Multi-Axis Vibration Testing

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When a vehicle moves down the road, it experiences vibrations not along one-axis, but along many. So it makes sense that automotive engineers test products along more than one axis. But in the past, engineers could only test along one axis at a time. They would mount the product to the single-axis shaker, test, take the product off, re-orient and remount the product along a different axis, retest, and so on for X, Y, and Z – the sequential, single-axis method for testing along more than one axis.

Today engineers can test products along multiple axes at once. In addition to being more realistic and time efficient, this multi-axis method causes products to fatigue faster. As Reference 1 points out, this means a product, although not failing in sequential, single-axis testing, might fail in a more realistic multi-axis test using the same time. Multi-axis vibration testing is becoming ever more popular, and so we are discussing the multi-axis configurations, concerns, and control methods.

There are many different ways to configure a multi-axis vibration test. But the two key characteristics of any configuration are:

- The number of shakers
- The number of axes/degrees of freedom

Let's consider some examples. A MESA (multi-exciter/single-axis) configuration involves two or more shakers (exciters) that shake in the same direction along one axis. Such a setup is used to test oversized products that require a shaker on each end, where the shakers are often synchronized using the same test profile.

A four-post configuration also involves multiple (four) shakers moving along the same axis (Figure 1) and is used for full vehicle testing. This setup is naturally designed for testing vehicles by placing a shaker underneath each wheel. Four-post testing is accomplished by playing back four recorded field data files (one from each wheel) to a corresponding shaker. The recorded vibrations are played back simultaneously as if the vehicle were actually moving on or off road. Some four-post configurations can even test along other axes at well.

In recent years the automotive world has seen a rising interest in another multi-axis configuration, the three-axis configuration mentioned in the introduction. The three-axis configuration belongs to the MEMA class (multi-exciter/multi-axis), and involves at least three shakers and motion along the X, Y, and Z axes simultaneously (Figure 2).

Three-axis testing is primarily used for component or sub-system testing and is accomplished by testing each axis to a random test profile, either identical or individualized test profiles. The primary advantage of this configuration is that it provides more realistic testing as compared to traditional single-axis testing.

We know a vehicle experiences vibration from many directions simultaneously during use, and the three-axis configuration accommodates the three major directions. Although a three-axis configuration incorporates the three linear directions of motion, it does not accommodate the three rotational directions of motion – roll, pitch, and yaw. A 6-DOF (six degrees of freedom) system handles all six: X, Y, Z, roll, pitch, and yaw. There are numerous ways to configure a 6-DOF system, but these won't be discussed here.

Multi-axis testing has a variety of applications in the automotive industry. We have already talked about four-post testing. Another application is squeak and rattle testing. No automobile driver likes a squeaky seat, but sometimes a seat needs to experience a very particular set of vibrations along more than one axis before the

Figure 1. Four-post shaker system with full vehicle under test.

Figure 2. Three-axis shaker system with table.

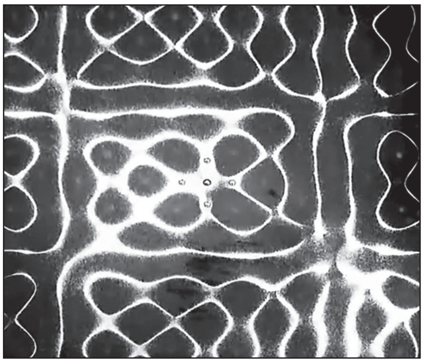

Figure 3. Salt on a shaker table demonstrating nodes at various frequencies. Where is the correct location of control accelerometer placement if nodes change with frequency?

seat emits noise, a scenario that can only be simulated with multi-axis testing. We have also already talked about how multi-axis testing brings products to fatigue failure faster – in a more realistic test. Fatigue damage is applied more realistically than sequential, single-axis testing. The advantage of multi-axis testing in automotive durability and stress testing as well as NVH (noise, vibration, and harshness) testing is clear.

However, with multi-axis configurations come a number of concerns. One concern is the coupling of multiple shakers to the table. How should the shakers be connected to the same table? Ideally, a shaker along one axis would be able to successfully transfer its motion to the table without affecting the other axes of motion.

This is the goal of coupling, and when coupling is done properly a shaker is able to move the table along the X axis without causing significant motion in Y or Z. The same can be said about a shaker moving a table along the Y or Z axis with respect to the other two axes. When excitation along one axis excites another axis or other axes, cross-axis motion has occurred – cross-talk. Think of a slip table moving side to side when it should only be moving forward and backward.

It is impossible to completely eliminate cross-axis motion, but proper coupling methods are able to minimize the effect of cross-axis motion. A common coupling method employs hydrostatic bearings, which allow connections to pivot freely while still allowing transmission of motion from shaker to table. Another method involves sliding hydrostatic bearings. Whatever the coupling method, the goal is the same: to transmit motion without exciting the other axes and to let the table move as freely as possible (without being impeded by the coupling) when any excitation is applied.

Resonances are also a concern in multi-axis testing, in light of cross-axis motion. Resonances are more difficult to control because excitation along any of the several axes could excite a resonance along any other axis or axes through the mechanisms of cross-axis motion. Reference 2 mentions the potentially elevated noise floor and nonlinear concerns involved in multi-axis testing. The head expander (or table), too, demands concern, since it must be designed so that resonances are minimized not just along one axis, but along several. The list goes on. Multi-axis testing shares the same concerns of single-axis testing, only compounded.

Accelerometer concerns are also amplified in multi-axis testing. Transverse sensitivities produce larger effects, since the system is intentionally moving in all directions. In addition, accelerometer placement deserves weighty consideration with respect to both the number of accelerometers and their locations. Most tables or fixtures aren't perfectly rigid, so location matters (Figure 3). Since multiple accelerometers are often used in conjunction to determine motion in a particular degree of freedom, placement effects become magnified.

There are several ways to control simultaneous, multi-axis vibration. Perhaps the most popular is matrix control. Matrix control applies to a MIMO (multiple input, multiple output) system that is often overdetermined (more accelerometers than mechanical degrees of freedom). The key in matrix control is the transfer function matrix containing the terms that define how each direction of motion affects the other directions of motion. In other words, this matrix defines the system's cross-talk. This matrix describes how excitation in the Y axis affects the X axis, the Y axis (i.e., the gain along the Y axis), and the Z axis, for instance.

Matrix control receives information from the accelerometers, determines the vibration along each mechanical degree of freedom involved, and with knowledge of the transfer function matrix and the system response, is able to compute the drives necessary to control. Although a natural danger with a control method involving matrices would be the event when a matrix is not able to be inverted (or an event when the matrix inverse is very large), a method exists to accommodate such an event (MIL-STD-810G).

Matrix control theory is comprehensive, taking into account the relationship of each axis with every other axis, and is able to simultaneously control all of the shakers involved in the test, so that they are all controlled "with each other," instead of each shaker being controlled as if it were independent from the other two.

Another, simpler control method is extremal control. Extremal control in multi-axis is like extremal control in single-axis testing – the controller controls off of the accelerometer with the maximum (or minimum) value. With extremal control, unlike matrix control, one control loop cannot account for all of the axes simultaneously. Rather, a three-axis system requires one independent control loop per axis of motion, and each separate control loop is controlled using the extremal method.

In either control strategy scenario, there is an understanding that reasonable control tolerances for multi-exciter testing need to be addressed, a point also referenced to in MIL-STD-810G.

We have only addressed a few multi-axis configurations and concerns and have only briefly discussed the available control methods. This article is not intended to be an exhaustive account but rather a brief overview of multi-axis vibration testing.

Multi-axis testing affords the automotive world an improved method of vibration testing, improved because in the real world, vehicles don't experience vibrations from just one direction at a time. Rather, vehicles experience vibrations from multiple directions simultaneously.

Multi-axis configurations allow engineers to test products in a more realistic manner, from four-post testing, which simultaneously replicates road data vibration to each wheel of a vehicle as if it were driving down the road, to the increasingly popular three-axis testing for random vibration testing.

For additional information, please visit vrsales@vibrationresearch.com.

1. downloads.hindawi.com/journals/sv/2002/109715.pdf
2. http://www.sandv.com/downloads/1409hoks.pdf

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