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Multiple-Input, Multiple-Output (MIMO) Control Systems – A New Era in Shaker Control

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The application of multiple degree of freedom (MDOF), closed-loop vibration control is steadily rising. This increase in popularity may partly be due to significant improvements in the ability to actually control complex motions and to available actuator choices. MDOF, or specifically multiple-input, multiple-output (MIMO) control systems, have ushered in a new era in shaker control.

We live in a 6-DOF world. The world is also random in nature. It also tends to produce periodic energy, quite often in the presence of random energy, all in 6 DOF. For more than 40 years, the test community has performed single degree of freedom (SDOF) testing to determine a product's ability to survive its environment, determine its useful life span, or prove that original design criteria had been met. There may be as many reasons to do SDOF testing as there are test specifications. With the advent of more powerful and sophisticated closed-loop control systems, we are no longer limited to SDOF testing.

Historically, MIMO was considered the domain of only time history replications. Attempts were made to use a time history replication capability to simulate swept sine control and even random control. The inherent weakness in these attempts stems from radical differences in the control process associated with sine control and random control to waveform replication. In the first case, swept sine control is expected to employ the same methods as in SDOF control or multiple-input, single-output (MISO) control.

Swept sine control is essentially a time domain control scheme, where the primary goal is to produce true sine waves that continuously change their frequency in an analog manner. Adhering to this premise ensures that the control system will not produce gaps in frequency while simultaneously controlling the amplitude of the drive signal. This also ensures that the control spectra will be accurate at the shaker table. In the presence of resonant responses, swept sine control is expected to dynamically adjust the amplitude of the driven signal so the response level tracks desired shape and level.

To help attain this goal, the tracking filter was invented. It requires a true sine wave that maintains fixed amplitude for the duration of the sine sweep to be supplied to the filter so the filter will remain centered on the driven frequency. The tracking filter, a band pass filter, sweeps its center frequency, tracking the driven frequency changes and maintaining the bandwidth selected by the engineer. The filter rejects energy outside the bandwidth of the tracking filter, enabling the test system to control to a user-specified response. None of these features can be implemented in waveform replication. This expectation is doubly true in MIMO-swept sine control, where the potential for extreme damage to the specimen and actuators is a constant concern.

Random control translates well from MISO applications to MIMO applications. Its successful implementation has eluded developers for years. As with swept sine control, waveform replication fails to meet the basic criteria of random vibration testing – constant re-randomization of spectral content, phase, and spectral amplitude. The failure to produce true random means "spectral holes" will occur in the data. Frequency content will be reduced and become repetitive. These are the very points that *must* be present to be a random vibration control system in both MISO and MIMO applications. The introduction of powerful digital signal processors (DSPs) and very powerful workstations has helped usher in the era of MIMO control (see Figure 1).

MIMO control has a subcategory called multiple-exciter single axis (MESA) control. The problem of limited-force, electrodynamic shakers that permit relatively high-frequency energy to be generated has spawned a process that combines multiple shakers, all driving in the same axis. This allows a significant multiplication of force and provides potentially much larger platforms to support the test article.

A very significant benefit of MESA control is the ability to influence the off-axis motion that often results when very large structures are base excited by a single large shaker. MESA testing permits the array of shakers to identify and cancel or at least counteract the tipping tendency of tall massive test articles. By virtue of having independent control of each shaker as well as many control and limit points to identify the onset of off-axis motion, the control system is able to correct motions while barely noticeable. This ensures greater lab, specimen and personnel safety as well as greater accuracy of test than may typically be possible with older techniques.

Figure 1. Spectral Dynamics' portable Jaguar structural and vibration system.

Figure 2. Three 20,000-lb-force shakers for simultaneously testing on three axes.

While there are many ways to implement MIMO excitation and control, perhaps the most ambitious test method is the three-axis X, Y, Z translation only. In this scheme, three actuators are combined into an orientation that permits simultaneous motion vertically and in both horizontal directions. As shown in Figure 2, the U.S. Navy in Keyport, WA, has implemented this scheme employing three 20,000-lb-force shakers capable of 2 in. of stroke. The goal of this endeavor is to implement testing previously performed one axis at a time in three axes simultaneously. Test regimens include random, swept sine and shock.

Random control of three axes simultaneously poses a theoretical dilemma. If all three actuators are driven with true random energy, the moving mass the shakers are attempting to push must at times experience identical energy from the three shakers attempting simultaneous motion. That would be impossible to produce without compressing the moving mass. Fortunately, the nature of random means that these occurrences are extremely rare.

The much larger concern is the other three axes of motion that we are *not* trying to implement – the three rotational DOF (roll, pitch, and yaw). The mechanical marriage of shakers, centrally located moving mass, clever bearing implementation and care in mounting and constraining the specimen are all keys to

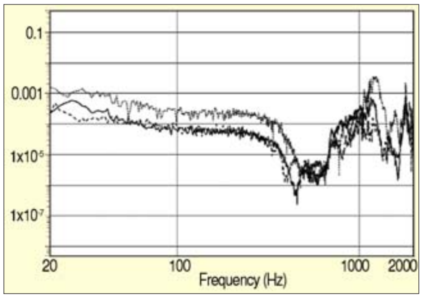

Figure 3. Triaxial vibration test data overlaid.

success. Since there is no controlled force available in the rotational axes, vigilance by the test engineers is required to monitor rotational energy.

Figure 3 illustrates an example of a test that required all three axes to employ the same reference. It shows the three drive spectra created to cause proper motion between three shakers to create an acceptable response at three different control locations. Note the obvious spectral differences in the overlaid data. The drive spectra are the product of each axis' impedance, the measure of efficiency of motion in each axis, and the control spectra for each associated drive.

Six-DOF testing adds more real-world accuracy. By introducing three more actuators in the rotational axes, direct influence can be asserted with the double benefit of causing the correct rotational shape and forces along with the ability to inhibit undesirable rotational responses – a feature missing in 3-DOF testing.

In the final analysis, the task of assembling three large shakers into a single test configuration with advanced thinking about the mechanical connections and specialized bearing design has demonstrated that the MDOF testing arena is real, it's here, and it will continue to re-

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