Multi Shaker Testing Technology and Applications

GUS Working Group

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Contents

Background

Multi shaker vibration testing is the use of two or more shakers to drive a single table or structure to produce vibration in one or multiple directions.

There several types of multi shaker tests and a variety of terms are used in describing multi shaker testing:

- Single-Degree-of-Freedom (SDOF) – tests that excite only single rigid body degree of freedom motion are referred to as SDOF tests. Single axis vibration testing is a SDOF test
- Multi-Degree-of-Freedom (MDOF) – any test that includes more than a single degree of freedom is considered a MDOF test. Multi degree of freedom tests include multi axis tests and tests that also include rotational degrees of freedom. Multi degree of freedom tests can include up to 6 rigid body degrees of freedom – three orthogonal translations (X, Y, Z) and rotations about each axis (θ_x, θ_y, θ_z).
- Multiple-Input/Multiple-Output (MIMO) – multi shaker tests require control of a system that has multiple inputs (multiple shaker drives) and multiple outputs (multiple control transducers) system. This is considered a multiple-input/multiple output (MIMO) system.

Multi shaker single axis tests are considered single axis tests because the objective is to produce single axis vibration. For single axis testing, multi shaker testing is typically required when the test article geometry is too large to be able to easily fixture the test article to be driven by a single shaker. Multi shaker, single axis testing is also required when the mass of the test article is so large that a there is insufficient force in a single shaker to meet the required acceleration levels. Multi shaker single axis testing can also offer better force distribution for large test articles.

The other important benefit of multi shaker testing is the ability to perform simultaneous multi degree of freedom tests. Multi degree of freedom tests include simultaneous vibration excitation is multiple axes and can include rotational excitation, as well. There are several benefits of multi degree of freedom vibration testing. The primary advantage is that multi degree of freedom tests better simulate the real vibration environment, establishing greater confidence in the real-world survivability of the device under test. In some cases the nature of the test requires multi axis excitation. Multi axis tests have been shown to reproduce failure modes that are not seen using the typical test method of sequential single axis tests. Finally, multi axis tests can reduce the test time required by, for example, running all three axes at once, instead of sequentially.

Multi degree of freedom testing can range from vibration testing in two axes testing to full six degree of freedom testing. MDOF testing has the benefit of better reproducing failures that can occur in a MDOF vibration environment. These failures modes can include,

- Fatigue, cracking and rupture sensitive to multi-axis excitation
- Deformation of test article structure, e.g., protruding parts
- Loosening of seals and connections
- Displacement of components
- Chafing of surfaces with single-axis design
- Contact, short-circuiting or degradation of electrical components
- Misalignment of test article components (e.g., optical)

Typical Multi Shaker Testing Applications

Multi Axis Earthquake Testing

Multi axis testing is commonly used for qualifying equipment to withstand earthquake vibration. The types of equipment that are qualified include equipment installed in nuclear power plants, telecommunications equipment. Multi axis earthquake test standards include IEEE 344 and AC156. The test standards include multi axis sine and multi axis Shock Response Spectrum tests.

Automotive Durability Testing

Automotive durability testing is commonly performed using six degree of freedom vibration on multi axial simulation tables. This testing is typically done using time waveform replication control to reproduce recorded vibration time history data from road tests.

Six DOF Electronics Testing

The Center for Advance Life Cycle Engineering (CALCE) is a consortium of electronics manufacturers that conducts research into electronics reliability. At CALCE, the effect of multi degree of freedom vibration on electronics is being studied.

Aircraft Seat Vibration

Airbus performed testing of pilot seats for the A380 aircraft using a six DOF vibration table. This table was a special “man-rated” table that enabled a pilot to be in the seat during operation.

Multi DOF Qualification of Military and Aerospace Components

The latest revision of Mil-Std-810 includes guidance for multi exciter testing (Method 527). Multi degree of freedom vibration testing is becoming more common for qualification of critical components.

Multi Shaker Single Axis Testing

An example of a multi shaker single axis test configuration is shown in Figure 1. In these configurations two electro dynamic shakers are driving a single head expander or slip table to product more force than can be produced by a single shaker. One of the drawbacks of large shaker is the size of the armature required to produce the higher force. The larger armatures will have lower first resonance frequency, limiting the usable frequency range of the shaker. Multiple smaller shakers will each have higher armature resonance frequencies, yielding higher force and frequency range when used together. Multiple smaller shakers will also offer the flexibility to be used individually, at even higher frequencies for testing smaller test articles.

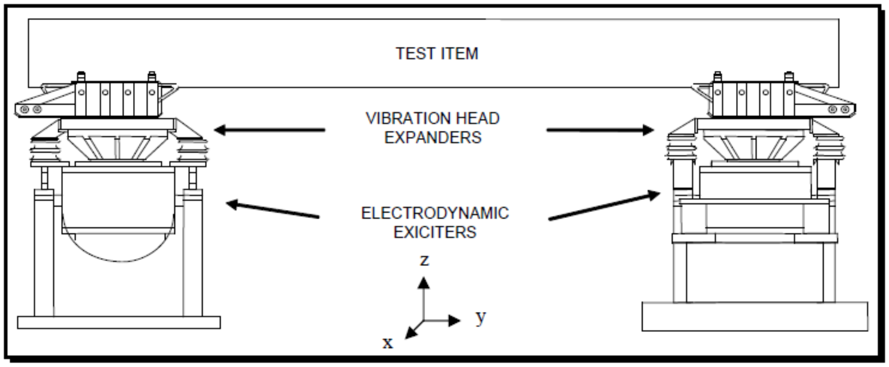

Figure 1. Multi Shaker Single Axis Test Configurations (Mil-Std-810G)

Push/Pull

When performing horizontal testing of long test articles, it can be convenient to arrange multiple shakers in a push/pull configuration. In this configuration, the test article is mounted on two slip tables and shakers are attached to each in in opposite directions as shown in Figure 2. The control system must compensate for the out of phase operation of the shakers. The slip tables have SDOF bearings as are used in typical single shaker testing.

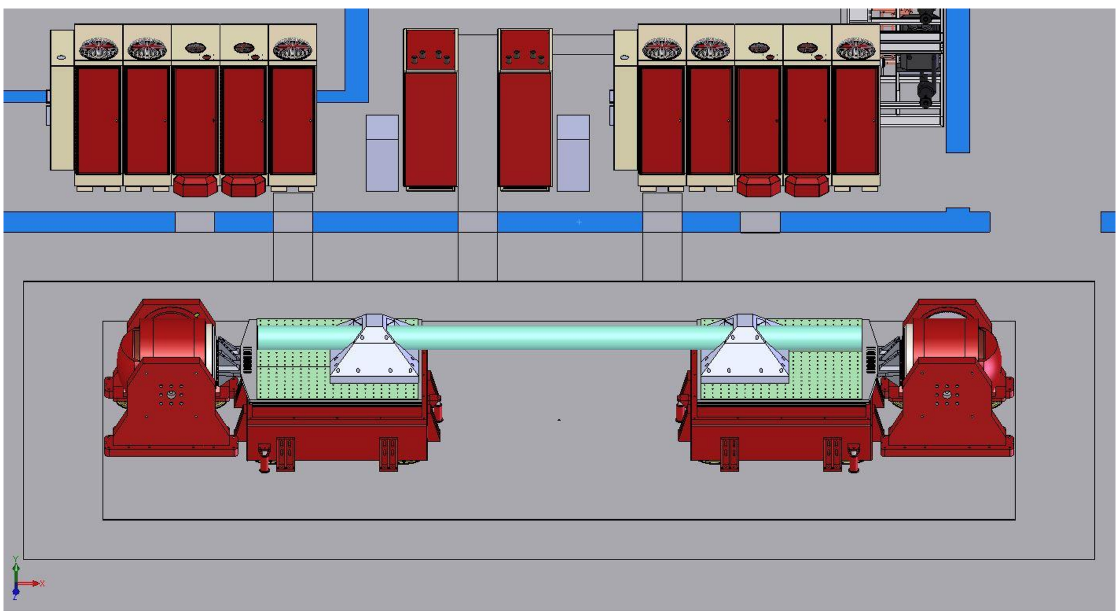

Figure 2. Push/Pull Configuration for Dual Shaker Single Axis Horizontal Testing

Push/Push

An example of a push/push configurations are shown in Figure 3. In this configuration the shakers are both driving the test article in the same direction. This is the most common configuration for dual shaker vertical tests. Special slip table and spherical couplings eliminate loads from out of phase actuation.

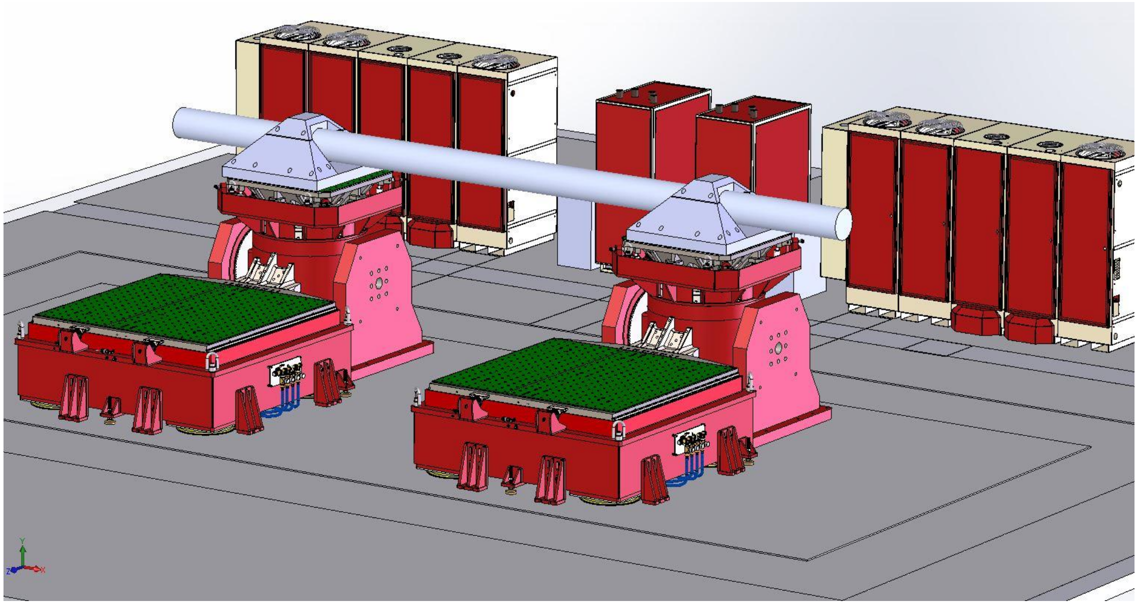

Figure 3. Push/Push Configuration for Dual Shaker Single Axis Vertical Testing

Multi Degree of Freedom Testing

Multi degree of freedom tests are typical defined by the number of rigid body degrees of freedom that are excited and controlled in the test. The table and test article are considered to be a rigid body for the purposes of the test definition and there are six rigid body degrees of freedom. The standard nomenclature for the six rigid body degrees of freedom is given below:

- Translations
    - X – typically horizontal - Longitudinal
    - Y – typically horizontal – Lateral
    - Z – typically vertical - Vertical
- 3 rotations
    - θ_x – rotation about X - Roll
    - θ_y – rotation about Y - Pitch
    - θ_z – rotation about Z – Yaw

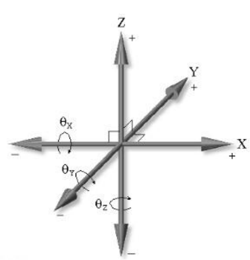

Figure 4. Rigid Body Degrees of Freedom (DOF)

Multi Axis Testing

Simultaneous three axis testing requires a bearing system to constrain the rotations about the three axes. In the example in Figure 5, three electrodynamic shakers drive a specialized integrated bearing under table interconnects all three shakers and allows translations, restraining rotations.

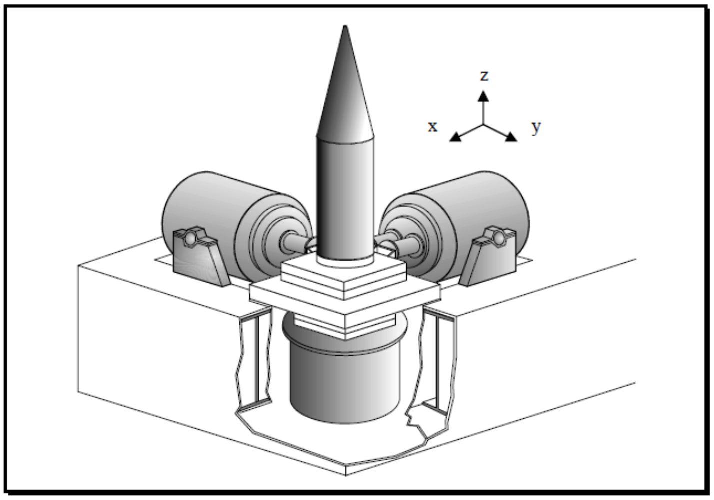

Figure 5. Triaxial Vibration Table (Mil-Std-810G)

Multi Axial Simulation Table (MAST)

Multi axial simulation tables are a very common six degree of system. There are six actuators, typically arranged with three in the vertical axis, two in one horizontal axis, and one in the other horizontal axis. Couplings on long links are required. These tables typically allow larger displacements and rotations, but are only suitable for very low frequency vibration.

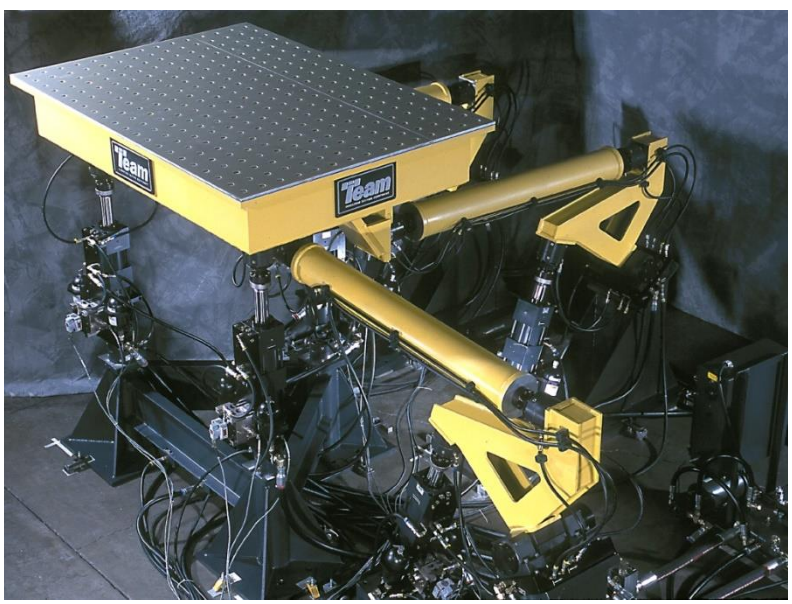

Figure 6. Multi Axial Simulation Table

Team Cube

The Cube is a six degree of freedom shaker system with internal hydraulic actuators and spherical pad bearings. The Cube is capable of six DOF vibration and has a higher frequency capability than typical MAST systems.

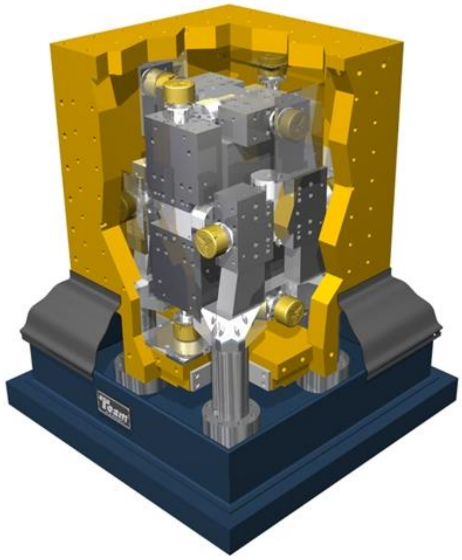

Figure 7. Cube Six DOF Vibration Table

Team Tensor

The Tensor is a six degree of freedom system that is capable of higher frequency ranges. It is a highly over constrained system with twelve electrodynamic shakers mounted in an integral reaction mass. Compact spherical and planar bearings are used to couple the ED shakers to table.

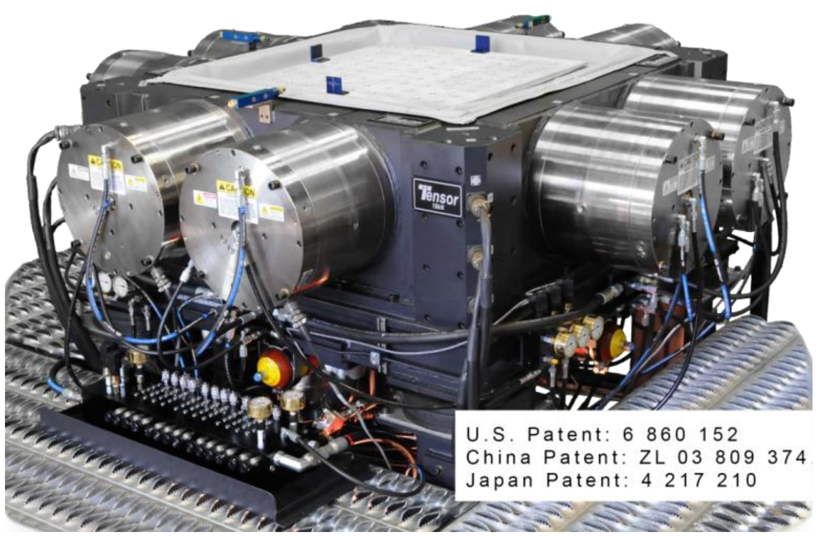

Figure 8. Team Tensor 18kN Six DOF Vibration Table

Design Considerations for Multi Degree of Freedom Vibration Tables

Vibration tables are characterized by the number degrees of freedom that can be driven and controlled. All unconstrained degrees of freedom must be controlled. The sum of all of the constrained and unconstrained degrees of freedom will always equal six. For single axis testing, bearings and flexures in the shaker and slip table constrained the rotation and cross axis translation degrees of freedom.

At least one actuator is required per controlled degree of freedom. In the case of multi shaker single axis testing, two are more actuators are driven in phase to produce single axis vibration. If the rotations and cross axis translations are unconstrained, out of phase motion can occur and can cause loads to be imparted to the actuator and the test object. This is shown in Figure 9.

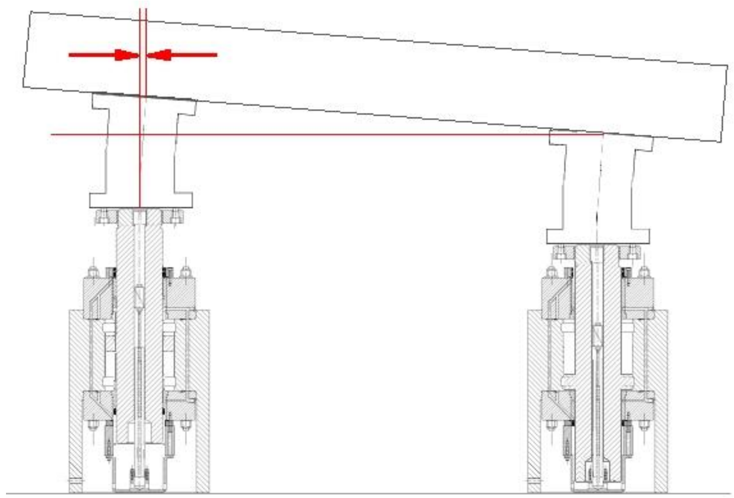

Figure 9. Lateral Foreshortening (cosine error)

When more shakers are used than there are unconstrained degrees of freedom, the condition is considered over constrained (Figure 10). The control strategies must consider this condition and manage the amplitude and phase of the shaker drive signals.

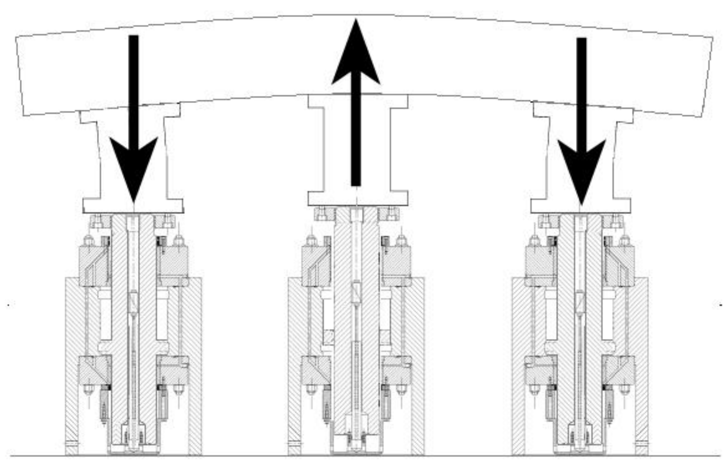

Figure 10. Over Constrained Systems

Bearings are used in multi degree of freedom tables to enable the desired vibration degrees of freedom and constrain the undesired degrees of freedom. The bearing design can have a significant effect on the performance of the MDOF vibration table. Hydrostatic bearing are preferred over mechanical ball and roller bearings because they can offer better load capacity, higher frequency, and longer life.

Figure 11 shows a hydrostatic spherical bearing that can be used in six DOF multi axial simulation tables. Hydrostatic spherical bearings use a spherical ball supported on oil film. They allow typically +/- 20 degreed of rotation in all directions. These bearings have the advantage of no backlash because the pressurized film maintains constant preload in all directions. When pressurized there is not metal to metal contact, reducing friction and increasing the life of the bearing.

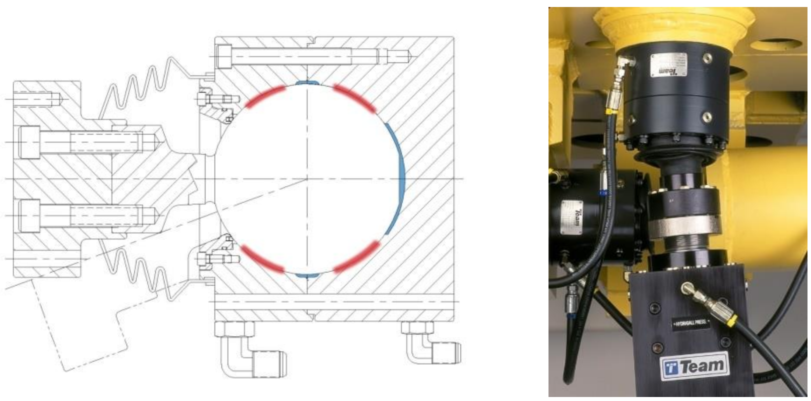

Figure 11. Team Hydrostatic Spherical Bearing

Another bearing type used in MDOF table is the spherical bad bearing. The spherical pad bearing combines spherical and planar bearings to allow five degrees of freedom. The spherical pad bearing is a fluid film bearing that can be used to drive the table in one axis while allowing translation in the other axes and rotations about all axes. This type of bearing is used in the Team Cube and Tensor six DOF tables.

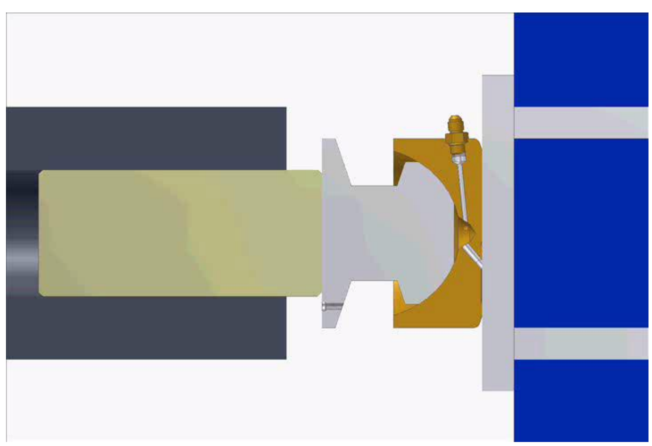

Figure 12. Spherical Pad Bearing

Double spherical couplings like the one shown in Figure 13 can also be used for five degrees of freedom. The double spherical coupling can carry both compression and tension loads.

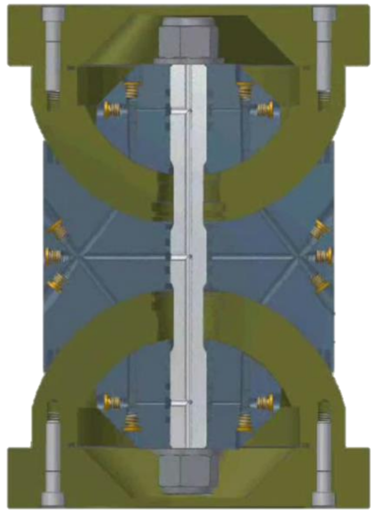

Figure 13. Double Spherical Coupling

Multi Shaker Control

Multi degree of freedom vibration is typically characterized by the six rigid body degrees of freedom - three translations in orthogonal axes and three rotations about each axis. If a structure is flexible within the frequency range of interest, there will be considerably more degrees of freedom.

When controlling an MDOF table, it is important to consider that all unconstrained degrees of freedom must be controlled. If there are no bearings in the table to constrain translation or rotation, the table must be instrumented to measure this vibration and the control system must actively control it. For example, if a six DOF table is used for a three axis test, the control system must control the translational vibration in each axis. It is equally important that it also actively constrain any rotations that may be induced by asymmetric loading or table and test article resonances.

The multi shaker vibration controller uses an array of triaxial accelerometers to measure the multi degree of freedom vibration of the table. The controller generates the drive signals for each actuator to produce the desired response on the control accelerometers.

There are several different strategies available to control multi degree of freedom vibration. All involve measurement of the multiple Input Multiple Output (MIMO) frequency response function matrix between the actuator drive signals and the control accelerometer response signals. All strategies must have at least as many control accelerometers as shakers.

Direct Control

The most common control strategy is to assign a reference profile to each of the control accelerometers. The control accelerometers must also be located to ensure that all unconstrained rigid body degrees of freedom are measured.

The first step in any multi shaker test is to characterize the system using a multiple input, multiple output frequency response function (FRF) measurement. This MIMO FRF matrix is then inverted to determine the initial drive signals required to achieve the desired control response. When there are an equal number of drives and control channels the control matrix is square and traditional methods of matrix inversion may be used.

It can also be desirable to use more control channels than drives to better characterize the response of the table and to be able to deal with flexible modes of the table. This control strategy is commonly referred to as “over determined” control. The over determined control scheme uses singular value decomposition for matrix inversion and can better handle singularities in the system frequency response function matrix. The table is controlled using a matrix of reference profiles that include not only the vibration levels for each control location, but also the relative amplitude and phase between control locations.

Kinematic Transformation

Another strategy for MDOF control is kinematic transformation. Kinematic transformation uses geometry information and rigid body kinematics to transform the linear acceleration measurements on the control accelerometers to the equivalent six rigid body degrees of freedom. An example of a transformation from four triaxial accelerometers on a six DOF table to the equivalent six rigid body accelerations is given below.

$$\begin{Bmatrix} X \\ Y \\ Z \\ \theta_x \\ \theta_y \\ \theta_z \end{Bmatrix} = \begin{bmatrix} 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 \\ 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 \\ 0 & 0 & 1.23 & 0 & 0 & 1.23 & 0 & 0 & -1.23 & 0 & 0 & -1.23 \\ 0 & 0 & -1.23 & 0 & 0 & 1.23 & 0 & 0 & 1.23 & 0 & 0 & -1.23 \\ -0.62 & 0.62 & 0 & -0.62 & -0.62 & 0 & 0.62 & -0.62 & 0 & 0.62 & 0.62 & 0 \end{bmatrix} * \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \\ x_2 \\ y_2 \\ z_2 \\ x_3 \\ y_3 \\ z_3 \\ x_4 \\ y_4 \\ z_4 \end{Bmatrix}$$

In this example the three translations (X, Y, Z) and the three rotations (θ_x, θ_y, θ_z) are computed.

Kinematic Transformation allows the user to define the test profiles in terms of translation and rotation. It also provides the ability to calculate the vibration response at other location using rigid body assumptions.

A key benefit of Kinematic Transformation in multi DOF testing is the ability to reduces the rank of the control matrix, when there are more shakers or control accelerometers than control degrees of freedom. This simplifies the control computations.

Flexible Mode Control

The challenges of controlling a multi degree of freedom table above its first resonance are not unlike the problems controlling a large head expander or slip table. Because of the non-uniformity due to resonances, the measured response will be dependent on the location of the control accelerometers on the table. Different locations can see significantly different acceleration response at certain frequencies. Figures 14 and 15 below show the finite element analysis of the first bending modes of a large head expander that is used with a single shaker and the Team Tensor 18kN six DOF table.

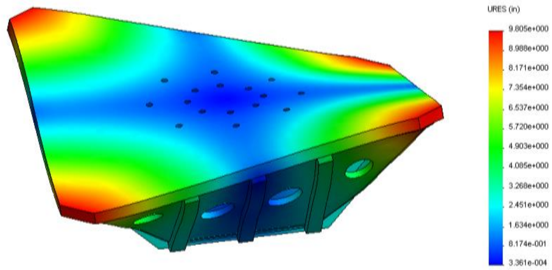

Figure 14. Head Expander Bending Mode

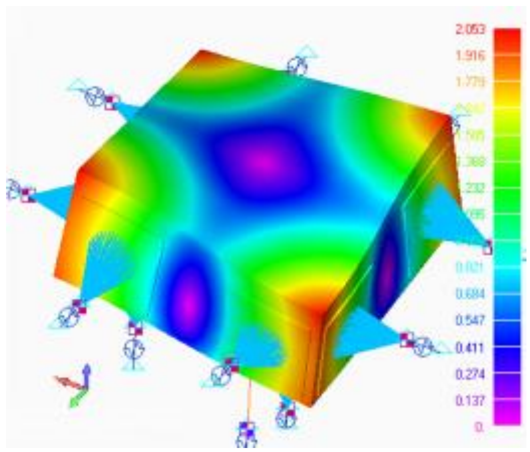

Figure 15. Team Tensor 18 kN First Bending Mode

When the number of actuators is equal to the rigid body DOF, there is nothing that can be done to control the flexible modes of the table. The table resonances will be excited in the same way that the head expander resonances are excited with a single shaker. Over determined control is often used to provide more control response locations in this case. However, if there are more actuators than rigid body degrees of freedom, and the actuators are properly located, kinematic transformation may be extended to include measurement of flexible mode response. In the transformation below, the first bending mode, φ_b of the table is added.

$$\begin{Bmatrix} X \\ Y \\ Z \\ \theta_x \\ \theta_y \\ \theta_z \\ \varphi_b \end{Bmatrix} = \begin{bmatrix} 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 \\ 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 & 0 & 0 & 0.25 \\ 0 & 0 & 1.23 & 0 & 0 & 1.23 & 0 & 0 & -1.23 & 0 & 0 & -1.23 \\ 0 & 0 & -1.23 & 0 & 0 & 1.23 & 0 & 0 & 1.23 & 0 & 0 & -1.23 \\ -0.62 & 0.62 & 0 & -0.62 & -0.62 & 0 & 0.62 & -0.62 & 0 & 0.62 & 0.62 & 0 \\ 0 & 0 & 0.13 & 0 & 0 & -0.13 & 0 & 0 & 0.13 & 0 & 0 & -0.13 \end{bmatrix} * \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \\ x_2 \\ y_2 \\ z_2 \\ x_3 \\ y_3 \\ z_3 \\ x_4 \\ y_4 \\ z_4 \end{Bmatrix}$$

Flexible mode control tests were run using the Matrix controller on a Team Tensor 18 kN six degree of freedom table at the Naval Air Weapons Station, China Lake. This table has four vertical actuators that are positioned such that they may be driven to counteract the first bending mode shown in the Figure 15.

The first test simply controlled the table using Kinematic transformation. The second test added measurement and control of the first bending mode of the table to the control strategy. It can be seen in the Figure 16 below that flexible mode control not only eliminated the control errors at the first bending mode, but also significantly reduced the effect of higher frequency modes in the vertical axis.

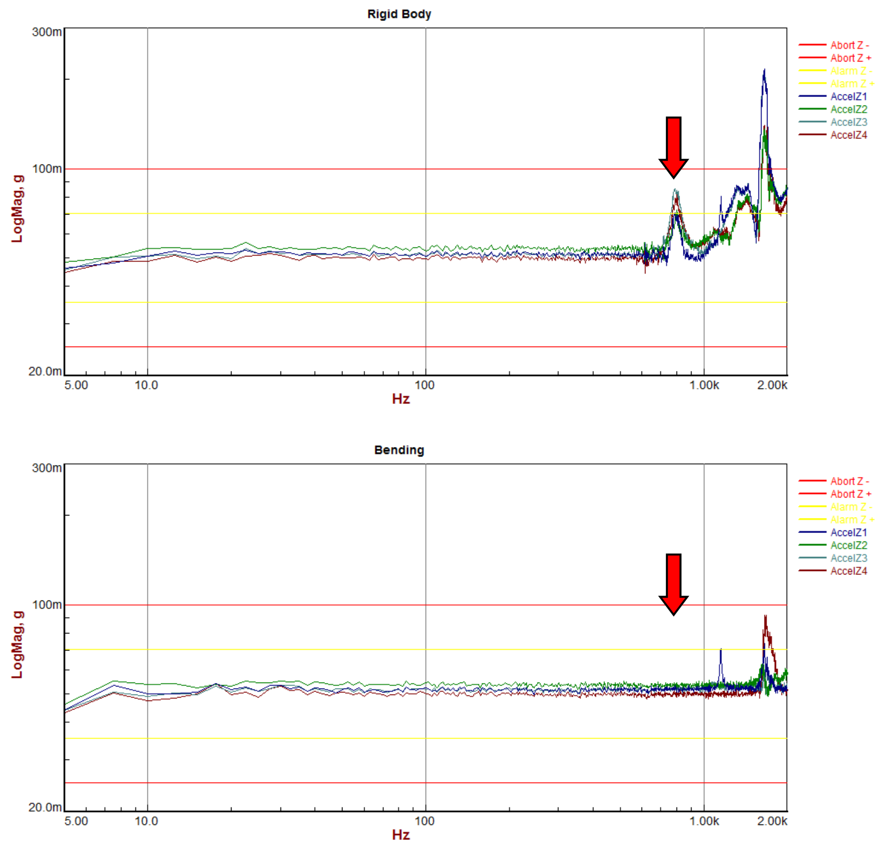

Figure 16. Comparison of Vertical Control Results Controlling the First Bending Mode

Recent Projects

Six DOF Spacecraft Testing – NASA Plum Brook Station

Data Physics and Team Corporation are in the process of commissioning a large six degree of freedom vibration table at NASA Plum Brook Station in Sandusky, OH. This table has 20 hydraulic actuators, 16 in the vertical direction and 4 in the horizontal direction. When complete this table will be able to perform sequential single axis sine test on the Orion space in each of three axes.

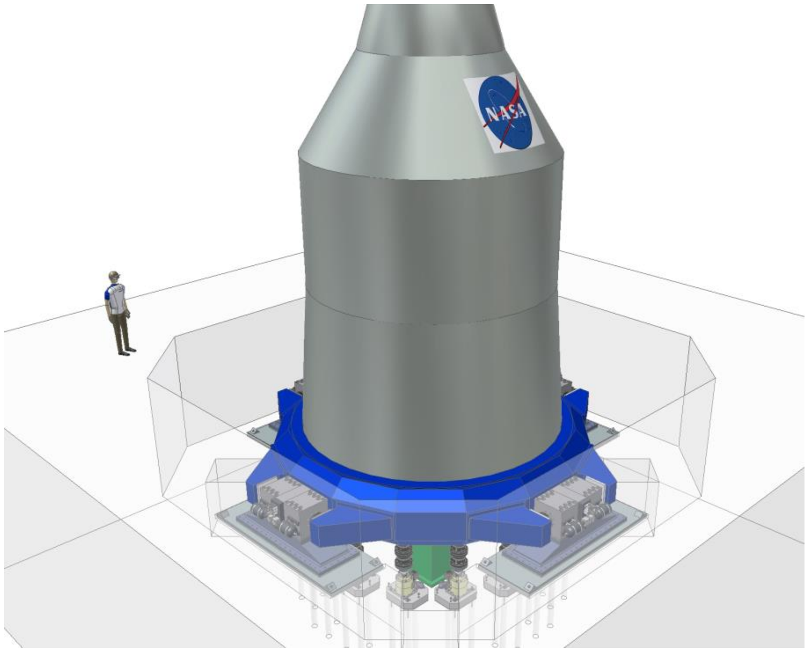

Figure 17. Six Degree of Freedom Vibration Table at NASA Plum Brook Station

Simultaneous Control of Dual 6 DOF Tables

Multi axis tests on long test article can be challenging. Figure 18 shows a test article bridged between two six degree of freedom tables. Simultaneous 3 axis vibration tests were performed. This required matching the translation amplitude and phase in each axis on both tables, and cancelling any rotations induced by test article dynamics.

Figure 18. Simultaneous Control of Dual Six Degree of Freedom Tables

Dual Shaker Single Axis Testing – James Webb Space Telescope

Team and Data Physics have begun construction of a dual shaker vibration test system for qualification of the James Webb Space Telescope. The payload is very large and has an offset center of gravity. There are separate horizontal and vertical test systems. The vertical test system is a dual shaker system to meet the large force requirements for such a large payload. The vertical test system include two Data Physics 50,000 lbf shakers and a guided head expander system from Team Corporation.

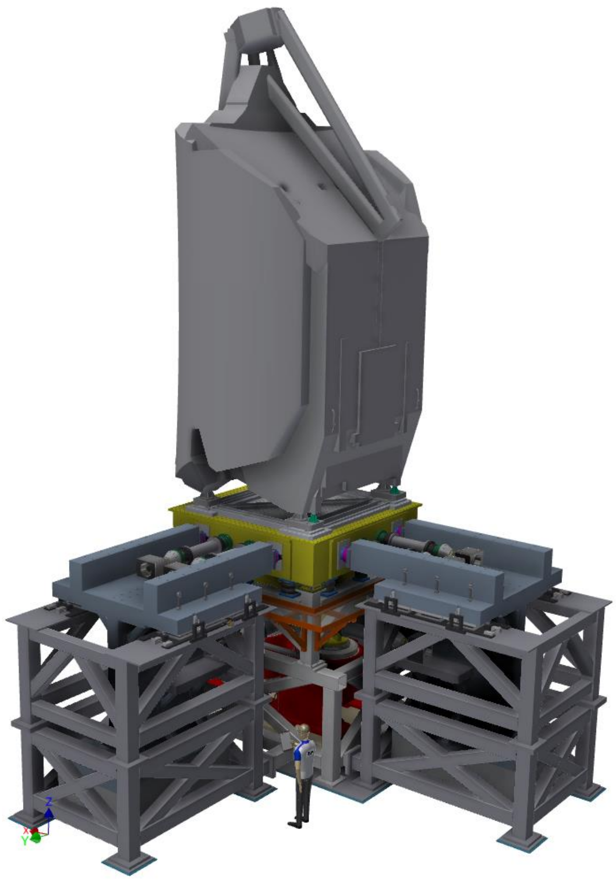

Figure 19. Dual Shaker Vibration Test System for James Webb Space Telescope

Summary

Multi shaker testing is becoming more common due to several key advantages. Multi shaker single axis testing can have significant benefits for SDOF testing of large test articles. Multi shaker testing is also increasing for MDOF testing because of its ability to better reproducing real world environments.

This paper covered a number of issues related to the understanding of the considerations of bearings and couplings, shaker characteristics, for design of multi shaker vibration tables. There are also many factors to consider with respect to control of multi shaker tables. Several critical considerations were covered including, transducer arrangement, and control schemes.

Several examples of multi shaker applications were also presented.