



Simulate and Stimulate

Creating a versatile 6 DoF
vibration test system

Team Corporation
September 2002

Historical Testing Techniques and Limitations

Vibration testing, whether employing a sinusoidal input, random input or replication of a deterministic waveform has proven to be a critical step in the successful development of new equipment. Traditionally, vibration tests have been conducted by sequentially applying uniaxial excitation to test articles along three orthogonal axes, using a linear shaker and rotating the test load after each test. Figure 1.0 shows a typical horizontal system with an electrodynamic shaker driving a fixture supported by hydrostatic linear bearings. Two methodologies have evolved from such testing. The first is an effort to emulate the characteristics of actual field conditions. Several standards and recommended practices have been produced that attempt to envelop the spectral peaks of specific environments. For example MIL STD-167 defines a typical shipboard vibration environment by specifying a given displacement for a given frequency band. SAE J1211 NOV78 defines the measured environment of various locations on a typical automobile. The drawback to this method is the inherent variation between possible field environments. In fact, SAE J1211 NOV78 specifically states "...actual measurements should be made as early as possible..." of each test



Figure 1.0 Typical single axis vibration test system with ED shaker and linear hydrostatic bearings



Figure 2.0 Simultaneous bi-axial vibration system used for qualifying small electrical components to IEEE-344.

vehicle as "...environmental conditions may change significantly with relatively minor physical location changes..." Conservatism has been built into each particular standard, however they still consist of an idealized representation of the expected field conditions.

On the other hand, stress screen vibration testing is product-dependent, not environment dependent. It attempts to detect defective parts that might fail in the field by subjecting the part to excitation derived from empirical tests rather than simulating the characteristics of actual field conditions.ⁱ Both MIL-STD-810F, 1 Jan 2000 and NAVMAT P-9492, May 1979, provide guidance and specifications for the conduct of these tests. The major shortcoming common to both

methods is sequential uniaxial excitation may not excite all the critical modes of the test object concurrently and therefore may fail to detect defective design.^{ii,iii}

Multiple Axis Excitation

Almost no standards have been written requiring multi-axis testing, the only notable exceptions being in the nuclear power plant field and defined by such standards as IEEE-344. This particular standard is used to simulate seismic events and their impact on components used in nuclear power plant construction. This particular standard calls for simultaneous bi-axial excitation of the test object. Several test systems have been produced which provide this capability, in the vertical axis and one axis horizontally. An example of a typical system is shown in Figure 2.0. Designed for small payloads, this device can be positioned at any intermediate angle between 30 and 60 degrees. During excitation, the force vector generates acceleration simultaneously in the horizontal and vertical axes. The response is coherent and in phase and the relative amplitudes can only be changed by varying the angle of excitation. Team Corporation introduced a different design, providing bi-axial excitation using separate shakers. The system can be operated in pure uniaxial modes or excitation can be simultaneously produced in both vertical and



Figure 3.0 Bi-Axial Test System for large payloads

longitudinal directions. A drawing of this system is shown in Figure 3.0. A single horizontal actuator and two vertical actuators drive the specimen mounting table. Both systems remain a compromise since not all three axes are excited simultaneously and the laboratory must run multiple tests^{iv}. As with uniaxial tests, the test object must be physically repositioned on the shaker table to conduct tests in all three axes.

It has long been recognized that multi-axis testing provides a more realistic representation of actual field conditions. However, the little research that has been conducted in systematically studying the differences between multi-axial vibration testing and single axis methods has not been incorporated into standard testing procedures. It has been shown that tri-axial excitation can cause approximately twice the fatigue damage as similar test levels and duration in single axis testing^v. In addition, the order in which uniaxial vibration is applied during a test can cause a significant variance in time-to-failure^{vi}. While these results do not confirm a serious lack in uniaxial testing procedures, they represent an important step in the rigorous investigation of differences between the results obtained with multi-axial and uniaxial methodologies.

Full 6 Degree of Freedom (6 DoF)

The introduction of very sophisticated test controllers in recent years has permitted much more complex test procedures to be applied. Several different configurations of test hardware have been developed that offer full 6 degree of freedom (6 DoF) testing capability, or excitation in three translations and three rotations simultaneously. The major roadblock to the implementation of higher frequency tests required by environmental stress screening and accelerated durability testing lies in current hardware configurations.

To address this limitation in frequency response, Team Corporation introduced a solution using hydrostatic couplings and high response, servohydraulic actuators in a compact, integrated package. Called the CUBE®, this full 6DoF device permits testing to 250 Hz in sine, expanding

that bandwidth to 500 Hz controllable random in the vertical axis. Figure 4.0 shows the CUBE® with a 1.5-m head expander and a cut-away view of the interior. Within the movable “box” of the CUBE (yellow portion in the drawing) are six servohydraulic actuators with hydrostatic bearings connecting the actuators to the box. Combined with Team’s high frequency response servovalves, this configuration has demonstrated controllable excitation in full 6DoF to 250 Hz in all axes and 500 Hz in the vertical axis.

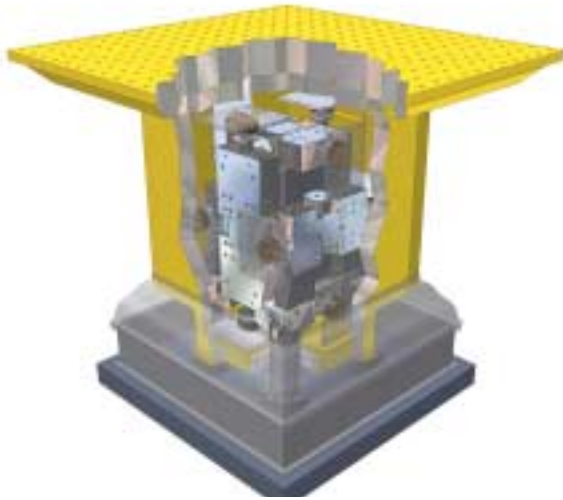


Figure 4.0 Team Corporation CUBE with a 1.5-m square head expander. Interior view shows servohydraulic actuator arrangement.

Applying true 6 DoF to AST

While offering a considerably broader useable test band than any other test equipment on the market, the CUBE is unable to produce meaningful energy much above 500 Hz, although excitation is present to 1 kHz or more. In 1999, Team Corporation conducted a series of tests to investigate the potential for creating a broad spectrum of excitation, with useful levels of energy through 2 kHz and above. The goal of the investigation was to prove the feasibility of a multi-use test machine, one that offers traditional testing capability, i.e. reproducible and controllable response, as well as one that can be used for accelerated durability testing.

The test apparatus consisted of a standard CUBE with a 42 inch by 48 inch by 1.25 inch aluminum plate

attached to the top surface. The plate was bolted to the CUBE in an asymmetric pattern. Between the plate and the upper surface of the CUBE were washers acting as stand-offs to minimize damping of the plate resonances. Six accelerometers were mounted in various locations to monitor vertical plate response. White noise was used as the drive signal to the two vertical actuators and the amplitude of the drive was controlled to produce a 50 Grms response out to 10 kHz. A plot of the accelerometer response is shown in the following graph, figure 5.0.

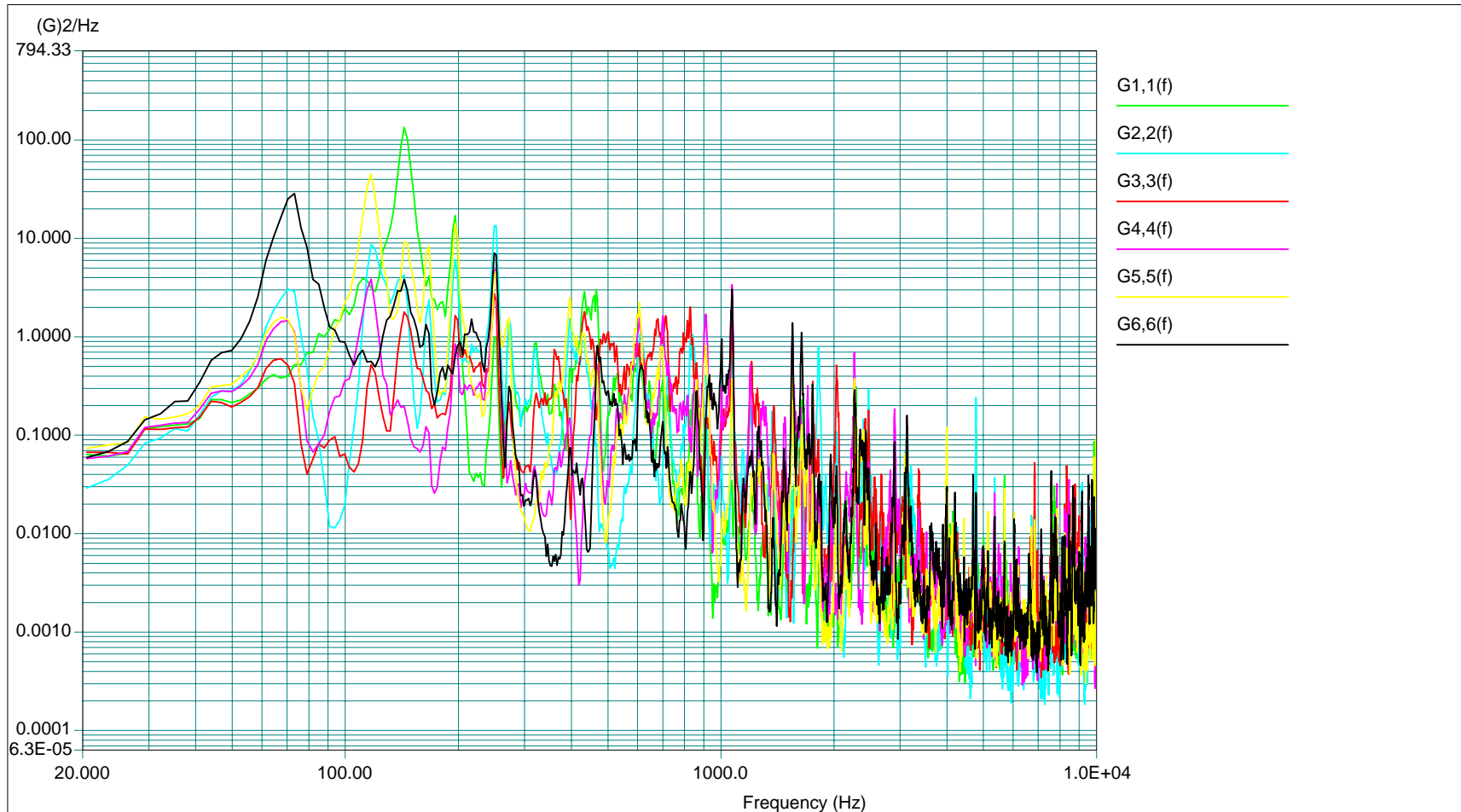
The results of this preliminary investigation have significance in two areas. The first lies in the distribution of energy as a function of frequency. Air-hammer tables typically have fairly low energy levels in the frequency band below roughly 300 Hz. Conversely, the CUBE demonstrated relatively high levels of energy beginning at 60 Hz and staying relatively constant to above a kHz. This is the frequency band where significant fatigue is accumulated in larger, mechanical test objects. The second area of significance is the dual nature of the test device. By simply bolting on a plate, the CUBE was transformed from a test system designed to provide reproducible, controllable excitation to a system well suited for the broadband, high-energy excitation required by accelerated durability tests.

The results of this very preliminary test suggest further avenues for investigation. Developing a more uniform, yet modally rich plate is an obvious direction to pursue. The influence of mounting a payload to the top plate and the resulting changes in plate response needs investigation. The premise of the initial test remains however, that through the use of a simple, bolt-on addition, a multi-function test system can be created.

It should be noted that Entela, a test laboratory in Livonia, Michigan, has developed a proprietary test protocol called Failure Mode Verification Testing (FMVT) where the CUBE plays a

fundamental role when testing large mechanical test objects. FMVT uses techniques very similar to HALT, where the test object is subjected to increasingly higher levels of environmental stresses to precipitate failures. Entela selected the CUBE as the test device for 1) ease of integration into a thermal chamber, 2) full 6 DoF excitation capability to relatively high frequencies, 3) low frequency, large displacement in both translations and rotations and 4) high payload capacity. Also, the very informative paper presented by Edward Buratynski of Lucent Technologies at AST 1999 suggests a true multi-axis vibration system capable of exciting modes in the 100 Hz range can precipitate failures at lower acceleration levels. His work demonstrated that single axis electrodynamic shakers operating at auto spectral densities about one fifth that of repetitive shock machines have equal effectiveness in precipitating the failures.^{vii} Mr. Buratynski concluded that electrodynamic shakers had more energy in the 130 Hz band where fundamental PCB modes lie and consequently caused the accumulation of stress more quickly. It seems reasonable to speculate that 6 DoF excitation can only improve failure precipitation if energy is concentrated in the frequency band where fundamental resonance is found.

Plot Header: 42" x 48" Modal Plate
Project File Name: Preliminary AST Investigation
Test Type: Signal Analysis and Waveform Source
Run Folder: .\Run Aug 06,1999 18-18-53



Data saved at 06:23:38 PM, Friday, August 06, 1999 Report created at 06:23:44 PM, Friday, August 6, 1999

Figure 5.0 Acceleration response of modally rich plate mounted on standard CUBE

ⁱ Chang, KY and A.M. Frydman. "Three-Dimensional Random Vibration Testing Definition and Simulation" In *Proceedings of the 36th Annual Technical Meeting of the Institute of Environmental Sciences*. Mount Prospect, IL: Institute of Environmental Sciences and Technology, 1990.

ⁱⁱ Whiteman, W. E. and M. Berman. "Inadequacies in Uniaxial Stress Screen Vibration Testing" *Journal of the Institute of Environmental Sciences and Technology* 44,4 (Fall 2001): 20-23

ⁱⁱⁱ Freeman, M. T. "3-axis Vibration Test System Simulates Real World." *Test Engineering and Management*. Dec/Jan, 1990-91: 10-14

^{iv} Bausch H. P., A. Franz, M. Lapin. "Simultaneous, Multiaxial Vibration Testing in Six Degrees of Freedom." *Sound and Vibration* Nov 1992: 6-11.

^v Himmelbau, H., and M. J. Hine. "Effects of Triaxial and Uniaxial Random Excitation on the Vibration Response and Fatigue Damage of Typical Spacecraft Hardware". In *Proceedings of the 66th Shock and Vibration Symposium*. Arlington, VA: Shock and Vibration Information Analysis Center, 1995.

^{vi} Whiteman and Berman, 23

^{vii} Buratynski, Edward, "A Comparison of Repetitive Shock and Electrodynamical Equipment for Vibration Stress Testing" In *Proceedings of the 1999 Workshop on Accelerated Stress Testing*. Boston, MA: IEEE Components, Packaging, and Manufacturing Technology Society, 1999.