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SIMPLE FIXTURE CONCEPTS FOR MULTI-AXIS VIBRATION TESTING*

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Abstract

This paper presents some simple concepts for fixtures that can be used in two and three-axis vibration testing. Two, two-axis fixtures were built and tested in the laboratory. Test results are shown, and serve to confirm the validity of the concept. Simple methods for extending the concepts for three-axis testing are discussed.

Introduction

The possibility of high frequency, multi-shaker, stationary random vibration testing has been considered for many years. Early tests described in Reference 1 showed that standard, one-shaker, linear theory, control systems can be used to perform multi-shaker random vibration tests, with limited accuracy, when the inputs at the different shakers are uncorrelated. However, single shaker control systems cannot generally be used to control a test item attached to multiple shakers when the test has high frequency content (say up to 2000 Hz, a limit frequently used in tests performed on electrodynamic shakers). The problem that occurs, even when an attempt is made to maintain independence between the inputs at the various shakers, is that when the body being tested has full body modes, the excitation at each shaker causes motion at the other shaker(s). This effect can make control in some frequency ranges impossible. Further, there are certain circumstances where instability in the control loop can occur. Because nearly all test fixtures and test surfaces have modes with frequencies lower than 2000 Hz, early attempts at multi-axis testing could not maintain satisfactory control.

About 10 years ago Smallwood (References 2 and 3) developed a method for simultaneously controlling multiple shakers. The method was successfully implemented, and several tests have been run at Sandia National Laboratories using two shakers to control motion of a test item. Further, methods for establishing parameters in Multi-shaker tests have been considered in several papers. (See References 4 and 5.)

Successful performance of multi-shaker tests generated interest in multi-axis testing, and a three-axis test system was built at the Harry Diamond Research Laboratories. The system is described in Reference 6, and uses three shakers arranged in orthogonal directions to drive a test surface. Because all three shakers are directly attached to the test surface, it was necessary to use a system of hydrostatic bearings in an attempt to uncouple the shakers. Reports on the results of tests performed using this system indicate that it yields satisfactory performance.

While the system described in Reference 6 establishes a useful solution for multi-axis testing of mechanical systems, it is not the only solution. Some alternate concepts for testing are presented in this paper. The present concepts are much simpler than the implementation at Harry Diamond Research Laboratories, and possess certain advantages and disadvantages.

In the following, a basic concept for two-axis testing is described. Both the merits and the limitations of the concept are discussed. Then the results of some experiments performed in the laboratory using a pair of two-axis test fixtures are presented. Simple methods for extending the two-axis test fixture concepts to three-axis test fixtures are also given. The paper concludes with a discussion of work in the area that remains to be done.

A Simple Two-Axis Test Fixture

The many possible approaches to the generation of multi-axis mechanical environments on shakers can be divided into two broad categories. These are approaches where (1) the motion of a test

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surface is excited using directly attached shakers, and (2) the motion of a test surface is the motion at some point on a fixture with special geometry, where the fixture may be excited at some distance from the test surface. The schematic diagram shown in Figure 1 is an example of the first approach to two-axis test generation. The second approach is the approach of interest in this discussion.

Three possible fixtures with test surfaces that execute two-axis motion when excited using two vertical shakers are shown schematically in Figures 2a, 2b and 2c. Each test fixture is generally triangular in shape, with a "deep beam" geometry that transforms the vertical motion at the shakers into a combined vertical and lateral motion at the test surface. The fixtures must be attached to the shakers using flex-web connections in order to maintain stiffness in the vertical direction, yet uncouple the fixtures from the shakers in flexure.

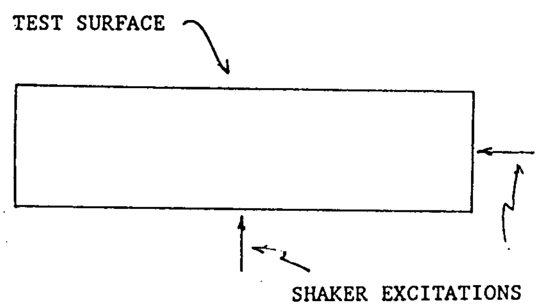

Figure 1. Two-axis test concept where shakers are attached directly to test surface.

If the fixtures were perfectly rigid, then the time histories of motions on the fixtures shown in Figures 2a, 2b and 2c would be simple linear functions of the time histories of motions at the shaker heads.

However, fixtures will usually not behave as rigid bodies up to the high frequencies generally used in vibration tests, therefore, a structural dynamic description of motion will be required to characterize the motion on the test surface. The motion of a two-axis test surface can be described as follows. Let $X_1(f)$ and $X_2(f)$ be the Fourier transforms of motions at the shakers, and let $Z_1(f)$ and $Z_2(f)$ be the Fourier transforms of vertical and lateral motions on the test surface. Let $H_{ij}(f)$, $i,j=1,2$, be the frequency response function of motion $Z_i(f)$ excited by the excitation $X_j(f)$. Then the motion of the test surface is given by

$$\{Z(f)\} = [H(f)]\,\{X(f)\} \tag{1}$$

where

$$\{X(f)\} = \begin{Bmatrix} X_1(f) \\ X_2(f) \end{Bmatrix} \tag{1a}$$

$$[H(f)] = \begin{bmatrix} H_{11}(f) & H_{12}(f) \\ H_{21}(f) & H_{22}(f) \end{bmatrix} \tag{1b}$$

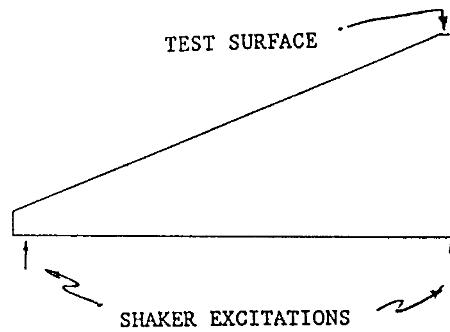

Figure 2a. Two-axis test fixture with vertical shaker excitations.

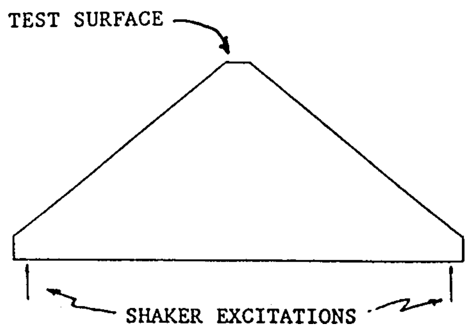

Figure 2b. Two-axis test fixture with vertical shaker excitations.

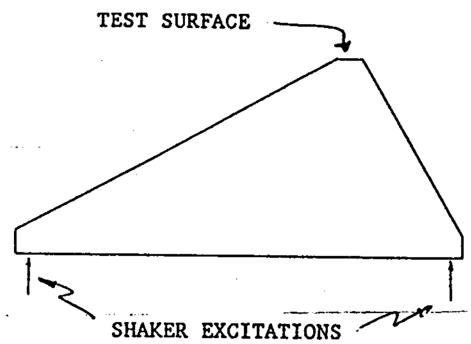

Figure 2c. Two-axis test fixture with vertical shaker excitations.

$$\{Z(f)\} = \begin{Bmatrix} Z_1(f) \\ Z_2(f) \end{Bmatrix} \tag{1c}$$

The specific geometry and physical properties of the test fixture will establish the precise form of the [H(f)] matrix. Specific motions on the test surface can only be generated within the limits of the motions that can be generated on the shakers.

When the excitations generated with the shakers are stationary random processes, Equation 1 can be used to derive the relation between the excitation spectral densities and the spectral densities of motions on the test surface. That relation is

$$[S_{ZZ}(f)] = [H(f)]\ [S_{XX}(f)]\ [H^{*}(f)]^{T} \qquad (2)$$

where $[S_{zz}(f)]$ is the matrix of spectral densities of $\{Z(f)\}$ and $[S_{xx}(f)]$ is the matrix of spectral densities of $\{X(f)\}$. The diagonal terms in the matrices are the autospectral densities, and the off diagonal terms are the cross-spectral densities.

When a particular spectral motion characteristic is desired in a test, then that characteristic is reflected in the matrix $[S_{zz}(f)]$. Because the matrix $[H(f)]$ is a set of complex constants at a given frequency, the elements in the matrix $[S_{xx}(f)]$ must be chosen to yield the desired test. A good fixture is one that makes it relatively easy (or at least possible) to generate shaker motions with characteristics $[S_{xx}(f)]$, that yield a wide variety test characteristics $[S_{zz}(f)]$.

Some characteristics of the functions in $[H(f)]$ that tend to facilitate test control are (1) slow and smooth variation, (2) absence of sharp peaks and troughs, and (3) time invariance. These can be achieved by building test fixtures that behave linearly and are well damped.

The two-dimensional fixtures shown in Figures 2a, 2b and 2c, have individual advantages and disadvantages. The fixture in Figure 2a has the advantage that control of vertical motion on the test surface is concentrated in the right side shaker, while lateral motion is controlled by the combined action of both shakers. This simplifies $[H(f)]$. One disadvantage is that if vertical motion on the test surface becomes uncoupled from the right side shaker, then the left side shaker cannot compensate for this loss very well. Further, the vertical environment is limited by the capacity of the right side shaker.

The fixture in Figure 2b has the advantage of symmetry. This may increase the vertical environment that can be generated on the test surface. A disadvantage is that if the test surface motion becomes uncoupled from one shaker at a given frequency, then it may be uncoupled from the other shaker also, because of the symmetry.

The problems of the previous two fixtures lead to the solution of Figure 2c. Its advantage is that when the test surface motion becomes uncoupled from motion at one shaker, it is unlikely to be uncoupled from motion at the other shaker. One disadvantage is that the asymmetry leads to limits on the potential environments that can be generated.

Before closing this section, one final issue must be mentioned. It is clear that all the fixtures discussed in this paper will display some roation during an experiment. This rotation has been and will be ignored, and only control of the autospectral densities of the vertical and lateral motions and the cross-spectral density between them is considered. Three comments are pertinent. First, every real environment has some rotational element. Though rotation may be uncontrolled in the applications described in this paper, the rotations that exist on the fixture are consistent with the geometry and material properties of the fixtures, and they can be assessed. Second, all fixtures display some degree of rotation during testing, whether the rotation is meant to exist or not. Finally, in some situations, the rotation of the test surface on the fixtures described in this paper might be controllable, to some extent, using the approach described in Reference 4. It was shown there that the control on the cross spectral density during a multi-shaker test can be sacrificed to control the autospectral densities at n^2-n locations in an n-shaker test. In the present situation, with the fixture of Figure 2c for example, the autospectral densities of motions in the vertical and lateral directions might be controlled. In addition, a rotational transducer might be used to control the autospectral density of rotation at some low level. Finally, one other autospectral density of motion at another point might be controlled.

Experimental Results

Two fixtures like the ones shown on Figures 2a and 2b were built for use in physical experiments. The dimensions and material properties of the fixtures are shown in Figures 3a and 3b. Because the purpose of the experiments was simply to test the multi-shaker test concept established in this paper, small models of the fixtures were used. The models weighed approximately two lb each, and five lb Ling shakers were used to drive them.

A typical frequency response function for acceleration on the test surface of the fixture in Figure 3a is shown in Figure 4. This function is an element in $[H(f)]$ for this fixture. A typical frequency response function for the fixture in Figure 3b is shown in Figure 5.

We wished to establish how well random vibration environments could be controlled in orthogonal directions on the test surface of each fixture, therefore, we considered two limiting cases. In both cases, the desired autospectral density of acceleration in the vertical and lateral directions is a white noise. In one limiting case, the desired coherence between motions in the vertical and lateral directions is set at zero. (For us, this has been the most difficult type of motion to control in past experiments.) In the other limiting case, the coherence between motions in the vertical and lateral directions is set at one. (This is referred to in Reference 5 as the minimum drive case.) All tests were controlled over frequency intervals that included at least one fixture resonance.

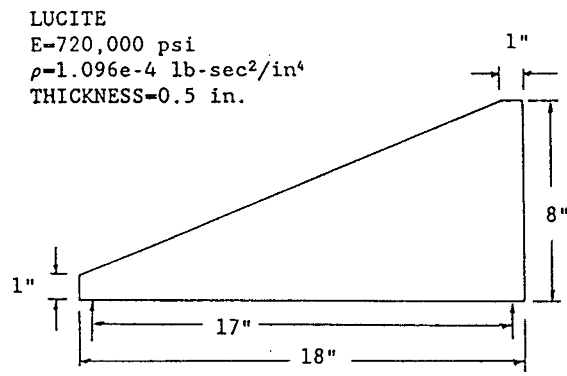

Figure 3a. Characteristics of a two-axis test fixture used used in experiments.

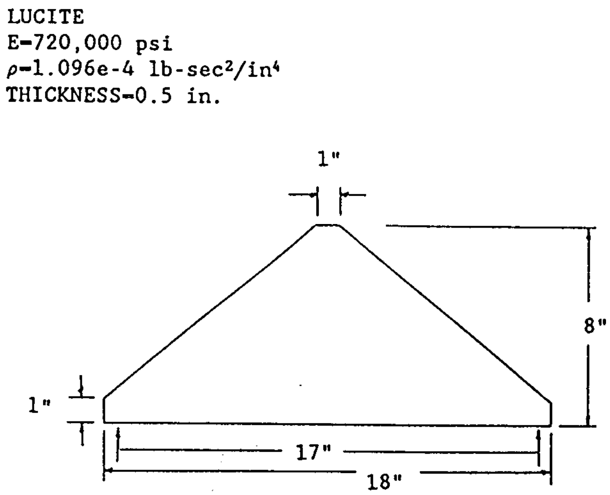

Figure 3b. Characteristics of a two-axis test fixture used used in experiments.

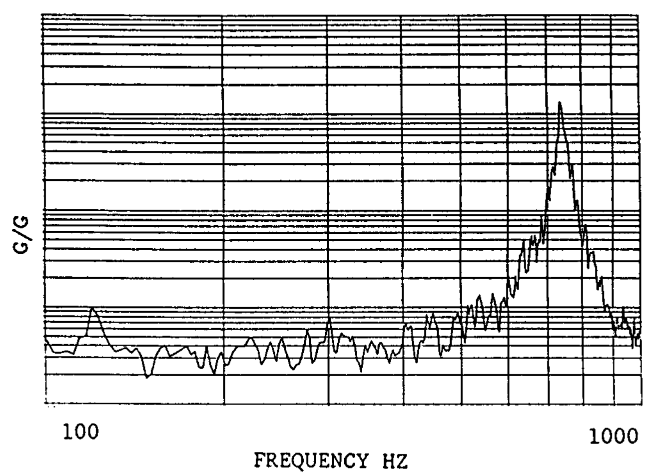

Figure 4. Frequency response function of lateral motion on the fixture of Figure 3a excited by input at left shaker.

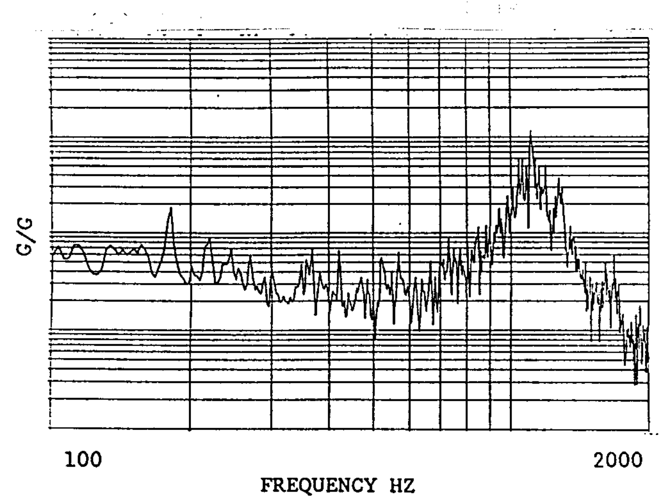

Figure 5. Frequency response function of vertical motion on the fixture of Figure 3b excited by input at right shaker.

Typical results are shown in Figures 6 and 7. Figures 6a and 6b show the autospectral densities of accelerations in the vertical and lateral directions on the test surface of the fixture of Figure 3a. Apparently, the autospectral densities were well controlled. The coherence between the accelerations in the vertical and lateral directions is shown in Figure 6c for the case where zero coherence was sought. Figure 6d shows the coherence between the vertical and lateral accelerations for the case where unit coherence was sought. Based on our past experiences, we consider these results very good. (Diminished coherence values at 120 Hz, etc., are probably related to 60 Hz noise.)

Figures 7a and 7b show the autospectral densities of accelerations in the vertical and lateral directions on the test surface of the fixture of Figure 3b. The autospectral density was well controlled at all frequencies in the vertical direction, and up to 1500 Hz in the horizontal direction. Figure 7c shows the coherence between the vertical and lateral accelerations on the test surface for the case where zero coherence was sought. Figure 7d shows the coherence between the vertical and lateral accelerations for the case where unit coherence was sought. The results appear satisfactory up to about 1500 Hz.

Because control can be maintained in these limiting cases, we feel that intermediate levels of coherence could be controlled on these fixtures.

Fixtures for Three-Axis Testing

Our success in controlling two-axis random vibration tests on the fixtures described above, leads us to consider the possibility of controlling three-axis tests using the same general concepts. We are, at present, unable to perform three-axis tests, but we have considered the types of fixtures that could be used to generate three-axis environments. Two specific

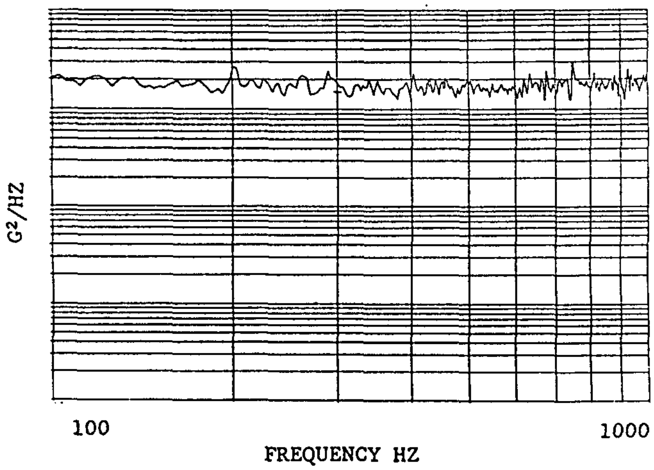

Figure 6a. Spectral density of vertical acceleration on fixture of Figure 3a. White noise desired.

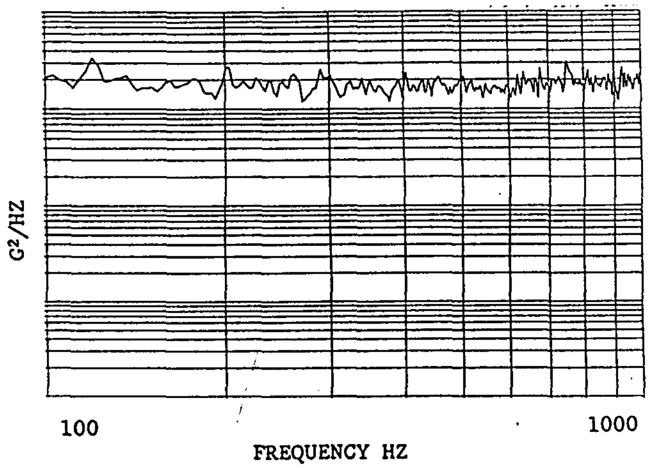

Figure 6b. Spectral density of lateral acceleration on fixture of Figure 3a. White noise desired.

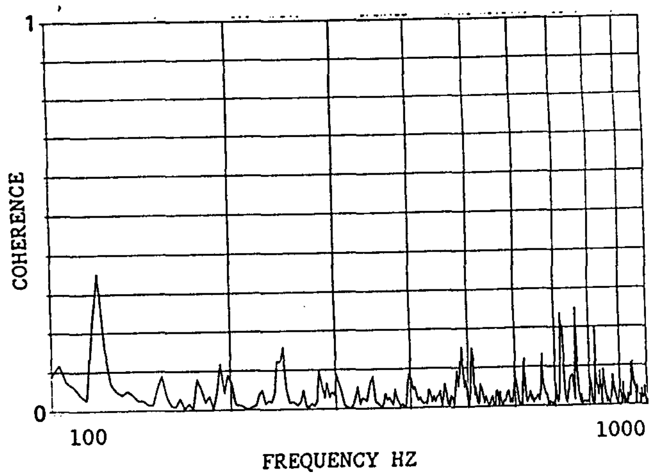

Figure 6c. Coherence between vertical and lateral accelerations on fixture of Figure 3a. Zero coherence desired.

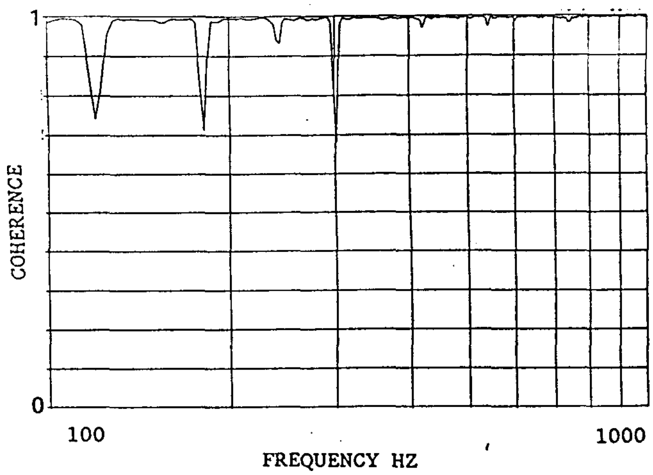

Figure 6d. Coherence between vertical and lateral accelerations on fixture of Figure 3a. Unit coherence desired.

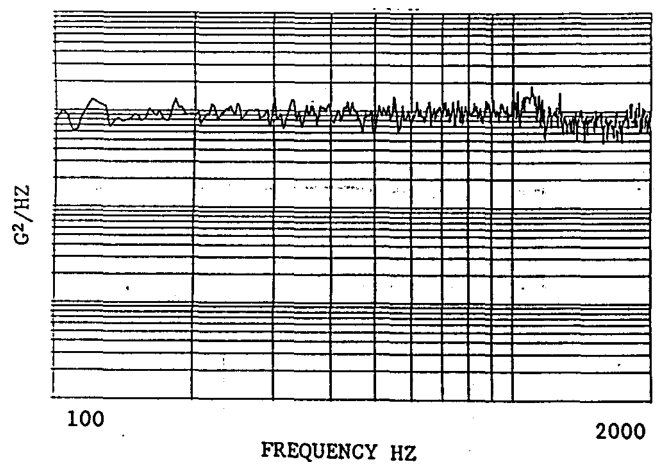

Figure 7a. Spectral density of vertical acceleration on fixture of Figure 3b. White noise desired.

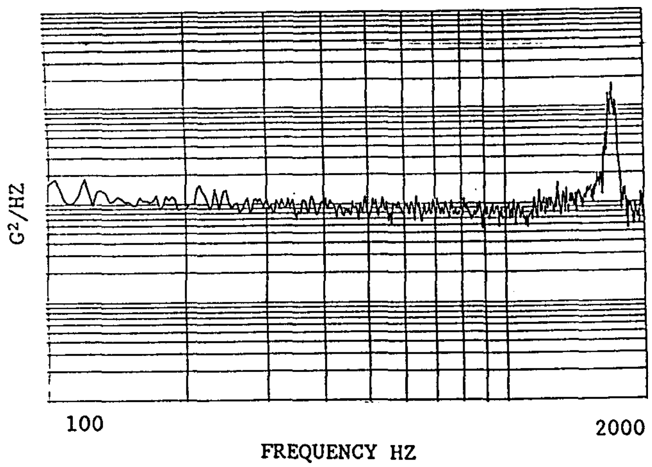

Figure 7b. Spectral density of lateral acceleration on fixture of Figure 3b. White noise desired.

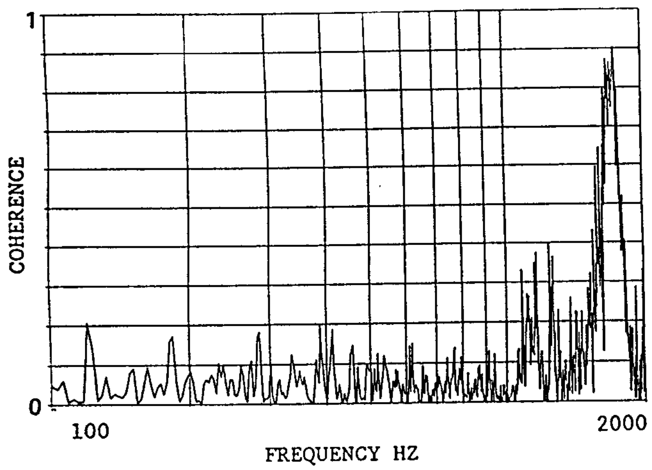

Figure 7c. Coherence between vertical and lateral accelerations on fixture of Figure 3b. Zero coherence desired.

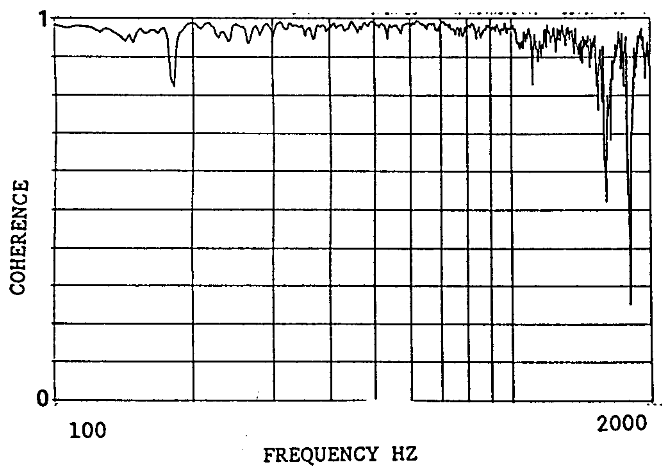

Figure 7d. Coherence between vertical and lateral accelerations on fixture of Figure 3b. Unit coherence desired.

concepts combine the two-axis fixtures described in the previous sections.

One fixture that could be used to generate a three-axis environment is that shown in Figure 8. It is simply a bilateral combination of the fixture shown in Figure 2a. Its advantage is that vertical motion on the test surface is strongly coupled to the motion of the middle shaker. Lateral motions in the two orthogonal directions are strongly coupled to the motions of the outer shakers and the center shaker. A disadvantage is that the vertical environment is limited by the capacity of the center shaker. Another disadvantage is that if the vertical motion of the test surface becomes uncoupled from the motion of the center shaker at some frequency, it is unlikely that the outer shakers can drive vertical motion at that frequency.

Another fixture that could be used to generate a three-axis environment is the one shown in Figure 9. It combines the fixtures shown in Figures 2a and 2b. One of its advantages is that vertical motion is driven by two shakers, therefore, the limit on the vertical environment is greater than that of the fixture shown in Figure 8. A disadvantage is that motion on the test surface can uncouple from the motion of the shakers.

Clearly, the assessment of these test fixture concepts (or any related concepts) awaits laboratory experimentation and numerical analysis.

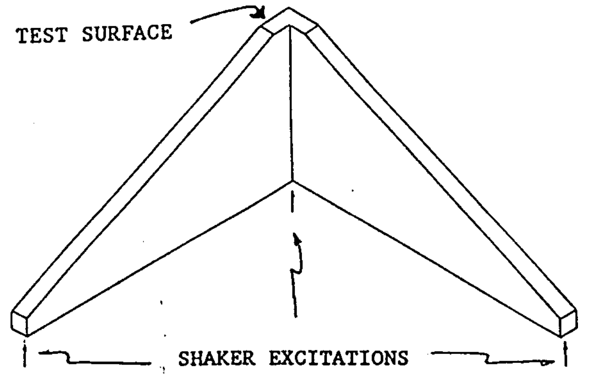

Figure 8. Three-axis test fixture based on the two-axis concepts presented earlier.

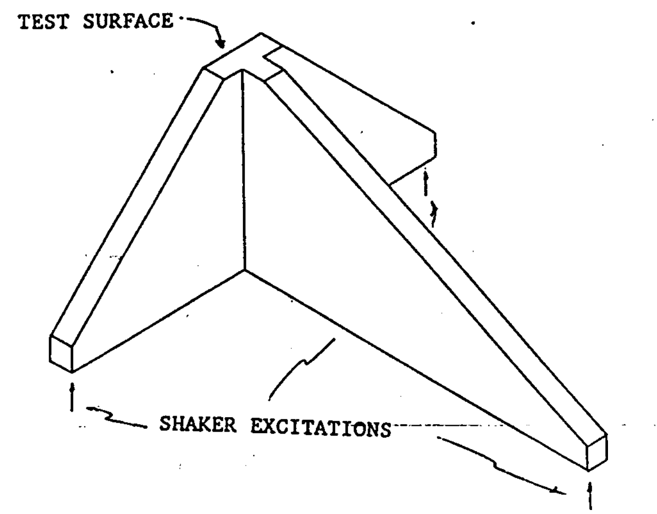

Figure 9. Three-axis test fixture based on the two-axis concepts presented earlier.

Discussion and Conclusions

Some concepts for the construction of multi-axis test fixtures have been presented in this paper. It was shown experimentally that two of the two-axis fixtures behave well, and accurately yield the desired environments. The fixtures used in the present experiments are small and well damped. These attributes tend to facilitate random vibration control. However, the fixtures also possess one or more modes in the frequency range where control was sought. Despite the presence of these modal frequencies, control was maintained in the laboratory experiments.

Other fixture concepts for multi-axis testing could also be tried on a small scale. Before construction of any full scale test fixture, this should be done. Further, finite element models should be used to investigate the characteristics of any proposed fixtures. The characteristics of physical models and finite element models should be assessed both with and without loads placed on the test surface.

Since damping in test fixtures tends to enhance their controllability, means for introducing damping into two and three-axis test fixtures should be investigated. The possibility of using non-metallic materials for fixtures should be considered, as well as the possibility of using energy absorbing, nonstructural materials in test fixture construction.

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