Vibration Test Evolution

Single-Axis, Single-Shaker to 6DoF

Abstract:

Vibration testing is widely accepted as a method to improve product quality by identifying structural weaknesses. Historically, single axis, single shaker testing is the method of choice. This is largely due to the lack of economical and effective test hardware and control software. Significant advances have been made in both arenas, resulting in test equipment design that permits multiple shaker applications, with both single axis or multi-axis excitation capabilities. This paper documents the chronology of test equipment design and reviews the advantages afforded by current hardware and software technologies.

Written by:

Curt Nelson
Team Corporation

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 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 a field environment rather than simulating the characteristics of actual field conditions.[1] 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.[2,3]

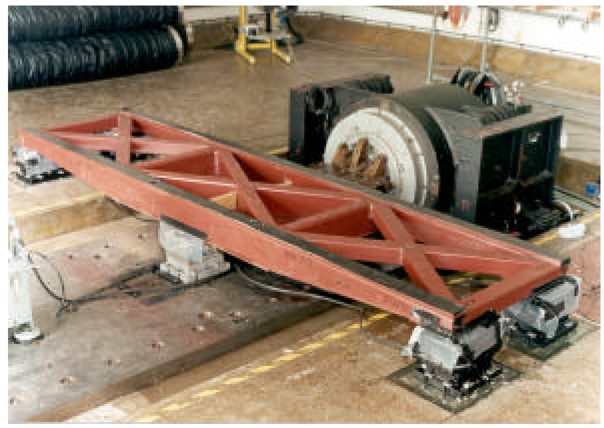

Figure 1.0 Typical single axis vibration test system with ED shaker and linear hydrostatic bearings

Although the vast majority of vibration testing uses a single vibration exciter, some conditions exist where a single shaker is not appropriate for the task at hand. Examples of this include:

- Design and Qualification testing of products such as long missiles where a single attachment point might damage the test article when applying the needed force to achieve the desired test levels
- Testing of objects where the physical configuration of the unit under test would require the design and fabrication of a prohibitively expensive fixture
- Testing of massive objects where the required force is greater than that available from a single shaker
- System identification or Characterization in which several waveforms need to be simulated simultaneously at different locations on a large structure[4]

Examples of such systems are shown in Figures 2.0 and 3.0. Several commercially available test controllers have the sophisticated computational capability, data throughput speed and convolution algorithms to solve the problems associated with multiple input multiple output (MIMO) control. A variation of MIMO is known as multiple exciter, single axis (MESA) where more than one exciter is used to provi de force in a single direction. In the case of MESA, the control system is typically asked to control the test platform motion with all control points moving

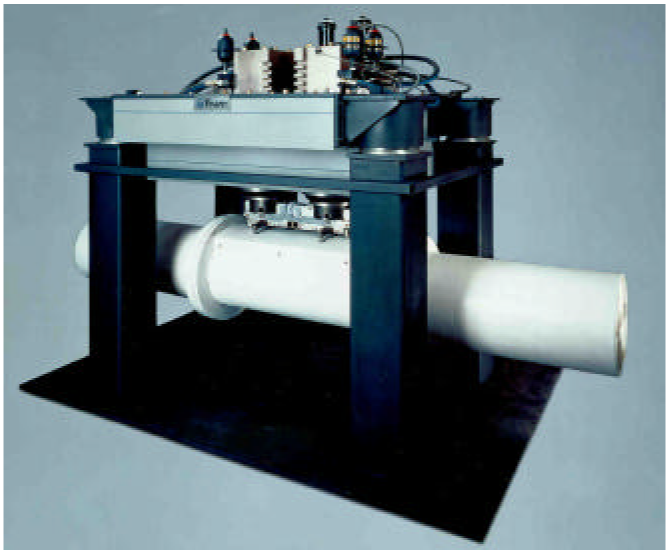

Figure 2.0 Dual Electrohydraulic shaker system driving a mock missile. *Photo courtesy of Northrop Grumman*

in phase. The major mechanical issue with these designs center on the mechanism attaching the linear shakers with the test platform. If the shakers go out of phase, for example during system characterization, very large moments can be generated in the test object and/or shaker armatures. Unless the kinematics of the system permits angular deflection, severe damage can occur. Early designs used a combination of spherical roller bearings, flexures and pivoting links to provide sufficient angular deflection. An example of this approach is the multi-shaker system at US Army Research (formerly Harry Diamond) Laboratory. Proven workable, it is less than an ideal solution since the clearances in the mechanical links can corrupt test data as force reversals cause impact loading. At high frequency test levels, the displacement of the test article is measured in mil and micro inches, approaching the clearances in the links. The solution is to increase the preload on the attachment pivots. However, this increases pivot stiffness, influencing test results. In addition, long duration tests result in high maintenance requirements as clearances increase due to repeated loading.

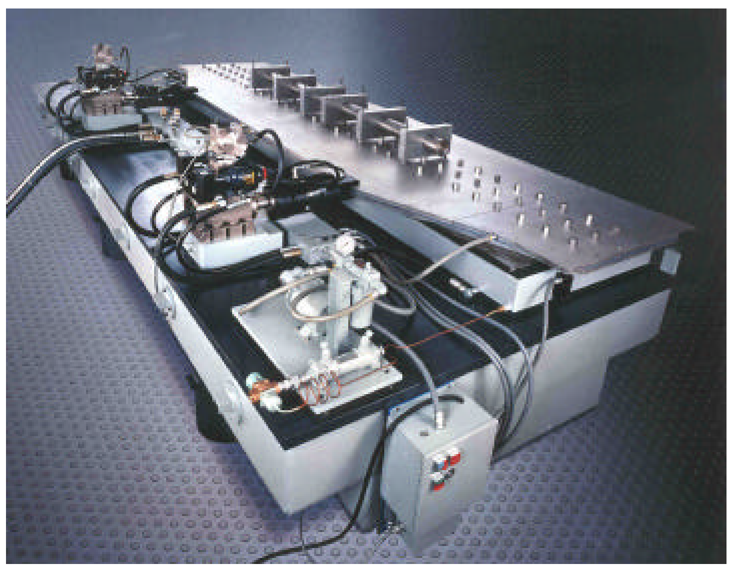

Figure 3.0 Dual shaker horizontal vibration system used for testing oil drill tooling. *Photo courtesy of Schlumberger*

A much more efficient solution is the use of hydrostatic spherical couplings. These couplings use a very thin film of pressurized oil to separate the surfaces of the coupling, as shown in Figure 4.0. The volume of trapped oil is quite small and the bulk modulus of the oil is relatively high, therefore the spring rate contributed by the oil film is virtually negligible in calculating the overall stiffness of the coupling. These couplings have very high transmissibility and are relatively well damped. In the late 1960's, White Sands Missile Range[5] (WSMR) embarked on a program to develop a multi-axial vibration system. The performance criteria were established as:

- No resonance below 500 Hz
- Usable to 2 kHz
- Capable of 0.025-m double amplitude in each of tree directions
- An attachment surface of at least 0.9-m x 0.9-m

- Capable of simultaneous as well as sequential excitation in each axis

WSMR's first two attempts in developing this capability proved the feasibility of such a system, but had serious drawbacks that limited their use as a testing tool. The problems centered on severe resonance and high distortion attributable to the drive links between the electrodynamic shakers and the test table. WSMR then contracted with Team Corporation to design a system using hydrostatic spherical couplings. A second system was produced for the French nuclear testing agency CESTA two years later using the same design criteria. An example of the resulting system that met the design criteria is pictured in Figure 5.0. It offered a vast improvement over what was previously available. The system is able to reproduce the measured vibration environment of missile and aircraft flight as well as ground transportation. The system has also proven durable, in operation since 1971. Virtually all of the high frequency high force multi-shaker test systems in use today use some variation of a hydrostatic spherical coupling to link the shaker to the test platform.

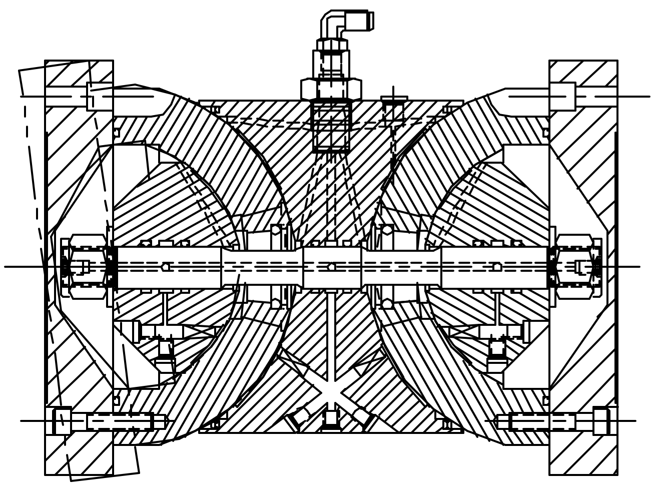

Figure 4.0 Double hydrostatic spherical coupling with +/- 6 degrees of deflection on both ends

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 6.0. 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 operated in pure uniaxial modes or excitation can be simultaneously produced in both vertical and longitudinal directions. A drawing of this system is shown in Figure 7.0 in an exploded view. A single horizontal actuator and two vertical actuators drive the specimen mounting table. Both systems remain a compromise since not all

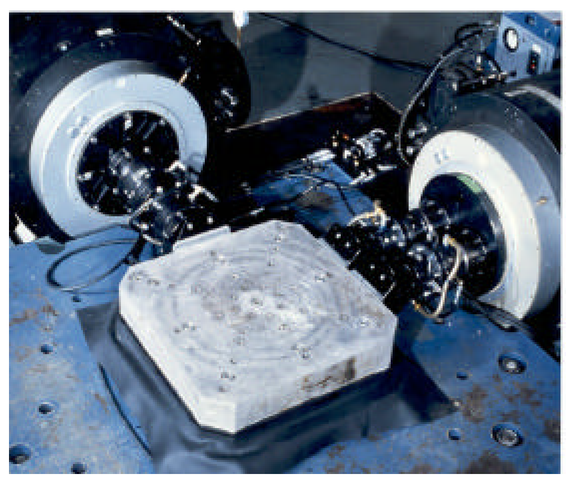

Figure 5.0 Tri-axial vibration system showing two of the three ED shakers and hydrostatic spherical coupling making up the shaker to table connection. *Photo courtesy of CESTA*

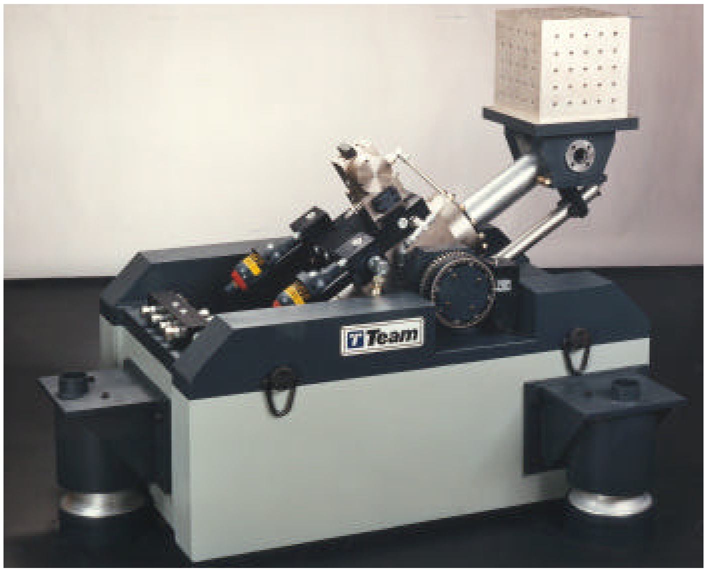

Figure 6.0 Simultaneous bi-axial vibration system used for qualifying small electrical components to IEEE-344.

three axes are excited simultaneously and the laboratory must run multiple tests[6]. 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 multiaxial vibration testing and single axis methods has not been incorporated into standard testing procedures. It has been shown that triaxial excitation can cause approximately twice the fatigue damage as similar test levels and duration in single axis testing[7]. In addition, the order in which uniaxial vibration is applied during a test can cause a significant variance in time-to-failure[8]. 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 multiaxial and uniaxial methodologies.

One industry where the lack of standard testing procedures for multiaxial excitation has not impeded its application is in the automotive world. The quest for improved product quality has led to the use of several different configurations of multi exciter test platforms. Two different designs are predominant, a system using a single axis shaker for each vehicle tire (commonly called 4-poster systems) and full six degree of freedom (6 DoF) test platforms. Well over a hundred systems are installed worldwide. A typical 4-poster test system is shown in Figure 8.0 and a full 6DoF system, termed a MAST rig, is pictured in Figure 9.0.

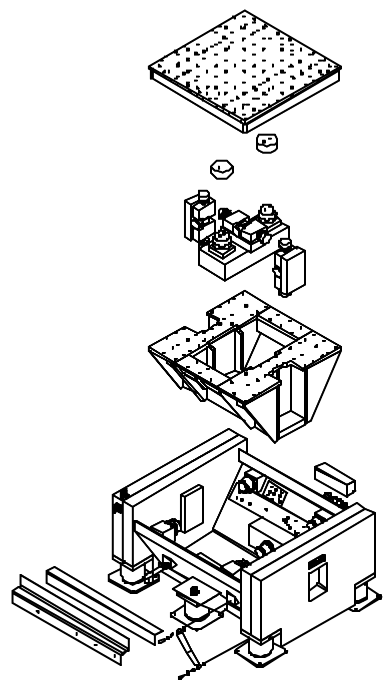

Figure 7.0 True bi-axial vibration system shown in an exploded view. Two vertical actuators flank single horizontal actuator. Other degrees of freedom restrained by hydrostatic planar bearings

4-poster systems permit the replication of recorded vertical road data for each suspension point. The much more complex system in figure 8.0 permits the application of three axial translations as well as three rotations to the test object. It was recognized very early in the application of multiaxial test platforms that not every combination of shaker/table/fixture and test object could be successfully controlled[9]. Test levels and phases, control transducer type and placement, excitation direction and input location can all contribute to the success, or lack thereof, for any particular testing regime. In addition, the use of long mechanical links in 6DoF systems limits the ability to reproduce frequencies much above 50 Hz due to resonance and lack of damping. Early efforts in this multiaxial testing concentrated on reproducing acceleration time-histories as recorded on the test track, permitting controlled laboratory testing. Although road data has significant frequency content over 100 Hz[10], reproduced data was typically limited to an upper frequency range of about 50 Hz to correspond with hardware restrictions. Random and sine testing to higher frequency levels was performed in single axis testing only, since the complex test controller algorithms and computational hardware necessary for minimizing cross axis coupling were in their infancy and prohibitively expensive. The introduction of very sophisticated test controllers in recent years has permitted much more complex test procedures to be applied. The major roadblock to the implementation of higher frequency tests required by environmental stress screening and accelerated durability testing lies in current hardware configurations.

Figure 8.0 Lawn tractor on a small 4-poster servohydraulic test rig. *Photo courtesy of MTD*

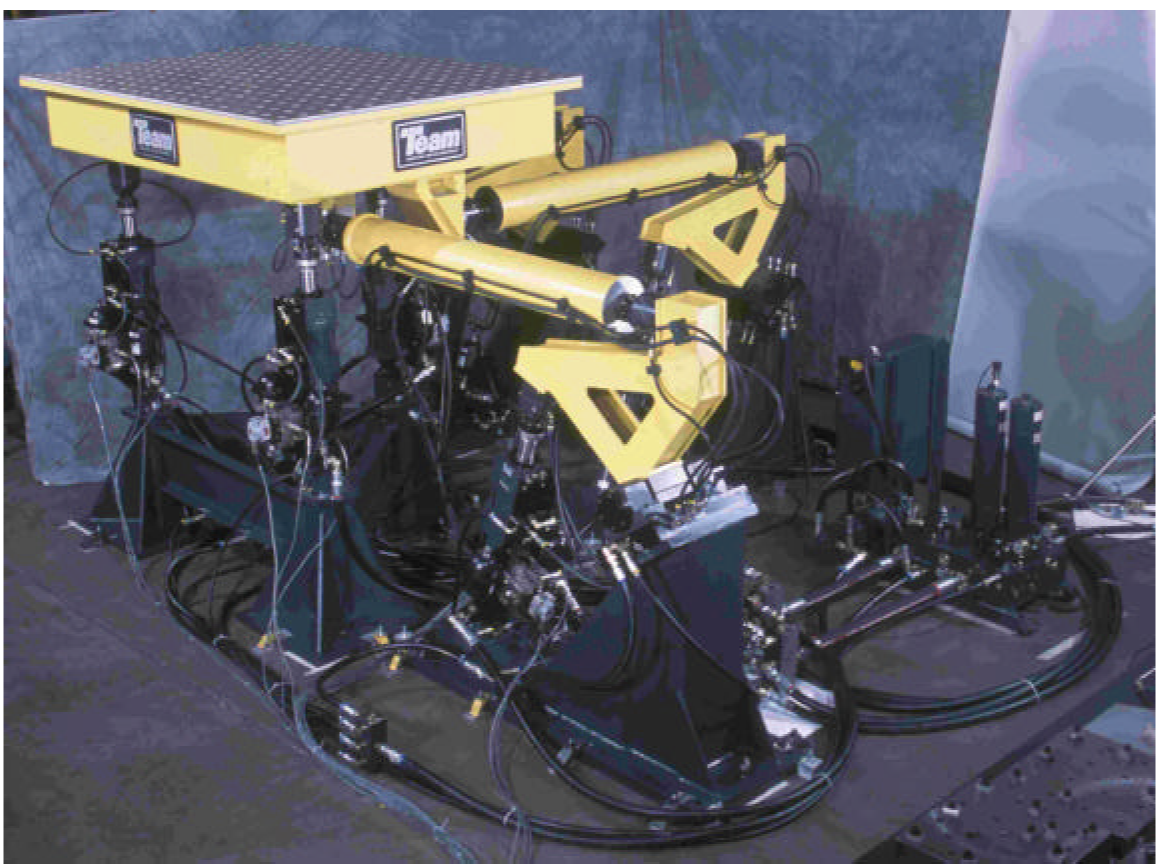

Figure 9.0 Multi Axis Shake Table (MAST) 6 degree of freedom test system. Provides full control of all three translations and three rotations. Normally limited to about 50 Hz in maximum frequency response, this table has a higher frequency bandwidth due to the use of hydrostatic bearings throughout.

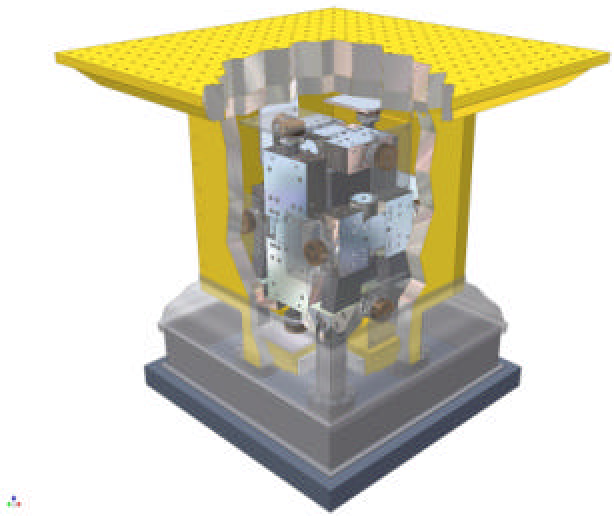

Figure 10.0 Team Corporation CUBE with a 1.5-m square head expander. Interior view shows servohydraulic actuator arrangement.

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 10.0 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.

In Figure 11.0, a typical durability test rig is shown with a portion of an automobile passenger frame mounted on a CUBE. This configuration successfully reproduces the "above axle" vibration environment typical found in a passenger automobile. It permits durability studies that have otherwise been difficult to address with more conventional systems. It's accepted that multiaxial testing excites all modes of the test object and induces a more realistic vibrational stress-loading condition. Properly applied, it can produce a more rapid accumulation of stress and can consequently reduce the time to produce failure.

Within the passenger cab, lower frequency road noise is attenuated to a large degree by the suspension of the automobile. However, excitation attributable to the engine and transmission plays a significant role and has a broader frequency band. This higher frequency content, albeit at very low acceleration levels, is critical to reproduce accurately when subjective ride quality tests are performed. A man-rated vehicle vibration simulator for the subjective evaluation of ride quality is pictured in Figure 12.0. The Ford Motor Company measured the acceleration time-histories from six vehicles used in test track studies and found the frequencies of interest to lie between 3 and 200 Hz[11]. This corresponds

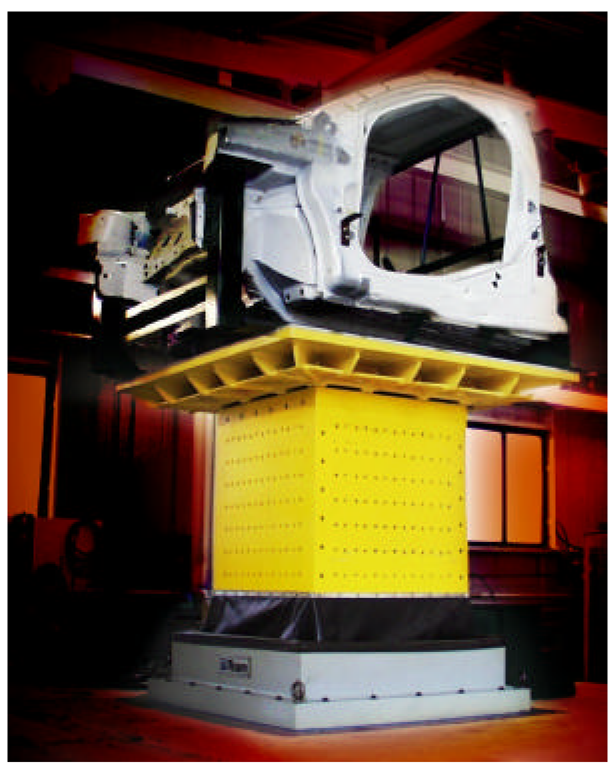

Figure 11.0 Typical automotive durability test set-up using the CUBE. *Photo courtesy of MIRA UK*

quite well with the field data used to test vehicle seating[12]. The greatest challenge faced in reproducing the proper environment in these cases is the low signal levels associated with idle vibration data. The acceleration amplitudes at higher frequencies are quite small, as low as 4 mg in the longitudinal axis[13]. Ford's evaluation of the CUBE® found that the background acceleration noise on all channels could be reduced to less than 2 mg through careful management of hydraulic fluid temperature and pressure. Conventional approaches to multiaxial test platforms cannot achieve the signal-to-noise ratios needed to accomplish this class of whole body vibration tests.

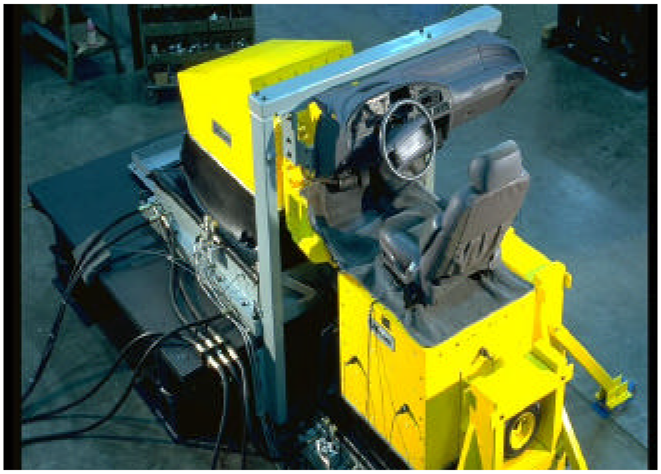

Figure 12.0 Vehicle Vibration Simulator used for subjective evaluation of ride quality. *Photo courtesy of the Ford Motor Company.*

Comfort of automotive seating is dictated by both static and dynamic factors[14]. However, the noises generated by seating (and other automotive interior components) are a prime factor in customer perception of product quality. Termed Buzz, Squeak and Rattle (BSR), these noises are generated by either fundamental vibration response or relative movement between two closely mated surfaces. Testing for these phenomena is usually done subjectively. No specific standards or recommended practices have been written to guide a systematic investigation of BSR detection and cure.

The key to successful BSR testing is a system that can precisely replicate the excitation environment as measured in the automobile at emitted noise levels that permit the identification and localization of any sound attributable to vibration. The CUBE is a unique tool for this evaluation. Road load data can be accurately replicated in all 6 degrees of freedom. The servohydraulic actuators are fully enclosed within the CUBE, minimizing the amplitude of noise contributed by the test system. Low-level excitation is generally found in the passenger compartment of a typical automobile, ranging from less than 0.2-g through 1.2-g[15]. The CUBE is an ideal multi-axis test solution capable of reproducing these levels without creating an unacceptably high background level of noise. Figure 13.0 shows a typical car seat mounted on the CUBE. It is clear that access to the entire seat from all sides is unimpeded and that a test technician can approach quite closely without interference from any moving portion of the test system mechanism.

Figure 13.0 Typical car seat mounted on a CUBE. Provides complete access for placement of microphones and other measurement equipment

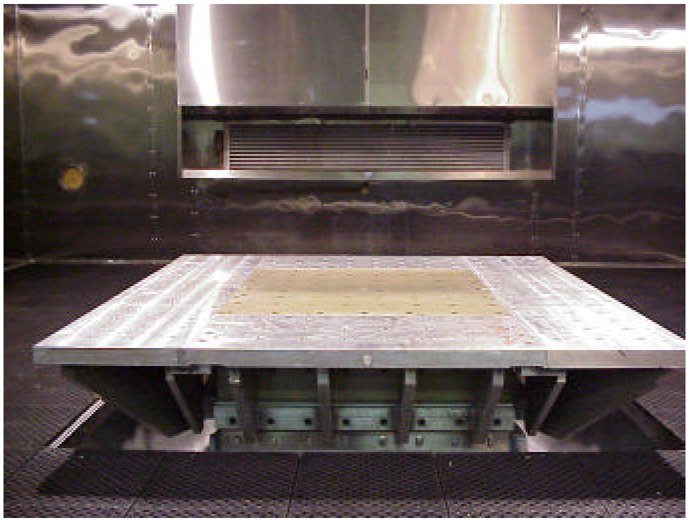

Figure 14.0 CUBE integrated with a thermal chamber. Shows head expander extending into the chamber interior. *Photo courtesy of Defiance Labs.*

Combined environmental testing can be critical to determine the true durability of a component in the field[16]. SAE J1211 specifically notes, "…temperature and vibration is a combined environment that can be significant…" Also, environmental stress screening depends upon combined environment testing to quickly precipitate product failures. The integration of a multi-axis test system into a thermal chamber can offer the test engineer a much more realistic and powerful means to qualify a product. However, the integration of a typical MAST system into a chamber is problematic since the specimen mount area is roughly 40% of the footprint of the entire test system, requiring an extremely large (and expensive) chamber. An alternate solution has the servohydraulic actuators outside the chamber with multiple wall penetrations for actuator to table links. This isn't a particularly elegant solution. The CUBE is very well suited for integration with an environmental chamber. In fact, roughly half of the CUBEs in service are used in a combined environment test system. Figure 14.0 shows a typical installation with just the head expander on top of the CUBE extending into the chamber interior. Another installation possibility is shown in Figure 15.0. The entire CUBE structure is located in the chamber. High temperature G10 epoxy insulation covers the exterior of the CUBE, minimizing heat transfer and permitting long temperature soak cycles.

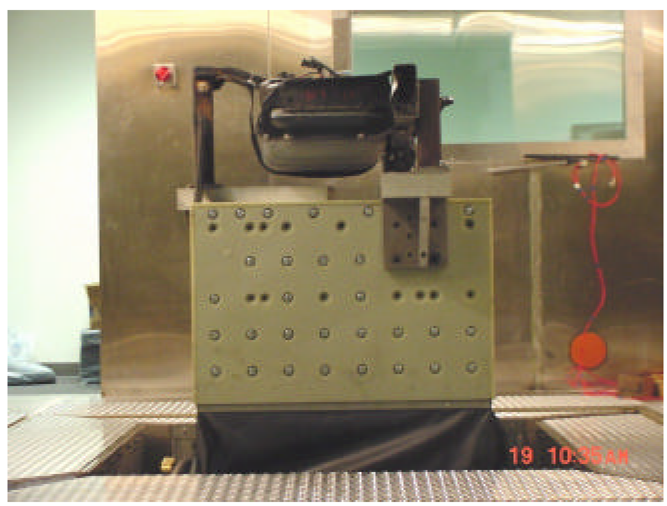

Figure 15.0 Alternate thermal chamber installation of the CUBE. Note the use of G10 epoxy insulation on the entire moving structure. *Photo courtesy of Visteon Global Technology Laboratory.*

The practice of vibration testing has experienced significant evolution over the last 30 years. New hardware and software solutions are being introduced at an increasingly rapid pace, opening new possibilities for manufacturers to explore in the continuing effort to improve product quality. The increasing sophistication and discrimination of users adds to the complexity of vibration testing challenges. With the commercial availability of successful multi-axis test controllers and the demonstrated capabilities of high performance, compact and powerful test hardware, manufacturers have an unprecedented ability to replicate real-world environmental conditions. The improvements generated by this realism in environmental testing are recognized as a critical factor in product quality, consumer satisfaction and brand loyalty.

[1] 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.
[2] 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
[3] Freeman, M. T. "3-axis Vibration Test System Simulates Real World." *Test Engineering and Management.* Dec/Jan, 1990-91: 10-14
[4] Underwood, M. A., T. Keller. "Recent System Developments for Multi-Actuator Vibration Control." *Sound and Vibration* Oct 2001: 16-23
[5] Edgington, F. M. "A Three Direction Vibration System"
[6] Bausch H. P., A. Franz, M. Lapin. "Simultaneous, Multiaxial Vibration Testing in Six Degrees of Freedom." *Sound and Vibration* Nov 1992: 6-11.
[7] Himelbau, 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.
[8] Whiteman and Berman, 23
[9] Underwood and Keller, 16
[10] Tustin, W., "Road Frequencies contain all frequencies simultaneously", *Test Engineering and Management.* Aug/Sept, 2001: 2-3.
[11] Meier, R.C., N. Otto, W. Pielemeir and V. Jeyabalan. "The Ford Vehicle Vibration Simulator for Subjective Testing" In *Proceedings of the Noise and Vibration Conference.* Traverse City, MI: Society of Automotive Engineers, Inc. 1997
[12] Davis, J. M., "Fitting Multi-Axis Vibration Testing into a Small Laboratory". *Test Engineering and Management* Aug/Sept 1995: 16-18
[13] Meier, Otto, et.al
[14] Ebe K. and Griffing, M. J., "Qualitative models of seat discomfort including static and dynamic factors", *Ergonomics,* 2000, 43(6), 771-790
[15] Bei, G., J. Gabiniewicz and J. Gatt, "Seat, Rattle and Roll", *Testing Technology International,* February 1999: 75-79.
[16] Bausch, Franz and Lapin, 6