Institute of Environmental Sciences and Technology

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Design, Test, and Evaluation Division
Recommended Practice 022.1

Multi-shaker Test and Control

1827 Walden Office Square, Suite 400 |
Schaumburg, IL 60173 USA
Phone: (847) 981-0100 • Fax: (847) 981-4130
E-mail: information@iest.org • Web: www.iest.org

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This Recommended Practice was prepared by and is under the jurisdiction of Working Group 22 of the IEST Design, Test, and Evaluation Division (WG-DTE022). The following WG voting members contributed to the development of this edition of this Recommended Practice.

Tony Keller, WG-DTE022 Chair, Spectral Dynamics

Brad Allen, Moog CSA

Robert L. (Andy) Anderson, National Technical Systems

Russ Ayres, Spectral Dynamics

David Banaszak, US Air Force Research Laboratory

Richard Cellary, NSWC IHEODTD Naval PHST Center

William H. Connon III, US Army Aberdeen Test Center

Michael T. Hale, Redstone Test Center

Joel Hoksbergen, Team Corporation

Samuel Kouretas, NSWC IHEODTD DET PICATINNY

Randy Patrick, Army Yuma Test Center

Stanley Poynor, Lockheed Martin Missiles & Fire Control

Thomas Reilly, Data Physics Corporation

Ken Salomon, Raytheon Corporation

David O. Smallwood, Consultant

Kenneth Thompson, US Army

Wayne Tustin, Equipment Reliability Institute

Marcos A. Underwood, Tu'tuli Enterprises

Del Wilson, Boeing

Jon Wilson, Jon S. Wilson Consulting

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1827 Walden Office Square, Suite 400 |
Schaumburg, IL 60173 USA
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1 SCOPE AND LIMITATIONS

1.1 Scope

The purpose of this Recommended Practice (RP) is to present guidelines and recommendations for different aspects to be considered when determining whether or how to perform vibration or shock tests using multiple exciters. This RP is not intended to provide a specification for a specific purchase. Rather it is a focused treatise on how the selection of exciters, fixtures, transducers, bearings, and controllers can all contribute to the successful performance of a multiple-shaker vibration test.

1.2 Limitations

Future revisions of this document will be expanded to include sections on the following topics:

- Impedance, phase, and coherence measurements
- Fixture considerations
- Nonlinearities
- Cross-axis motion
- Controller considerations
- Test equipment characterization
- Special applications
- Troubleshooting techniques
- Data acquisition
- Instrumentation
- Data reduction (processing)
- Expand multiple input/multiple output (MIMO) theory as applicable

Also planned for future revisions is further information on types of testing along with additional illustrations for reporting MIMO tests (section 9 and Appendix A). The multi-exciter user community is highly encouraged to provide feedback to IEST based on real-world experiences, to aid in improving future editions of this document.

2 REFERENCES

2.1 Applicable documents

The following documents are incorporated into this RP to the extent specified herein. Users should apply the most recent editions of the references.

IEST-RP-DTE009: *Vibration Shaker System Selection*

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IEST-RP-DTE011: *Mechanical Shock and Vibration Transducer Selection*

IEST-RD-DTE046: *Terms Commonly Used in the Digital Analysis of Dynamic Data*

MIL-STD-810G CN1, *Test Method Standard for Environmental Engineering Considerations and Laboratory Tests*, Methods 525 and 527

2.2 Sources

IEST
Institute of Environmental Sciences and Technology
1827 Walden Office Square, Suite 400 |
Schaumburg, IL 60173 USA
Phone: 847-981-0100
Fax: 847- 981-4130
Website: www.iest.org

Military Standards
Standardization Document Order Desk
700 Robbins Avenue
Bldg #4, Section D
Philadelphia, PA 19111, USA
Website: http://assistdocs.com

3 TERMS AND DEFINITIONS

See section 10 for a detailed discussion of special terms pertaining to this RP. See IEST-RD-DTE046 for a glossary of terms.

actuator
Another word for shaker.

exciter
Another word for shaker.

multiple-exciter testing (MET)
The use of more than one actuator or to create complex vibration motion that is not possible with single-exciter testing.

multiple-input/multiple-output (MIMO)
More than one actuator attached to a single unit under test (UUT), with multiple feedback control transducers and one or more control vibration spectra.

> **multiple-exciter/multiple-axis (MEMA)**
> The more general case of MIMO control that uses multiple exciters to create a controlled environment of two or three axes.
>
> **multiple-exciter/single-axis (MESA)**
> A form of MIMO control in which all exciters are aligned to provide force in a single direction. The control system is then, typically, set to control "platform" motion, with all control points moving in phase or inverted phase.

multiple-input/single-output (MISO)
A single actuator attached to a single UUT, with multiple feedback control transducers and one control vibration spectrum.

single input/multiple output (SIMO)
Typical single-shaker system with multiple control transducers for average or peak limit control. In addition, a single transducer may be used, sometimes called a single-input single-output (SISO) system.

shaker
A device that creates the motion that shakes payloads.

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4 BASIC REQUIREMENTS

Before testing can be approached, some basic requirements should be defined. Often these requirements originate with the owner of the test article, who knows the environment in which the test article will be used. In many cases, however, the owner of the test article requires assistance in defining a suitable test. The following list of parameters should be used during the initial stages of developing and tailoring a MIMO test.

Frequency range is usually known by the owner of the test article and may be specified in a testing standards document.

Number of degrees of freedom (DOF) dictates which translations or rotations will be active and is usually based on anticipated service life. In addition, the field data used to define the test should be able to support the number of DOF.

Number of shakers is usually determined from the number of DOF and from the size and weight of the test article.

UUT attachment method is dependent on the number of shakers and the size and weight of the test article. The selection of flexible attachments or rigid attachments will greatly affect the resulting MIMO test. Generally, attachment mechanisms should be kept as simple as possible.

Number of transducers is determined by the number of DOF to be measured. In addition, the placement of transducers is critical for measuring the DOF.

Control strategy refers to the ratio of transducers to exciters. Many MIMO tests begin with the same number of control transducers as exciters, which is referred to as "square control." As the test progresses, rectangular or input/output (I/O) transformation control may be required to create a successful MIMO test.

Response control vs. input control should be determined. For example, munitions tests typically are controlled by the response of the test article because field data is available from a measurement during actual use. The control transducers are usually mounted at the data measurement location. Earthquake tests are controlled by field data from seismic measurements on the ground and these tests determine how a structure reacts to a known earthquake pulse. The control transducers are usually mounted at the base of the structure.

Response limiting, sometimes called drive limiting, is a technique to cause the drive signal to be low in a selected frequency range in order to protect cantilevered locations from receiving too much energy at the natural frequency of the cantilever.

Special fixturing may be required to attach unusually awkward or heavy test articles to the shakers.

5 BACKGROUND AND OVERVIEW

5.1 Background

5.1.1 Working with MIL-STD-810G and beyond

The publication of MIL-STD-810G has placed additional emphasis on the need for multi-exciter testing, and for this RP, with the introduction of two new Test Methods. Method 525, "Time Waveform Replication," and Method 527, "Multi-Exciter Testing," for the first time legitimize the use of multiple exciters when conducting vibration tests in accordance with MIL-STD guidelines. It is suggested that this RP be used in conjunction with Method 527 to expand upon the fundamentals described therein.

5.1.2 Application of multi-shaker technology

There are many cases where more than one exciter may be required, such as the following:

- Design and qualification testing of long, slender objects such as missiles, where force application at one point may not create the desired motion at several points, may damage the test article, or both.
- Testing of structures shaped such that the use of a single exciter would require the design and fabrication of a very expensive fixture that may be used only once.
- Testing of large structures that require more input force than would be available from a single shaker.

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- Multi-axis tests that require simultaneous inputs in several directions to meet the test criteria, such as automotive or earthquake simulations.
- Faithful reproduction of an in-service environment that includes multiple axes during simultaneous excitation.
- The requirement to introduce controlled rotational as well as translational motion into the UUT.
- Reducing test time to achieve equivalent simulation effects.
- Providing a compensating actuation force to counteract large overturning moments, which may occur during horizontal testing of tall structures, such as satellites, where the center of gravity may be many meters above the surface of the attachment plate.

5.1.3 Limitations of multi-shaker technology

Whereas it is typically possible to run a single exciter test by performing judicious setup and transducer placement modifications, it may not always be possible to run a multi-shaker test, for various reasons, many of which may not be immediately obvious.

If the test uses actual field measurements that are to be replicated in the laboratory using multiple exciters, extra care should be taken to record good phase information in addition to magnitudes such as power spectral density (PSD). It is also important to duplicate as closely as possible the mechanical impedance and boundary conditions of the test item in its service environment, in the laboratory during the test.

A multi-shaker random test designed from scratch requires only the complete definition of the PSD at each of the control points plus the desired phases and coherences between pairs of control points. The PSDs represent the major diagonal of the spectral density matrix (SDM). The control system will then, typically, fill in the off-diagonal terms, representing the cross spectral densities. However, if a multi-shaker test is to be performed by replicating field data, then the entire SDM, including the complete upper off-diagonal terms, should be fully entered. If the test calls for a physically impossible phase condition, which may result in a not-positive-definite condition of the reference SDM, the test may not be able to start unless parameter changes are made. Guidance for this situation is provided in MIL-STD-810G, Method 527 CN1, Annex E, paragraph 5.1.1.

Whereas single-exciter tests typically are problematic at the resonant frequencies of the UUT, MIMO tests tend to have the biggest challenges at the anti-resonant frequencies of the entire system of UUT, fixtures, shakers, and bearings. Since the SDM must be inverted to form the *impedance matrix* (see section 10), anti-resonances in the SDM can form uncontrollable singularities in the impedance matrix if these anti-resonances are not handled with special care by the control system.

It is never recommended that a coherence of 1 be specified when designing a MIMO test. A coherence of 1 can create a situation where the drive SDM becomes singular, effectively reducing the drive DOF to 1, and the test cannot be performed. Maximum values of coherence up to 0.98 are suggested to successfully complete a MIMO random test.

Since a multiple-exciter test (MET) is intended to impart multi-axis motion to the UUT with or without field data, a minimum amount of fixturing should be added to adapt the UUT to the multiple-exciter environment. Not only does this practice prevent the addition of unnecessary weight, but it may also help prevent the addition of unwanted and unnecessary structural resonances. For example, experience has shown that the use of head expanders, often required in the performance of a multiple-input/single-output (MISO) (i.e., single-shaker) test, should be avoided if at all possible in MIMO testing. Minimizing the required fixturing and fixture mass during a MIMO test should always be a high priority goal.

5.2 Overview

When planning a multi-shaker or MIMO test, a basic decision must be made early in the process. The objective is to simulate complex, controllable motion with multiple exciters and possibly in multiple axes simultaneously. Will the test be based on a specification of magnitudes, phases, and coherences; on measured field vibration data; or on a combination of those two specifications? The answer to this question will determine the complexity of the test, what kind of data will be required, and how much, if any, off-line processing of field data will be necessary.

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As described in section 5.3, a multiple-shaker test setup may involve a complex UUT, some fixturing, bearings to permit the desired motion and protect the shakers, the exciters, power amplifiers, transducers, and cables. This combination is best defined in a matrix formulation, relating inputs and outputs as an SDM. If measured field vibration data will be used, it is critical to have good phase and coherence measurements in addition to measured PSD values (see Appendix B: Underwood, Ayres, and Keller, 2009).

Consider, for example, a test of an aircraft missile that is secured under a wing by two attachment points. Field measurements may include magnitude, phase, and coherence values between two points measured near the missile attachment points. If the exciters are to be attached directly to the missile attachment points, most of the required information may be available. However, if the laboratory simulation is to take place with shakers attached to the aircraft fuselage or wheel carriages, information about the frequency response functions between fuselage excitation points and missile control points will also be necessary. The available data must be sufficient to fill in the entire system matrix to achieve successful simulation using field data.

5.3 Theory

Many multi-shaker vibration tests are performed on the basis of having one control accelerometer per shaker. This setup is termed "square control" and assumes N control points for N shakers. Additional channels may also be available for response measurements and limit control of amplitudes without affecting phase parameters. Controlling multiple shakers simultaneously requires an understanding that the drive signal to any one shaker will have an effect on all control points, not just the point nearest the shaker being driven. Thus, the solution of a multi-shaker control problem is best defined in matrix terms, involving all drive and control signals simultaneously.

Figure 1 shows a block concept of a typical four-shaker excitation and control system.

In a controlled test environment, the drive signals will come from the multi-shaker digital vibration control system (MSDVCS) and the control signals (shown in Figure 1 as response vectors) will be fed back to the MSDVCS. The relationship between these signals, described as a complete system matrix, is shown in Figure 2.

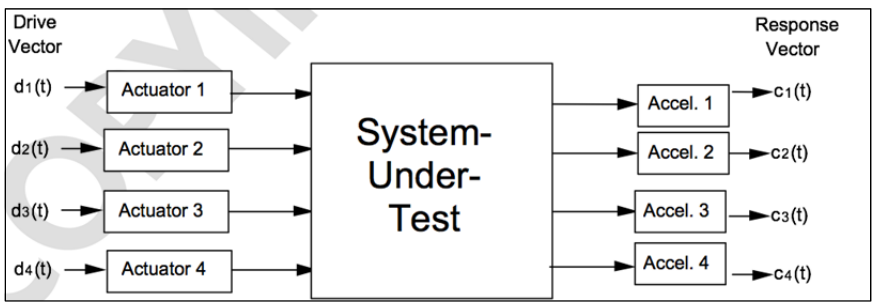

Figure 1—Block concept of four-actuator (shaker) test system.

$$\begin{Bmatrix} c_1(f) \\ c_2(f) \\ c_3(f) \\ c_4(f) \end{Bmatrix} - \begin{bmatrix} h_{11}(f) & h_{12}(f) & h_{13}(f) & h_{14}(f) \\ h_{21}(f) & h_{22}(f) & h_{23}(f) & h_{24}(f) \\ h_{31}(f) & h_{32}(f) & h_{33}(f) & h_{34}(f) \\ h_{41}(f) & h_{42}(f) & h_{43}(f) & h_{44}(f) \end{bmatrix} \begin{Bmatrix} d_1(f) \\ d_2(f) \\ d_3(f) \\ d_4(f) \end{Bmatrix}$$

Figure 2—Matrix formulation of system inputs and outputs.

In Figure 2, the control signals, $c_i(f)$, and the drive signals, $d_i(f)$, are related by the set of complex frequency response functions, $h_{ij}(f)$. Equation 1 puts this into a more compact notation.

$$\{C(f)\} = [H(f)]\{D(f)\} \tag{1}$$

This says that the frequency response function multiplied by the drive gives the control value. However, at the start of a test, having measured the system's frequency response function matrix, the control system must calculate the set of "first drive" signals. This requires the calculation of the inverse of the $H(f)$ matrix as seen in equation 2.

$$[Z(f)] = [H(f)]^{-1} \tag{2}$$

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If some of the anti-resonances measured in the $H(f)$ matrix have very low values, the inversion of this matrix may produce uncontrollable singularities while using the impedance (or system sensitivity) matrix, $Z(f)$, to calculate the system drives.

$$\{D_0(f)\} = [Z(f)]\{R(f)\} \tag{3}$$

where $\{R(f)\}$ is the reference vector. (Note that a different formulation is required for MIMO random.)

In such cases, special care should be taken when inverting the frequency response function matrix and calculating system drive signals as shown in equations 2 and 3. One characteristic of a MIMO control system must be that it is stable under all test conditions.

For the case of MIMO random, equations 1 and 3 take the form shown in equations 1a and 3a.

$$[G_{cc}(f)] = [H(f)][G_{dd}(f)][H(f)]^* \tag{1a}$$

where $[G_{cc}(f)]$ and $[G_{dd}(f)]$ are, respectively, the control-response and drive SDM, $[H(f)]$ is the frequency response matrix (FRM) of the system under test, and $[H(f)]^*$ is its conjugate-transpose.

$$[G_{dd}(f)] = [Z(f)][G_{rr}(f)][Z(f)]^* \tag{3a}$$

where $[G_{dd}(f)]$ and $[G_{rr}(f)]$ are, respectively, the initial drive and reference SDM, $[Z(f)]$ is the inverse FRM of the system under test, and $[Z(f)]^*$ is its conjugate-transpose.

5.4 Testing in multiple axes

Six unique displacement vectors define the location and orientation in space of an object. “Unique” means there are no redundant displacement vectors. Each displacement vector can be viewed kinematically as a link arm with a swivel joint on each end, a single degree of constraint.

An example of a redundant load path would be the placement of more than two parallel links on the same line.

All rigid-body motions are defined by 6 DOF. Cartesian coordinates are expressed in terms of three translations and three rotations about the X,Y, and Z axes. In fact the body motions need not be orthogonally oriented and may be described by a unique set of six vector coordinates, Si (Figure 3).

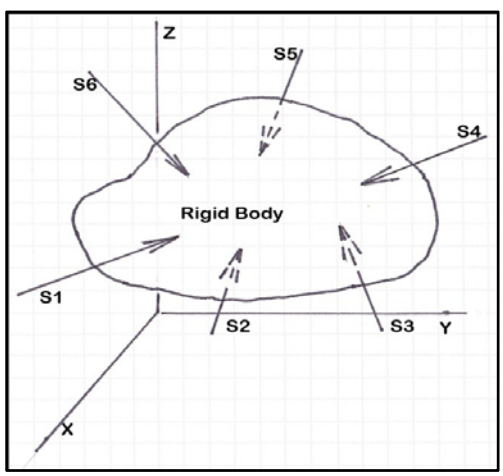

Figure 3—Unique set of six vectors describing rigid-body motion.

Consider the replacement of a rigid link with a hydraulic actuator, a “hydrashaker.” The actuator can replace one or all of the links. For each actuator installed, the degrees of motion are increased from 0 to 6 or some number in between.

Replacing just one link with a hydrashaker enables motion in 1 DOF. The motion, a combination of translations and rotations, is determined by the geometry of the five fixed links and the motion link.

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