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MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) VIBRATION CONTROL SYSTEM

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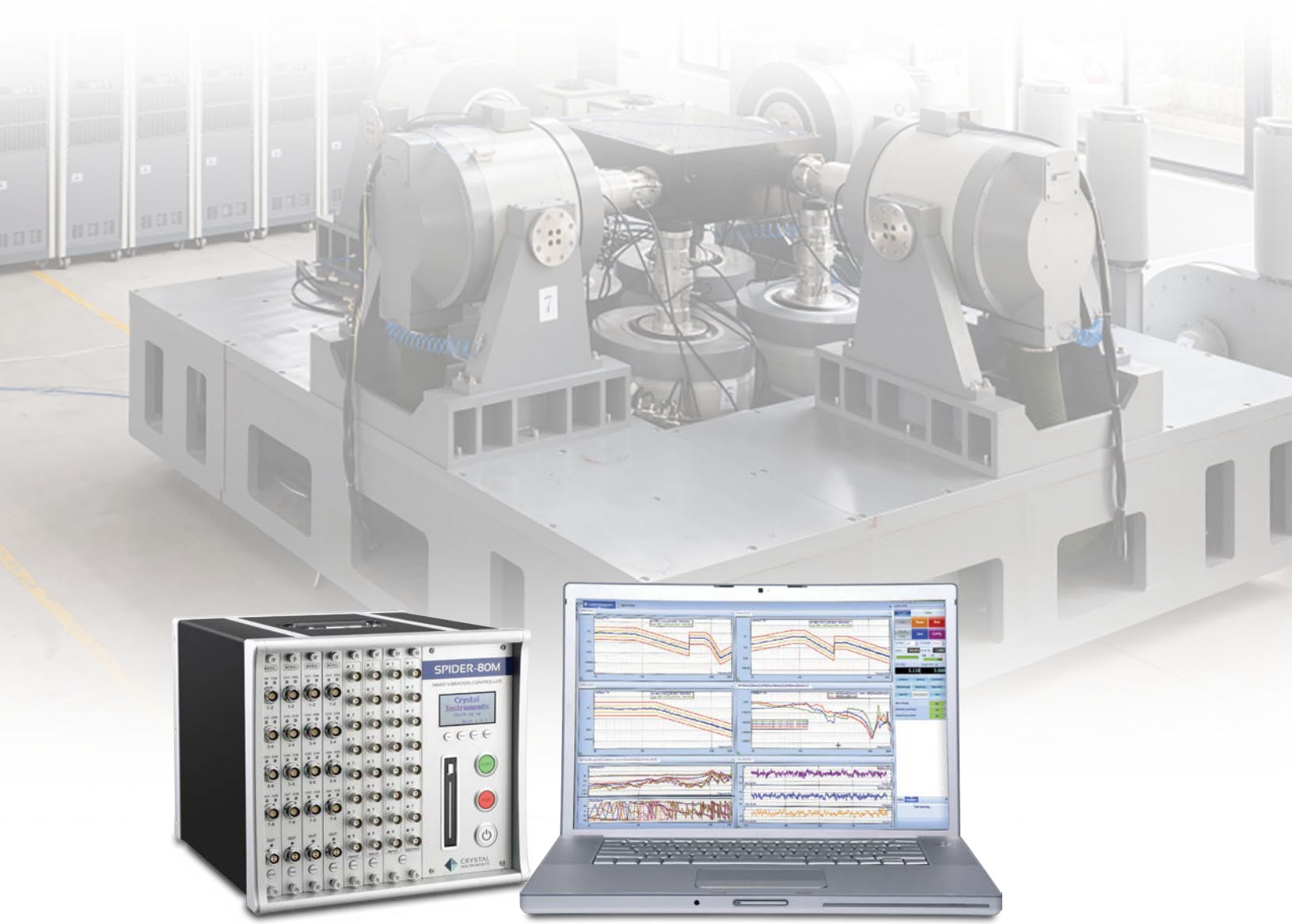


Multiple Input Multiple Output (MIMO) Vibration Control

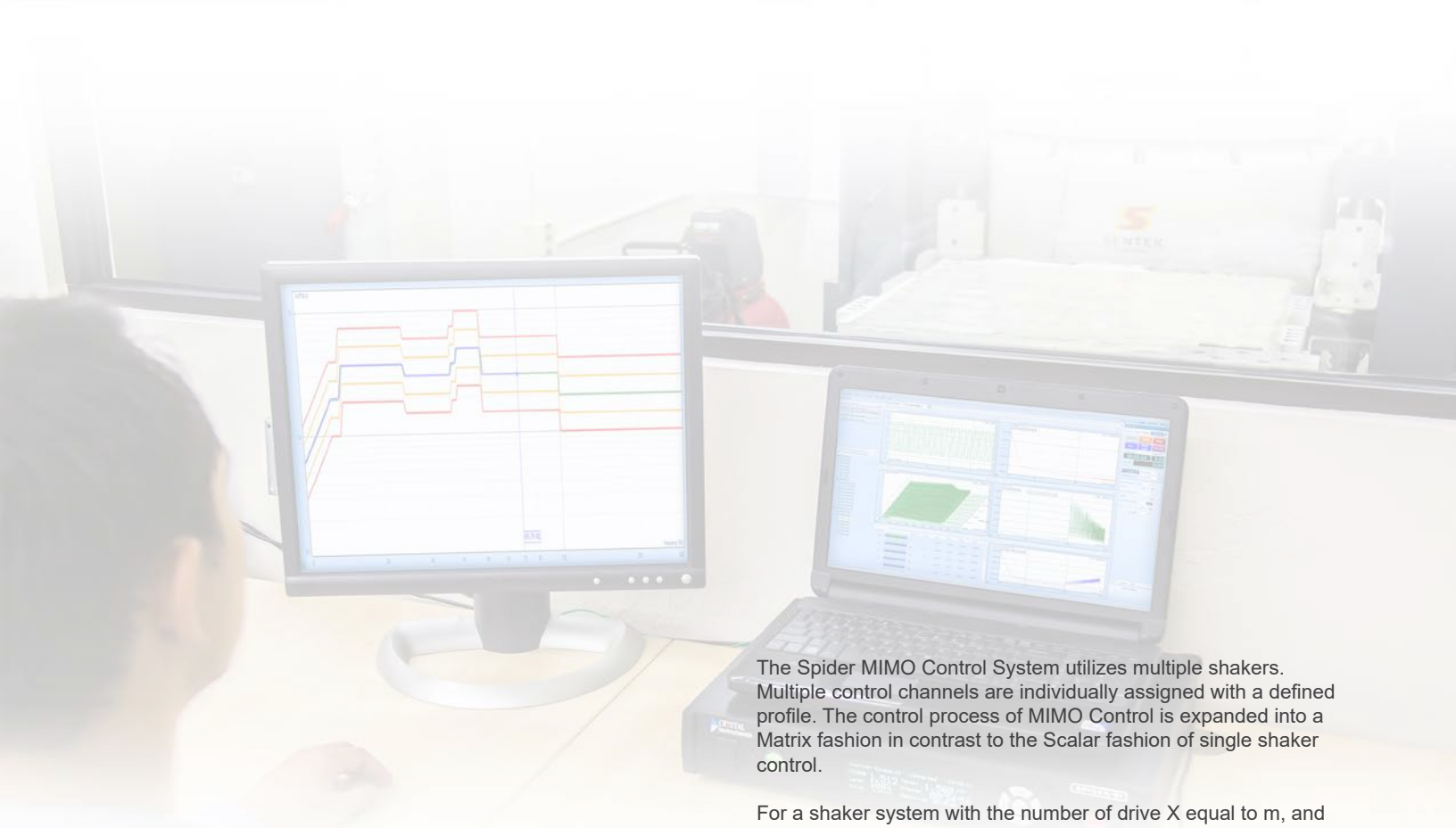
MIMO Vibration Control Overview

MIMO Testing has gained a huge momentum in the past decade with the development of multiple shaker table systems, the availability of Multiple-Input Multiple-Output (MIMO) controllers, and the readiness of the standards (e.g., Mil STD 810G method 527 and IEST DTE 022 working group recommendation,). The usage of multiple shaker testing systems includes military, defense and space organizations, with their use expanding to commercial and automotive industries as well.

In the real world, structural vibrations are excited from sources in all directions. To simulate a real-world vibration environment, testing must be performed simultaneously in multiple directions. Many applications require MIMO testing for various reasons, such as large structure testing with a single shaker requiring extensive fixturing, large structure testing with a single shaker providing insufficient force, or tests requiring simultaneous multi-axis excitation (translation only, or with rotation). MIMO testing is recommended when SDOF testing is inadequate to properly distribute the vibration energy required to satisfy the specification.

MIMO testing with multiple direction excitation decreases the overall testing time by eliminating the time required to change the fixing of the DUT to the table and change shaker orientations (e.g., from vertical to horizontal). In general, MIMO Testing provides a distribution of vibration energy to the test article in more than one axis in a controlled manner without relying upon the dynamics of the test article for such distribution. The physical configuration of the test article is such that its slenderness ratio is high, thus Single Exciter Testing must rely upon the dynamics of the test article to distribute energy. For large and heavy test articles, more than one exciter may be required to provide sufficient energy for the test item. MIMO Testing allows more degrees-of-freedom in accounting for both impedance matches and in-service boundary conditions of the test article.

The multi-shaker systems range from Multiple Exciter Single Axis (MESA), to Multiple Exciter Multiple Axis (MEMA) with 2 to 6 shakers involved, or even up to single axis, three axis translational shaker table, 6-DOF Multi-Axis Shaker Table (MAST) table, etc.



The Spider MIMO Control System utilizes multiple shakers. Multiple control channels are individually assigned with a defined profile. The control process of MIMO Control is expanded into a Matrix fashion in contrast to the Scalar fashion of single shaker control.

For a shaker system with the number of drive X equal to m, and number of Control Y equal to n, it will follow the system equation,

$$\{Y\}_{nx1} = [H]_{nxm} \{x\}_{mx1}$$

The $[H]_{nxm}$ is the system transfer function matrix, which is typically evaluated during the pretest stage. {Y} is the linear spectrum vector of the responses (controls), and {X} is the linear spectrum vector of the drives.

When using the same number of control channels and drive channels, it is referred to as square control. Rectangular control is when different numbers of control channels and drive channels are used. When the number of control is larger than the number of drive (shaker), it is referred to as over-defined control. In the opposite situation, it is regarded as under-defined control. Square control and over-defined control are more commonly used than under-defined control.

MIMO Random Control, like MIMO Sine Control, can control phase between shakers and between axes. By maintaining a multi-dimensional system matrix, the Spider system determines the contribution from each shaker to the overall response and properly differentiates according to each shaker so that proper, accurate, and safe control is always assured. The complex issue of singularities is addressed with an elegant solution that permits intricate tests to be performed without having to resort to test segmentation as an attempt to avoid singularity.

In a Random test, MIMO produces true Random with one control per profile. The same quality of control offered by Single Shaker Random control is inherent to MIMO Random control. Adaptive control guarantees rapid equalization and accurate control when non-linear responses occurs. This also reduces the time required to achieve full level testing.

Spider-80M MIMO Vibration Controller

Dual Shaker Vertical Push-Push Arrangement

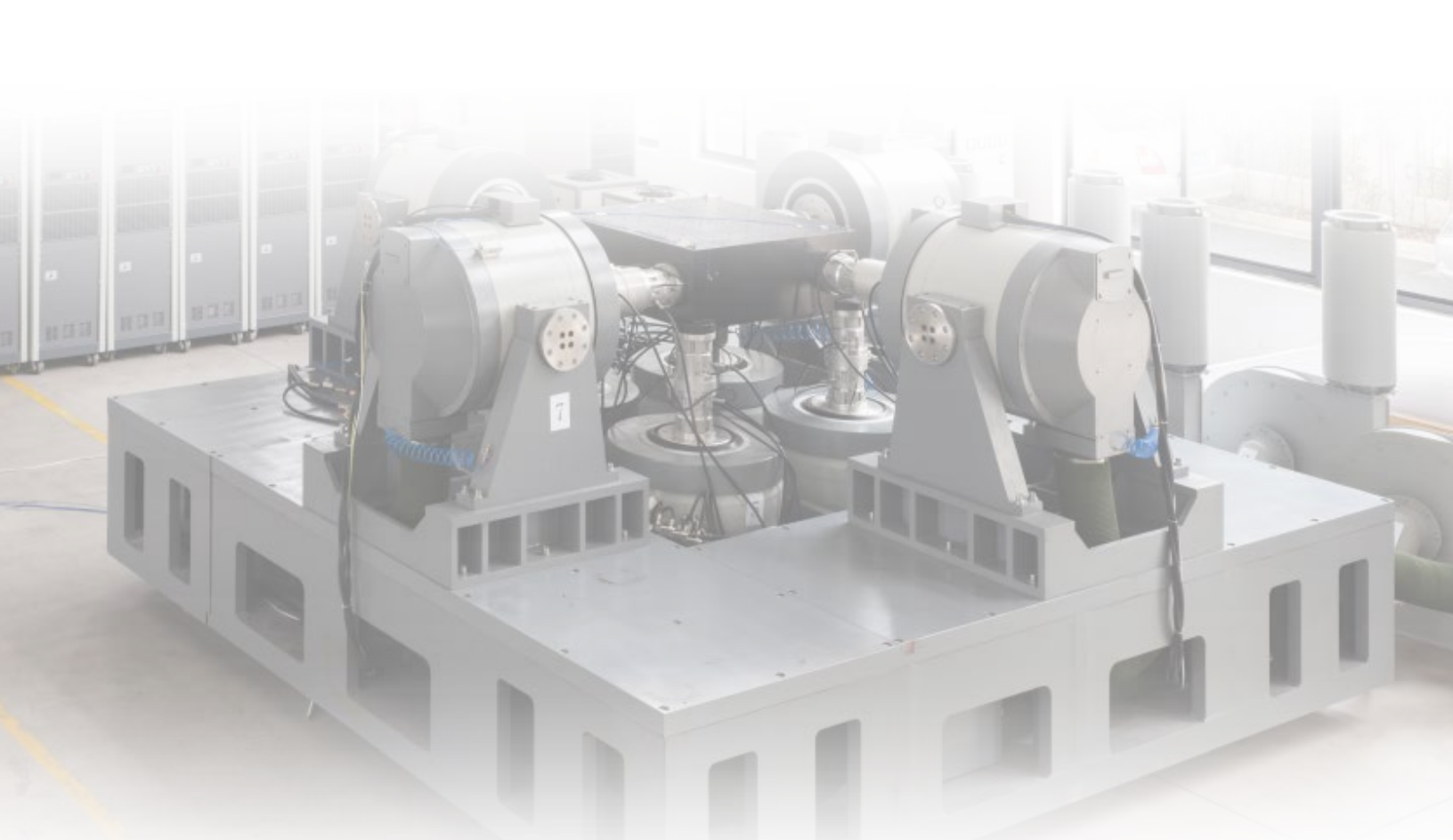
Multiple Shaker System
There are many different types of multiple shaker table arrangements based on MIMO testing applications.

Multi-Exciter Single-Axis (MESA) is an application in which multiple exciters provide dynamic input to a test item along a single axis. For cases in which the two exciters are driven to a common specification with respect to both phase and amplitude, the output may be described basically in one axis of excitation. For cases in which the two exciters are driven to independent magnitude and/or phase specifications, the output may need to be described in terms of a forward axis and aft axis, and perhaps, a rotational axis about the test item's center-of-gravity (CG).

Note that the system would require appropriate bearing assemblies to allow a pure rotational MESA or combined linear and rotational motion. The following photo illustrates a dual shaker vertical push-push arrangement.

Three axis shaker tables are available for Multiple-Exciter Multiple-Axis (MEMA) test arrangements. Many testing applications require testing the DUT in simultaneously all three directions. With a three- axis shaker table system, the overall testing time is reduced by two-thirds over single-axis testing along each axis. More importantly, it identifies failures otherwise undetected with single-axis testing.

The automotive industry has been running tests on their vehicles for decades using four poster testing systems. Nowadays, with the availability of sophisticated MIMO control, testing with four posters is raised to a whole new level. Users can accurately reproduce time waveforms recorded from the testing tracks or real road conditions inside the lab



The vibration environment is incomplete without rotation. The MEMA Type 6 DOF Shaker Tables are available for these types of testing. The arrangement of shakers among all three axes allows the row, pitch, and yaw to be achieved along with the three-dimensional translation motions from the table.

The six-DOF testing table shown above consists of eight electro-dynamic shakers arranged along all three directions. Four shakers under the table will provide the excitation along the vertical axis translational motion together with the roll and pitch rotational motion. The four shakers, with two along each horizontal direction, will excite the table to generate transverse and longitudinal translational motion, as well as yaw rotational motion.

MIMO Vibration Control Software

MIMO Vibration Control has always been a challenge for testing engineers. With Spider MIMO Control software, it is now possible to perform accurate and precise MIMO testing using multiple shakers to reproduce real-world complex vibration environments. Spider MIMO Control software covers the complete range of multi-shaker test requirements.

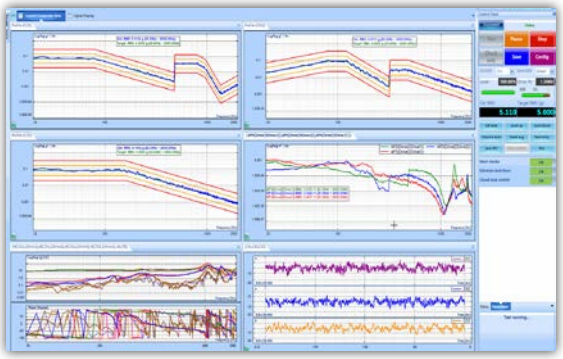
Spider MIMO Control employs continuous control to adapt to the dynamics of the system under test. On top of that, the proven non-linear control algorithm further corrects any error that may arise in the system. Also consider the coupled responses from multiple inputs, simultaneously resulting with very high control accuracy. Spider MIMO Control not only controls the amplitude for each control channel but also controls their phase relationships as well.

With this release, the MIMO Control applications supported are MIMO Random Control, MIMO Sine Control and MIMO Time Waveform Replication.

MIMO RANDOM CONTROL

Features:

- Easy-to-use testing process
- Supports up to 8 output channels
- Shaker configuration with user defined Drive DOF and shaker
- User defined H update rate
- Non-linear control to correct error
- User selected ramp-up ramp-down rate
- Run pretest or use saved FRF
- Pretest with uniform or shaped random, user specified average #
- Control mode of magnitude only, mag and phase, or advanced
- Profile library, import/export
- Run schedule with user defined level/duration, loop
- Safety check of open loop channel, RMS abort, alarm/abort, max drive, etc.
- Default report, fully customizable report



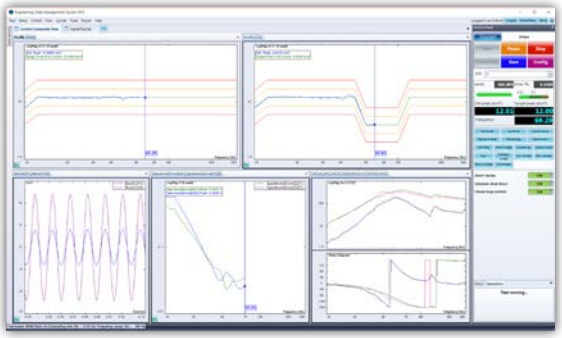
MIMO Random Control
MIMO random control is one of the more commonly used multiple shaker control methods, which provides precise control in real time. The device under test is subjected to true random noise with a precisely shaped spectrum with Gaussian amplitude statistics. The recording option records time-stream data at the full sample rate on all input channels.

For MIMO random control, multiple random profiles are defined for each control channel. The relationship among these controls can be defined and controlled, or not. This results in different MIMO Random control modes: Magnitude only control, Mag and Phase control, and Advanced control.

MIMO SINE CONTROL

Features:

- Easy-to-use testing process
- Supports up to 8 output channels
- Shaker configuration with user defined drive DOF and shaker
- User defined # of signal plot points
- User selected sweep type of Log or Linear
- User selected measurement strategy of filter, RMS, mean, or peak
- Filter type of proportional or fixed
- User selected compression rate, ramp rate and abort ramp down rate
- Run pretest or use saved FRF
- Pretest with uniform or shaped random, user specified average #
- Control mode of magnitude only, mag and phase
- Profile library, import/export
- Run Schedule with user defined left/right/start frequency, initial sweep direction, level, sweep speed, sweep #
- Safety check of open loop channel, RMS abort, alarm/abort, max drive, etc.
- Default report, fully customizable report



MIMO Sine Control
MIMO Sine control is another commonly used multiple shaker control method, it provides precise control in real time. This method controls multiple sine waves with a control dynamic range up to 100 dB. With MIMO Sine control, linear spectrum profiles of Mag, or Mag/Phase are defined and assigned to multiple control channels. With the sweep rate defined, the sine waveform in the time domain is determined.

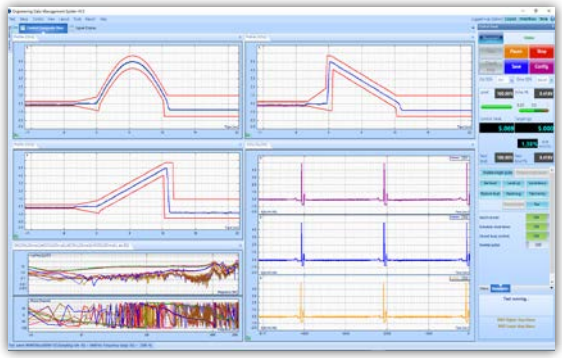
Random signals are applied during pretest to identify the system FRF matrix. During control, the closed loop control will correct errors from all control channels. Tracking filters are most often used for control as well as measurement channels to calculate the sine signal amplitude and phase.

Crystal Instruments Vibration Controllers - Scale up to 512 Channels

MIMO SHOCK CONTROL

Features:

- Easy-to-use testing process
- Supports up to 8 output channels
- Shaker configuration with user-defined drive DOF and shaker
- User defined correction rate (0.0 – 1.0)
- Run pretest or use saved FRF
- Pretest with Uniform or Shaped Random, user specified Average #
- Profile editor, with “use one profile for all control channels” option
- Classical shock pulse type: half-sine, terminal or initial-peak saw tooth, triangle, rectangle, trapezoid, or haver-sine.
- Tolerance: Mil STD 810G, 810H, STD202F, IEC 60068-2-27, etc.
- Compensation: pre-post, pre, post
- Run schedule with user-defined level/pulses, loop
- Safety check of open loop channel, RMS abort, alarm/abort, max drive, etc.
- Default report, fully customizable report



MIMO Shock Control
EDM MIMO Shock Control is now added to the MIMO VCS software group which already includes MIMO Random Control, MIMO Sine Control and MIMO Time Waveform Replication control tests. MIMO Shock Control is used to measure the reliability and durability of an object under test.

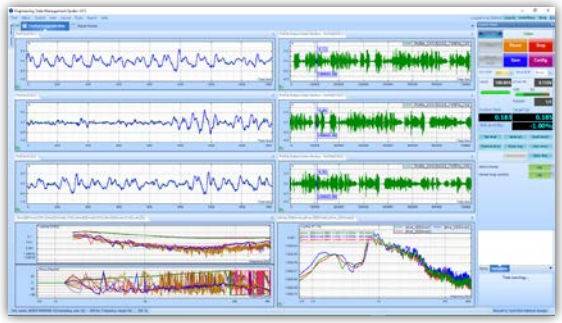
MIMO Shock Control is a multiple shaker system control method which provides precise, real-time, multi-channel analysis of classical shock waveforms in the time domain. The MIMO Shock Control process is essentially a time-domain waveform replication process that uses an FFT based algorithm to correct test system dynamics.

A MIMO shock test outputs a series of pulses to test a structure. The responses are measured at multiple locations on the structure and spectral analysis is used to determine its frequency characteristics. The Fourier transform of the impulse response is the Frequency Response Function (FRF) of the system.

MIMO TWR CONTROL

Features:

- Easy-to-use testing process
- Supports up to 8 output channels
- Shaker configuration with user defined drive DOF and shaker
- Control strategy of reference/FRF, or real-time
- User defined H update rate (with real time control strategy)
- User defined low pass filter
- User selected ramp-up/ramp-down rate
- Run pretest or use saved FRF
- Pretest with uniform or shaped random, user defined # of average
- Profile addition/removal/uploading/downloading
- Run schedule with user selected profile, level, and repeat times
- Safety check of open loop channel, RMS abort, alarm/abort, max drive, etc.
- Default report, fully customizable report



MIMO TWR Control
MIMO Time Waveform Replication (TWR) is a popular method to use when reproducing field recorded data on a multiple shaker table in the lab. With MIMO TWR control, a time waveform profile containing multiple channels of data can be imported, pre-processed (such as bandpass filtered, etc.), and selected as a control profile.

Each channel of time waveform in the profile has the same sample rate and length. MIMO TWR control is carried out based on block by block of data. There are two control algorithms to select from. One control algorithm keeps the system FRF matrix measured from the pretest stage while updating the drive to correct errors from one block to the next. The other control algorithm updates the system FRF Matrix online as the test operates.

MIMO Control Modules Specifications	
MIMO Control	
Output Channels:	Number of Output: 2 to 8
Safety:	Abort Sensitivity; Shaker Safety Limits; Open Loop Detection; RMS Limits (Random); Control Spectral Limits (Random/Sine); Max Drive Limit; Shutdown (Random)
MIMO Random Control (VCS-20-Cxx-Sxx)	
Provides precise, real-time, MIMO control and analysis; Supports up to 512 input channels, and up to 8 output channels (shakers). Besides the control channels, the rest input channels can be set up as monitoring and time data recording channels. A unique hardware design provides a fast loop time of less than 15 ms.	
Control Parameters:	• Frequency Range: auto calculated per profile, or selectable up to 4,900 Hz • Spectral Resolution: 200, 400, 800, 1,600, 3,200 and 6,400. • Loop Time: 12.5 ms for 2000 Hz. • Average Number: 1 - 500 (2 - 1000 DOFs) • Overlap Ratio: none, 50%, 75%, and 87.5% • Control Dynamic Range: 90 dB • Control Accuracy: ±1 dB at 99% confidence with 200 DOF • Drive Sigma Clipping: 3 - 10, or disabled • Ramp-up Rate: Fast (20 dB/s), Slow (2 dB/s), Fastest (60 dB/s)
MIMO Sine Control (VCS-40-Cxx-Sxx)	
Provides precise, real-time, MIMO control and analysis. Supports up to 512 input channels, and up to 8 output channels (shakers). Input channels can be enabled for control, monitoring, and time data recording channels. A unique hardware design provides a fast loop time of less than 10 ms.	
Control Parameters:	• Frequency Range: auto per profile, or selectable up to 4,900 Hz • Sweeping Speed: Log (Oct/Min): 0.001 to 6000; Log (Dec/Min): 0.001 to 2000; Linear (Hz/Sec): 0.001 to 6000 • Sweep Rate Increment: Log (Oct/Min): 0.001 to 6; Log (Dec/Min): 0.001 to 2; Linear (Hz/Sec): 0.001 to 6 • Sweep Speed Control: Oct/Min, Hz/Sec, Dec/Min, Sweeps/Min, Sweep Time/Sweep, Cycles/Min • Level Change: customizable in both logarithmic and linear rate • Compression Rate: Fast (60 dB/S), Slow (20 dB/S), and Customized • Ramp Rate: Fast, Slow, Customized, Fastest • Spectrum Display Resolution: 256 to 4,096 • Loop Time: 10 ms typical • Control Dynamic Range: 100 dB typical • Measurement Strategy: Filter, RMS, Mean, Peak • Tracking Filters: Proportional: 7% – 100%; Fixed (Hz): 1 – 500 Hz • Control Accuracy: ±1 dB through resonance with Q of 50 at 1 Oct/min • Frequency Resolution: as fine as 0.000001 Hz
MIMO Shock Control (VCS-60-Cxx-Sxx)	
Provides precise, real-time MIMO control and analysis. Supports up to 512 input channels and up to 8 output channels (shakers). Classical pulse types include half-sine, haver-sine, terminal-peak sawtooth, initial-peak saw tooth, triangle, rectangle, and trapezoid. Users can apply shock response spectrum analysis to any input signal.	
Key Features:	• Different or same profile (pulse) can be used for all control channels • Many standards are available: Mil STD 810G, 810H, STD202F, IEC 60068-2-27, ISO 8568 etc.
Control Parameters:	• Sampling Rate: automatically calculated based on the profile, or selectable from multiple ranges up to 102.4 kHz • Time Block Size: 512 to 65,536 points. • Average Number for Control: 1 – 4 • Correction Rate: 0.0 to 1.0 • Test Start Method: pretest runs with Random. Pretest may be skipped with saved FRF's (signal properties must match test settings).
MIMO Time Waveform Replication (TWR) Control (VCS-80-Cxx-Sxx)	
Provides precise, real-time, multi-channel control for long waveform duplication. TWR is capable of running an unlimited number of time profiles in a defined schedule. Multiple long waveforms can be duplicated precisely on the shaker just as they were recorded. It includes Waveform Editor (EDM-WE), a flexible importing and editing tools for long waveform signals. Up to 512 channels can be enabled, with up to 8 as control channels, the rest monitoring, and time data recording.	
Key Features:	• Number of Waveform Profiles: Infinite number of Waveform recordings (subject to the available flash memory) is supplied simultaneously to automatically run one after the other on the test specimen. • Maximum number of points: all internal flash memory space is used for storing profile data (currently 3.7 GB), which corresponds to approximately 1 billion data points. At a sampling rate of 200 samples / sec. It can replicate a waveform of about 50 days. • Maximum Frequency Range: waveforms of up to 18 kHz (fa) can be replicated. • Maximum Sampling Rate of Data: waveforms of any sampling rate up to 102.4kHz can be imported into the Waveform Editor tool and converted to a suitable frequency range.
Control Parameters:	• Sampling Rate: up to 18 kHz, automatically calculated based on profile • Display Time Block Size: up to 4,096 points • Transfer Function Update Ratio: transfer function is updated continuously in real-time depending on the transfer update ratio which can be entered by the user between 0 – 0.5. • Pretest: a random close-loop pretest logic is built-in to generate an initial FRF value

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