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Bringing Broadband 6-DOF Field Vibration Environments into the Lab – Tensor 18kN Vibration Test System

Joel Hoksbergen, Team Corporation[1]

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Abstract

Commercially available vibration test systems able to reproduce and accurately control multiple-input, multiple-output vibration tests are often constrained by a limited frequency band due excessive tare mass and low natural frequencies of the fixtures. Consequently, their use in Department of Defense test facilities is limited to a select number of test profiles found in MIL STD documents and/or platform specific tests where the frequency band of interest is below 500 Hz. This frequency limitation has now been addressed with the introduction of a new system based upon multiple electro-dynamic shakers hydrostatically coupled to the specimen mounting table. This system, called the Tensor 18kN, has been designed, built, and tested by Team Corporation and has been delivered to two sites in the USA. This paper discusses the design, with an emphasis on mechanical solutions that have increased the frequency bandwidth and provide multiple points of control authority for performance to 2,000 Hz. Additionally, the system response for two specific vibration tests is presented in detail with a discussion of the system control.

Introduction

What is a Tensor? Wikipedia defines a Tensor as "a geometric object that describes the linear relations between vectors, scalars, and other tensors. Elementary examples of such relations include the dot product, the cross product, and linear map. A tensor can be represented as a multi-dimensional array of numerical values."[1] In basic engineering you may think of a Tensor in terms of the 3-dimensional stress state of a solid object. Remember the cube element showing the normal and shear stresses on each face? Now, in vibration testing you can think of a Tensor as the solution to reproducing high-frequency, multi-axis vibration "stress states" in the lab. Team Corporation's new Tensor 18kN is the most advanced commercially available vibration test system capable of replicating field vibration environments out to 2,000 Hz. Twelve independent excitation inputs are linearly mapped into six controlled degrees-of-freedom (DOF).

The basic concept of the Tensor 18kN originated in a much smaller system developed in the mid 2000's, namely the Tensor 900. This system was novel in that twelve electro-dynamic (ED) shakers were configured in such a way, with the proper bearing arrangement, to provide 6-DOF control out to 2,000 Hz. In fact, the users of this system have successfully operated it past 3,000 Hz. This is a small system, and was used to develop the basic premise of the over determined control scheme. It has 200 lbf RMS per axis and an 8" x 8" table. The first customers were Sandia National Laboratories, who has over the last several years presented

[1] J. Hoksbergen, Team Corporation, 11591 Watertank Rd., Burlington, WA 98233
Email: joel.hoksbergen@teamcorporation.com

several papers on the successes they've had operating it, and the University of Maryland's Center for Advanced Lifecycle Engineering (CALCE), who use it heavily as they research the reliability of printed circuit boards subjected to various vibration environments. Figure 1 presents the Tensor 900.

Figure 1: Tensor 900 Vibration Test System

The design of the Tensor vibration test system is covered under the following patents:

- U.S. Patent: 6 860 152
- China Patent: ZL 03 809 374.X
- Japan Patent: 4 217 210

Mechanical System

The Tensor 18kN expands the design of the Tensor 900 to a size more practical for the typical user. The system is still designed to be over-constrained and uses twelve custom made ED shakers for excitation out to 2,000 Hz. However, now 900 lbf RMS shakers are used to drive a 30 inch square table. With four shakers in each axis, this system produces 3,600 lbf RMS per axis and has a bare table moving mass of nominally 430 lbm. Figure 2 is a photo of the Tensor 18kN system and Table 1 lists the system's performance specifications.

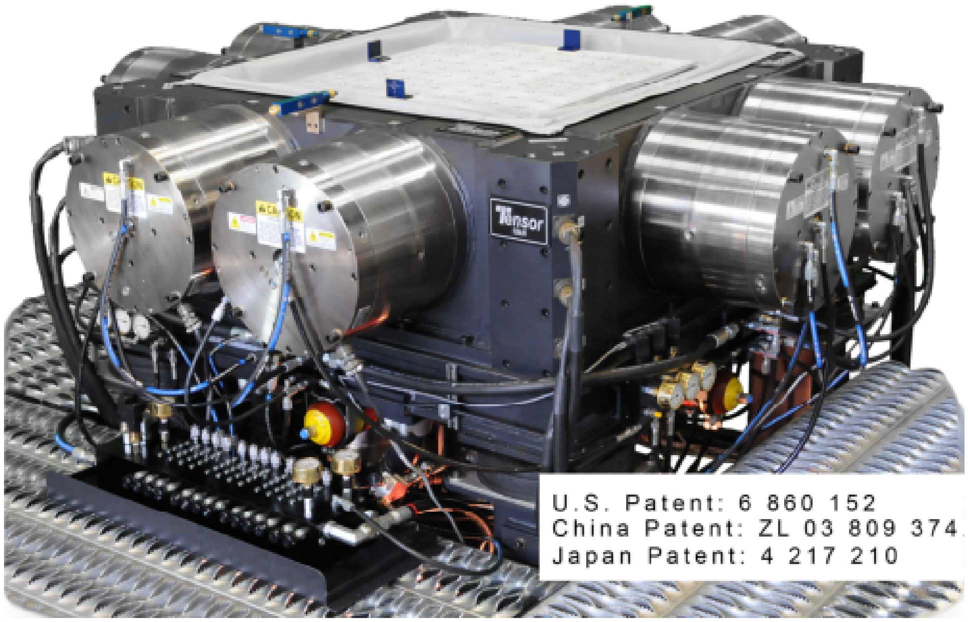

Figure 2: Tensor 18kN Vibration Test System

The main components of the Tensor 18kN system are:

- (12) custom ED shakers
- 30 inch x 30 inch vibration table
- Highly damped reaction mass
- Vertical preload actuator
- Hydraulic power supply
- Power amplifier set

The design of the shakers is based on a standard field coil and voice coil driver set. However, beyond this the similarities with standard ED shakers end. The armature flexures have been replaced with hydrostatic journal bearings. There is no specimen mounting surface, but rather the end of the armature incorporates a version of Team Corporation's signature hydrostatic pad bearings. These bearings only transmit the armature force through the pad's axis, and allow the table to move unrestrained in the other 5-DOF about each armature. Incorporating hydrostatic pad bearings directly into the armature frees up the necessary DOF to the system such that twelve shakers can be used to drive all 6-DOF without mechanically locking up. The hydrostatic connection to the table is an extremely stiff and friction-free interface, providing for high frequency response and no mechanical wear.

The mechanics of the Tensor 18kN require the shaker armatures to be preloaded against the table for proper operation. To accomplish this, each shaker has a preload mechanism integrated into its armature. In the horizontal axes, opposing shakers react each other's preload to remain in static equilibrium. In the vertical axis, a preload actuator is required to hold the table down against the armature preload. This actuator is hydraulically controlled and includes a variety of hydrostatic bearings to keep the system kinematically sound. The vertical preload actuator is essentially a soft spring with a large static load capacity and has minimal effect on the control of the system. Figure 3 shows the layout of the ED shakers relative to the vibration table.

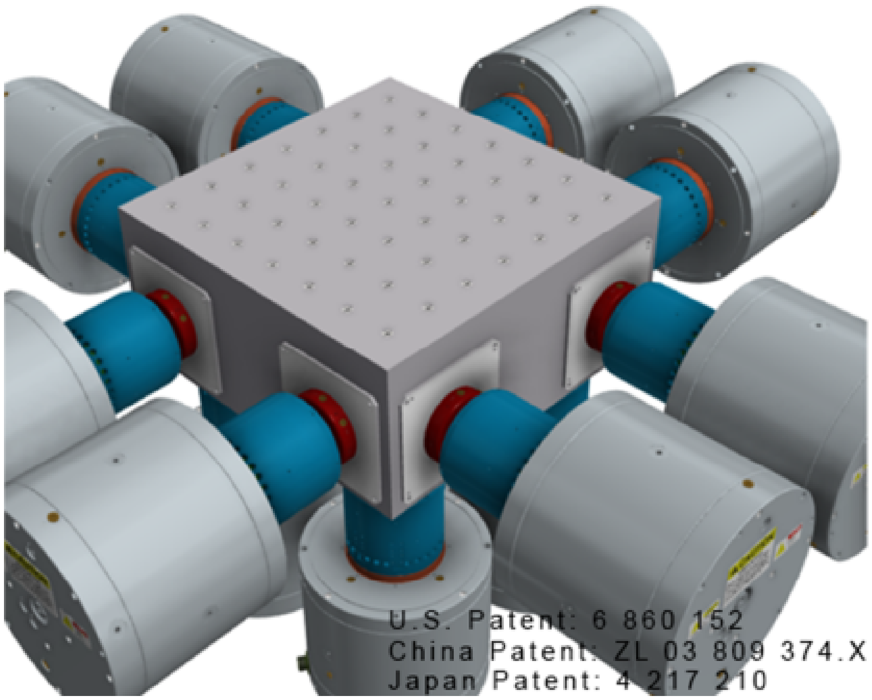

Figure 3: Tensor ED Shaker Configuration

In addition to pressurizing the hydrostatic bearings, hydraulic oil is also used to remove the heat generated from both the field and voice coils of the shakers. Hydraulic oil provides more effective heat transfer than forced air convection used in most shakers, and the Tensor 18kN is configured to handle the flow of oil and keep it properly contained. A further benefit of oil cooled coils is that the shakers are much quieter than conventional shakers because an external blower is not required.

The ED shakers, vibration table, and vertical preload actuator are all integrated into a highly damped reaction mass. This reaction mass rests on air isolators and creates a system that is self-contained and isolated from the existing facility. No additional reaction mass is required for operation, only a floor capable of supporting the system weight of nominally 17,000 lbm [7,700 kg]. This allows for a system that is easily integrated into an existing laboratory facility.

A hydraulic power supply (HPS) provides the required hydraulic pressure and flow, while a bank of twelve Power Amplifiers provides the electric voltage and current to the shakers. Both of these sub-systems can be located remotely from the Tensor 18kN to minimize the noise levels present in the lab. This, along with the oil cooled coils, provides for low ambient noise levels inside the laboratory.

Table 1: Tensor 18kN Performance Specifications

Specification (per Axis)	English Units	SI Units
Peak Sine Force	4,800 lbf	21.4 kN
RMS Random Force	3,600 lbf	16,0 kN
Moving Mass	430 lbm	195 kg
Peak Velocity	50 in/sec	1.3 m/sec
Dynamic Stroke	1.00 in. p-p	25 mm p-p
Static Stroke	1.50 in. p-p	38 mm p-p
Max. Rotation	±4.0 deg	±4.0 deg

Control Scheme

The Tensor 18kN requires an advanced multiple-input, multiple-output (MIMO) vibration test controller, capable of controlling twelve shakers using, at a minimum, twelve control accelerometers. To date, two commercially available vibration controllers have been used to successfully control the Tensor systems; namely the Spectral Dynamics Jaguar and the Data Physics SignalStar Matrix. The data presented in this paper was collected using the Data Physics SignalStar Matrix controller.

There are three MIMO control schemes that can be used to control the Tensor 18kN. These are commonly referred to as:

- Square Control – Equal number of drive and control points.
- Rectangular Control – Unequal number of drives and control points, with more control than drive points.
- Coordinate Transformation – Linear mapping of both the drive and control points to some pre-determined DOFs used for control.

The results presented in this paper were produced using Coordinate Transformation Control. The number of DOF that this algorithm can control is limited in theory by the number of drive points, but a test can be configured to control fewer. In the case of the Tensor this limit is twelve DOF. Typically, the mapped DOF of a 'Virtual Point' are chosen to be the rigid body DOF of interest. The location of the Virtual Point is defined by the user. Additional DOF can be defined, up to the number of drives. These DOF may be flexible body modes of the table. The intent of adding flexible body DOFs to the control is to give the system more control authority over the table so it can work to suppress these particular vibration modes.

Four tri-axial accelerometers were used as the control points of the Tensor 18kN and were placed directly in-line with the shakers, as shown in Figure 4. The Coordinate Transformation method was used to map the response of the twelve control accelerometers to the Virtual Point, which was chosen to be the center of the table's top surface. The transformations were defined such that the linear and angular accelerations of the Virtual Point were the reference points for the 6-DOF control.

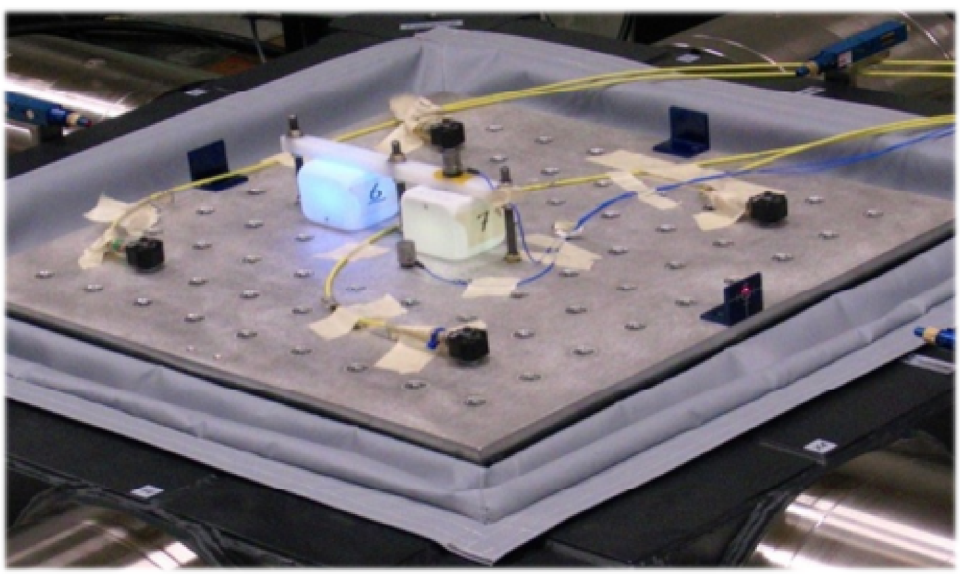

Figure 4: Tri-Axial Control Accelerometer Placement

The Coordinate Transformation scheme, in a certain sense, is a MIMO averaging method. For a single-axis vibration test, it is common to average the response of multiple control accelerometers to achieve acceptable response of a given system and control through vibration modes. This single-axis averaging is done in the frequency domain on the magnitude of the response power spectral density (PSD) at each frequency measurement. Since the PSD contains only the magnitude of the spectrum, no consideration is given to the phase of the response signals. In a MIMO vibration test, however, the Coordinate Transformation scheme averages both the magnitude and phase of the responses in the time domain. Considering the phase in the MIMO case is important because it is possible for the responses to be driven out of phase, even as a rigid body, due to the nature of the multi-axis equipment. This is in contrast to single-axis systems, which are mechanically constrained, or guided, and do not allow responses to be driven out of phase. For this reason, the Coordinate Transformation method provides a more accurate average response measurement of a MIMO system.

Vibration Tests

Two specific tests were run on the Tensor 18kN to demonstrate the system's capabilities. The details of each are given below.

Test 1 – Modified Version of MIL-STD 810g Composite Wheeled Vehicle Test (Method 514.6, Annex C, Table 514.6C-VI) [2]

- Simultaneous excitation of each linear DOF
- Bandwidth: 15-500 Hz each axis
- X-Axis (Longitudinal)
  - Acceleration: 3.2 g-rms
  - Velocity: 10.0 in/sec peak
  - Displacement: 0.08 inches peak
- Y-Axis (Transverse)
  - Acceleration: 3.2 g-rms
  - Velocity: 16.9 in/sec peak
  - Displacement: 0.15 inches peak
- Z-Axis (Vertical)
  - Acceleration: 3.2 g-rms
  - Velocity: 15.2 in/sec peak
  - Displacement: 0.13 inches peak
- Case 1: Active suppression of 3 rotary DOF
- Case 2: Active excitation of 3 rotary DOF at a low level

Test 2 – 5-2,000 Hz Broadband Random Profile

- Simultaneous excitation of each linear DOF
- Bandwidth: 5-2,000 Hz flat profile each axis
- Acceleration: 4.5 g-rms each axis
- Velocity: 8.0 in/sec peak each axis
- Displacement: 0.14 inches peak each axis
- Active suppression of 3 rotary DOF

Composite Wheeled Vehicle Test Results – Case 1

As noted, this test is a modified version of the profiles detailed in MIL-STD 810g Method 514.6 Annex C [2]. To remain within the displacement limits of the shakers, the breakpoints below 15 Hz on all three profiles were removed. Two separate cases were conducted for this particular test. Case 1 excited all three linear DOF, X, Y, Z, simultaneously and actively worked to suppress the rotatary DOF, roll (Rx), pitch (Ry), yaw (Rz), to a null RMS reference level of 0.70 rad/sec^2 (3-DOF excitation). Case 2 controlled the linear DOF in the same manner, however, now all rotary DOF were simultaneously excited (6-DOF excitation). The profile for the rotary DOF excitation, in this case, was defined to be a flat profile with a RMS level of 8.50 rad/s^2 from 15-500 Hz. It's important to note that both cases are full 6-DOF tests because all twelve shakers are being driven to control (excite or suppress) rotations as well as translations.

Figure 5 - Figure 7 show the linear response of each axis and Figure 8 shows the rotary DOF of all three axes for Case 1. The graphs of the linear DOF plots the individual acclerometer responses in addition to the response of the respective Virtual Point DOF. The graph of rotations shows all three rotary DOF of the Virtual Point relative to the null reference level.

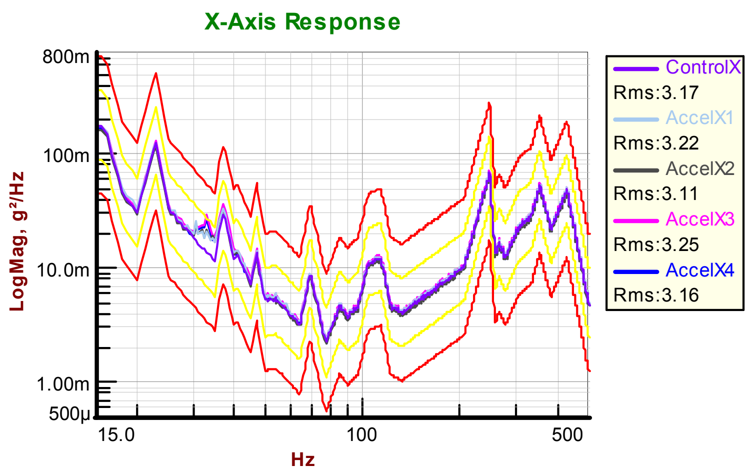

Figure 5: Test 1, Case 1, X-Axis Response

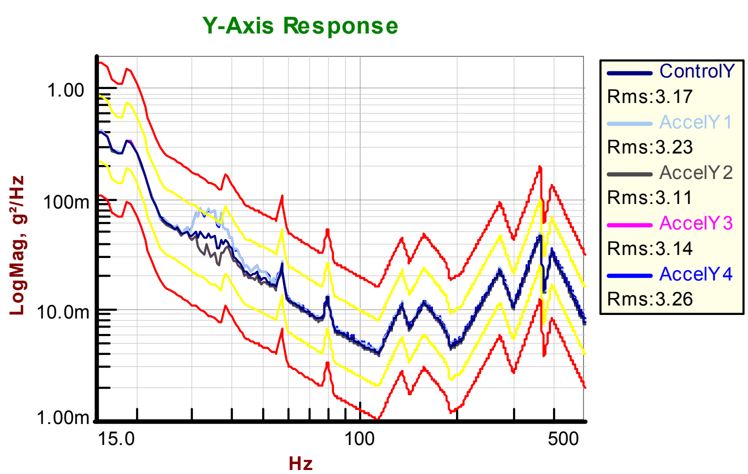

Figure 6: Test 1, Case 1, Y-Axis Response

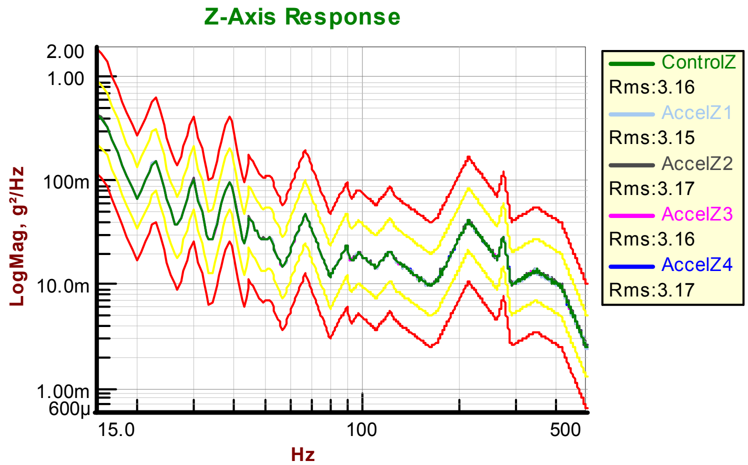

Figure 7: Test 1, Case 1, Z-Axis Response

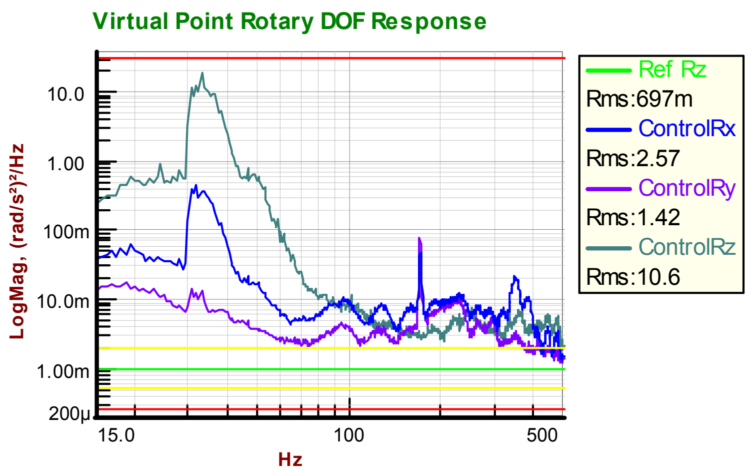

Figure 8: Test 1, Case 1, Rotary DOF Response

Overall, the system performed very well in the linear directions, with some minor deviation around 35 Hz in the X and Y axes of the individual accelerometers. The control of the rotary DOFs cannot be suppressed down to the reference null level and they begin to diverge below 100 Hz, with a peak at 35 Hz also. This frequency is the shaker preload resonance, and the controller has difficulty suppressing its response with the rotation reference levels set so low. The explanation for this is that the reference null level is set below the noise floor of the instrumentation. As a result, the controller is unable to resolve the signals well enough for control. Case 2 addresses this problem.

Composite Wheeled Vehicle Test Results – Case 2

The control of the rotary DOF was altered in Case 2 of the Composite Wheeled Vehicle Test such that the rotations were excited to a low level slightly above the accelerometer noise floor. The difference being that now the controller attempts to drive the rotations rather than suppress them to a null level. It is a subtle difference and can be thought of as a 6-DOF excitation test compared to a 3-DOF excitation test.

The results for the linear DOF of Case 2 are given in Figure 9 - Figure 11 and the rotary DOF in Figure 12. Exciting the rotations created a significant improvement in the overall control of the system. Now, the controller is able to maintain control over the rotations at the reference level over the full bandwidth. The change to the rotary control also improved the response of the system in the X and Y axes at 35 Hz. The resonance at this frequency is very well controlled, and the virtual point and individual accelerometer responses for each axis matches the reference levels extremely well over the entire test bandwidth.

This test provides a clear example of how important it is to properly define a MIMO vibration test and to understand the capabilities of the system. Each shaker input of the Tensor 18kN has an effect on all accelerometer outputs (per the geometric definition of a Tensor – linear mapping), resulting in a closely coupled system. If a reference level is set outside of the system's limits (high or low), most likely the response of other DOF will degrade as the system is unable to control the DOF with the unreasonable reference. This test highlights how a very minor increase in one parameter can significantly improve the control of the overall system.

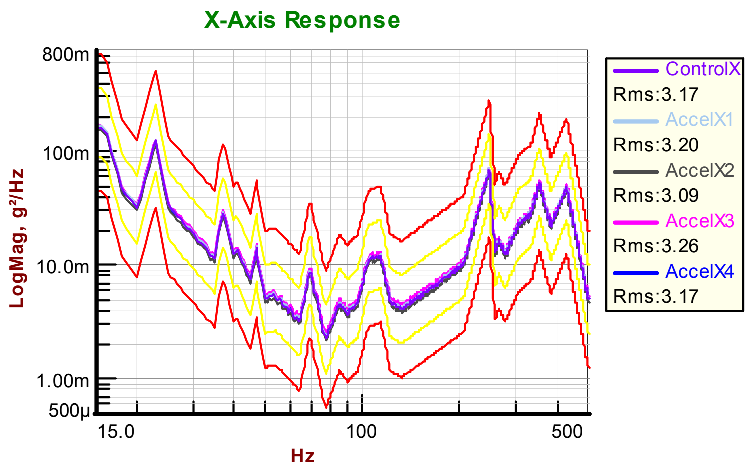

Figure 9: Test 1, Case 2, X-Axis Response

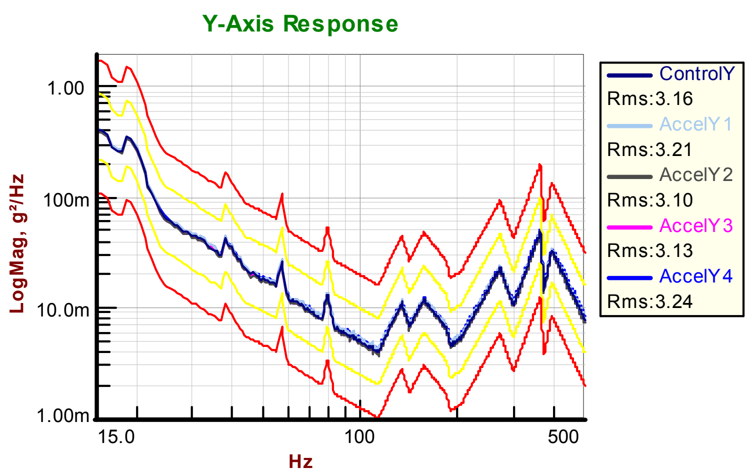

Figure 10: Test 1, Case 2, Y-Axis Response

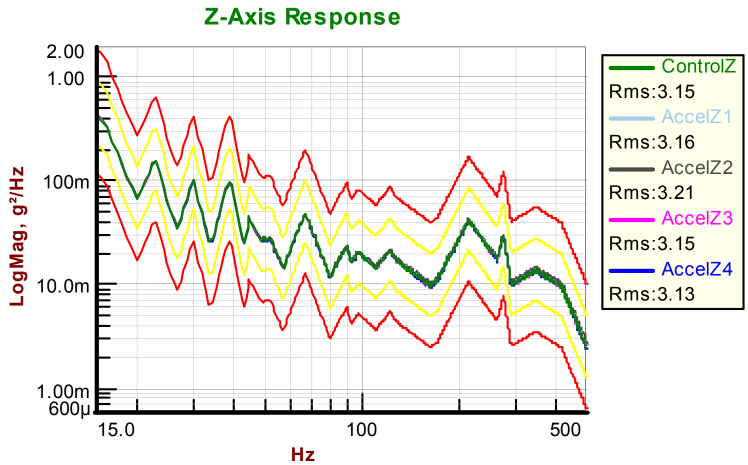

Figure 11: Test 1, Case 2, Z-Axis Response

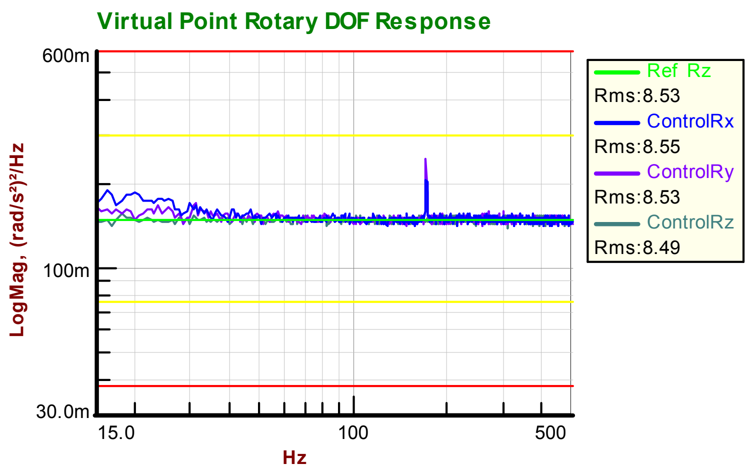

Figure 12: Test 1, Case 2, Rotary DOF Response

Broadband Test Results

The focus of the broadband random vibration test, Test 2, was to excite the Tensor 18kN system over its full bandwidth to showcase the system's ability to control the vibration spectrum to high frequencies using the Coordinate Transformation control method. As noted, this test excited all three linear DOF simultaneously and suppressed the rotations to a null level. The profile of each axis was flat with an RMS acceleration level of 4.5g.

The improvement to the control detailed in Case 2 of the previous test was not implemented for the broadband test simply because it was not realized until after the results of this test were collected. Future testing with this system will implement these subtle changes and it is expected that the same improvements can be gained for the broadband test.

Similar to Test 1, the Coordinate Transformation method was used for controlling the mapped Virtual Point to the reference profile. For rigid body motion it is expected that the individual accelerometer responses will closely match the virtual point response. However, when the system hits a resonant frequency this method acts to control the virtual point to be the average of the accelerometer responses, in both magnitude and phase. This methodology is similar to the single DOF case when averaging of accelerometer magnitudes is used to improve control of a vibration mode. Approaching the control in this manner is logical because it is extremely difficult and costly to develop a large structure that is resonant free through the full bandwidth, especially for high-frequency tests. Although, it should be noted, that in the design of the Tensor 18kN every attempt was made to push the first mode of the table as far out in frequency as possible.

Figure 13 - Figure 15 plot the response of the virtual point's linear DOF for each axis. These plots show that the controller is able to maintain excellent control of the Virtual Point across the full bandwidth. Figure 16 gives the Virtual Point's response for all of the rotary DOF. Note, again, that the controller is unable to bring the rotations down to the reference null level because the profile is below the noise floor. Implementing Case 2 of Test 1 should improve this response.

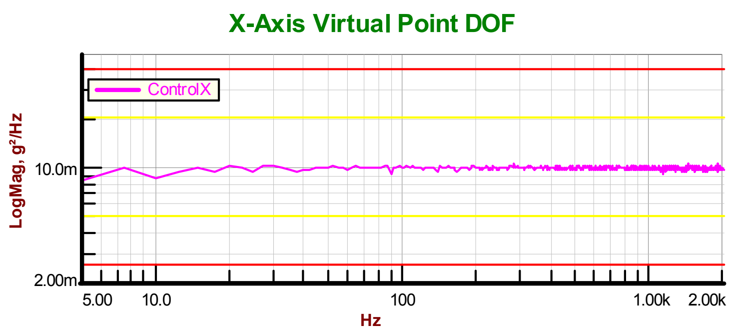

Figure 13: Test 2, Virtual Point X-Axis Response

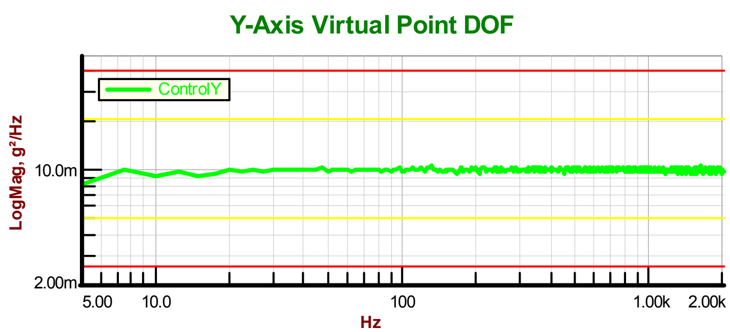

Figure 14: Test 2, Virtual Point Y-Axis Response

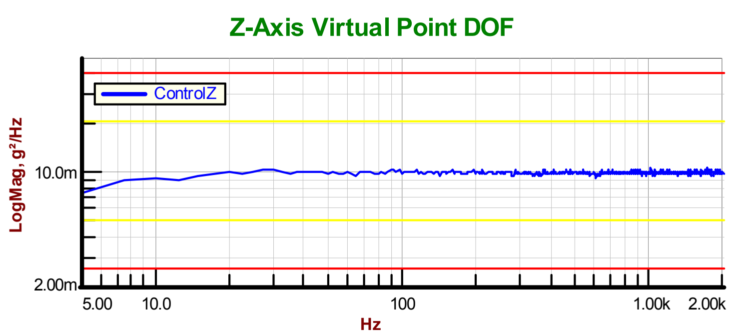

Figure 15: Test 2, Virtual Point Z-Axis Response

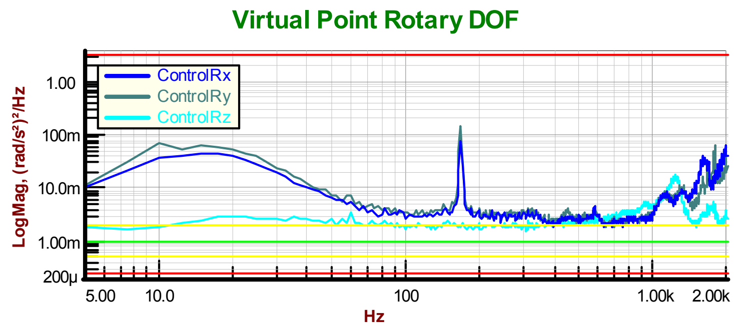

Figure 16: Test 2, Virtual Point Rotary DOF Response

Figure 17 - Figure 19 plot the individual accelerometer responses for each axis. These plots show nice control up to around 800 Hz. This indicates that the system is resonant free to this point since the accelerometers closely match the Virtual Point. Above this frequency, three resonances show up in the accelerometer responses. The first and second modes of the system occur at 810 Hz and 930 Hz, respectively. The first mode shape is the typical torsion mode of a square plate where the corners of each side move out phase. The second mode shape is an in-plane shear mode where the square structure deforms to a 'diamond' shape. This is due to the vibration table having significant depth and no longer behaving as a thin plate.

The most difficult mode to control is at 1,620 Hz, which is actually the sixth system mode. The mode is an out-of-plane mode similar to the first mode, but now the center of a given edge moves out of phase with the center of each adjacent edge. This mode is sometimes referred to as a 'saddle' or 'potato-chip' mode shape and it is the first mode where there is not a shaker acting against the high response regions of the mode shape, resulting in the controller having the most difficulty minimizing its response.

The third, fourth, and fifth modes are all in-plane modes and were found by a finite element model of the system. These modes do not cause any out of tolerance response of the individual accelerometers. They are easily controlled by the system and/or do not affect the top surface response because they are in-plane 'breathing' mode shapes.

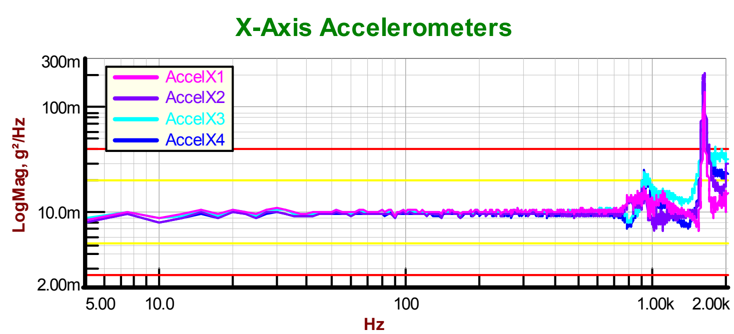

Figure 17: Test 2, Control Points X-Axis Response

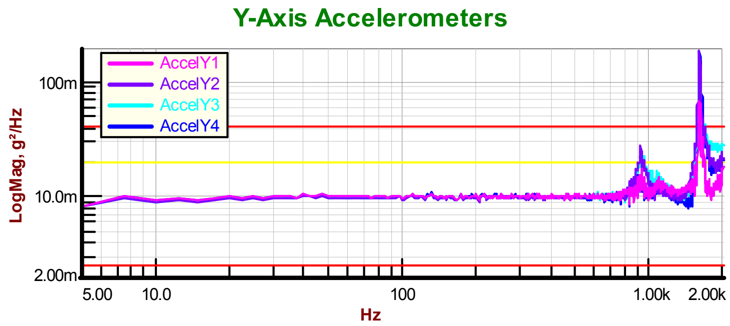

Figure 18: Test 2, Control Points Y-Axis Response

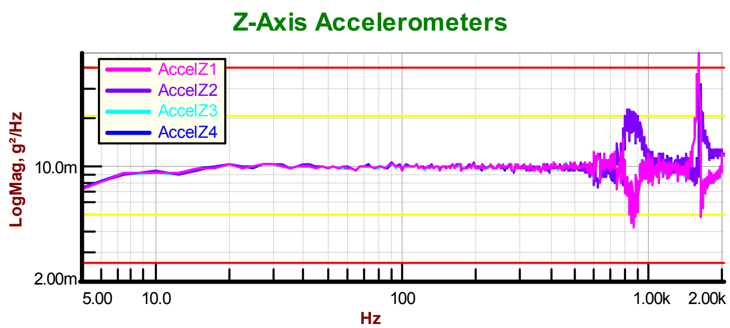

Figure 19: Test 2, Control Points Z-Axis Response

Overall, this test produced excellent average control of the accelerometer control points as shown in Figure 13 - Figure 15. There are deviations from the reference level of the individual accelerometers at three high frequency vibration modes, but this, to a certain extent, is to be expected for this size of a structure. There are techniques that can be applied to the control system to reduce the response at these frequencies. However, due to the time that was available with this system they were not implemented. Plans have been made to continue testing with the Tensor 18kN as detailed in the following section.

Future Testing Plans

The Tensor 18kN is a new system capable of performing advanced high-frequency vibration testing. This was demonstrated in the results. However, due to the over constrained design, it is inherently a complex system to control and there is still much to learn regarding the control nuances that can be applied to advance the system performance. Further testing is planned to investigate several subtle changes as well as more advanced techniques using the Coordinate Transformation method. A few of these are:

- ***Asymmetric accelerometer locations*** – All testing to date was done with symmetric locations measuring the same point on the table in each quadrant. Testing will be done to see what effect asymmetric control locations have on the control. The goal is that measuring different locations in each quadrant will provide a better averaging scheme.
- ***Define additional Virtual Point DOFs*** – The results presented were for the six rigid body DOF of the Virtual Point in the Coordinate Transformation. The over constrained design of the Tensor 18kN can be exploited by defining various flexible body mode shapes to be additional controlled DOF of the Virtual Point. The goal is that the system could control out mode shapes of the table. This testing will

begin by adding one mode shape at a time. The concern is that due to the stiff design of the vibration table it may take excessive force to accomplish this control.

- ***Apply narrow band notching*** – This technique could be applied to decrease the response of the higher frequency modes by notching the reference profiles and will be applied only if the previous two techniques are unsuccessful.

This testing will be conducted on the first system installed, which is located at the Life Cycle Environmental Engineering Branch of the Naval Air Warfare Center Weapons Division in China Lake, CA. The intent is to publish the results in a future paper.

Conclusion

The Tensor 18kN is the newest multi-axis vibration testing system available from Team Corporation. It expands a novel concept of using twelve electro-dynamic shakers to excite all 6-DOF of a vibration table to 2,000 Hz. Team Corporation first applied this design in a proof of concept system referred to as the Tensor 900. The Tensor 18kN now brings this proof of concept to a size more practical for typical vibration testing applications.

The results presented show that this system produces excellent control of the vibration table using the Coordinate Transformation control methodology. Various subtleties were discussed regarding the control of the system, with suggestions for possible ways to increase performance. This research will continue as the state of the art for vibration testing continually advances.

References

1. *Tensor*. (n.d.). Retrieved February 13, 2013, from Wikipedia, The Free Encyclopedia: http://en.wikipedia.org/wiki/Tensor

2. MIL-STD 810g Department of Defense Test Method Standard, Method 514.6 Vibration, Annex C. (31 October 2008). 514.6C-11.