monitor and control multiple controllers over a 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 if desired.

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 ±1 degree cross-channel phase match up to 20 kHz. With this 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 attached. In this mode, a PC is used only to configure the control system before it 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 first VCS designed for fail-safe operation even in the event of a 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 has 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 ground loop problems due to installation.

Designed for High Accuracy

Using a patented technology, Spider-81 is the first VCS that achieves 130 dB input dynamic range. Each measurement channel can detect signals as small as 6 μV and as large as 20 V. This completely eliminates the need for the input range or gain settings.

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 provides improved capability for resonance search, and for dwell or control at high Q resonances. Its higher performance also provides 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 easier. 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 that can be entered by the user as metadata.

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, MBBM, 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:

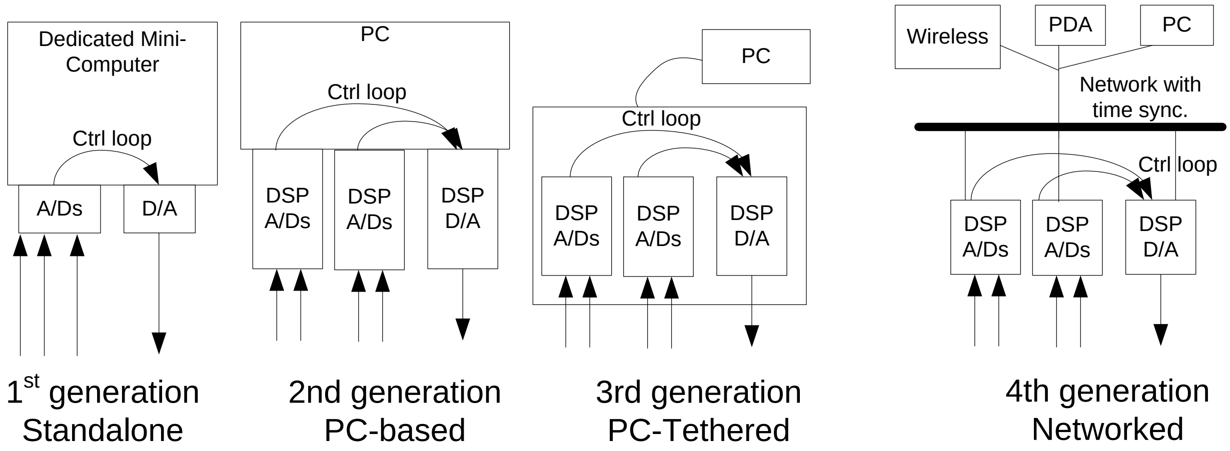


Figure 5 Architecture of four generations of VCS

Role of PC

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

In the 4th 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 act as an 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 1st generation VCS were not true real-time systems. Real-time means every single data point of the input samples is used for creating the part of the next drive signal. The CPU of the mini-computer had to skip input data frames when it computed the system transfer function. Therefore the loop-time could be as long as seconds.

The 2nd 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 3rd 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 1st and 2nd 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 3rd 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 of the test and the dynamic range of the transducers. 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 ever before.