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Optimization of Shaker Locations for Multiple Shaker Environmental Testing

Randy Mayes
Structural Dynamics Department
Sandia National Laboratories*
P.O. Box 5800 - MS0557
Albuquerque, NM, 87185
rlmayes@sandia.gov

Luke Ankers, Phil Daborn, Tony Moulder, Philip Ind
Structural Dynamics Team, AWE Plc
Luke.Ankers@awe.co.uk, Philip.Daborn@awe.co.uk, Tony.Moulder@awe.co.uk, Philip.Ind@awe.co.uk

1) Abstract

It has been shown previously that multiple controlled shaker inputs on a test body with approximated boundary conditions can reproduce a field environment for a test article. The resulting test more closely replicates the true field environment than a single degree of freedom shaker vibration test. This method was named the Impedance-Matched Multi-Axis Test (IMMAT). Since the development of IMMAT, there has been a need for a test planning tool to optimize shaker locations. Often the field environments are at high amplitudes so that achieving a controlled multi-shaker ground test is difficult. This is because of physical limitations such as maximum available amplifier current, voltage, power and shaker force or stroke. Exceeding any of these can cause the IMMAT test to fail to reproduce the field environment. The key found here is the characterization of the shaker/amplifier system attached to the test structure. If a model of the shaker/amplifier system is available, then multiple shaker models can be coupled to a modal model of the test article with classic substructuring approaches. Here we characterize the shaker/amplifier pair and calibrate an appropriate model. Then the shaker/amplifier model is coupled to a test article and validated with the corresponding single shaker test frequency response functions. Finally, an optimization tool is used to find a set of shaker locations meeting all requirements. The corresponding IMMAT ground test is performed to attempt to replicate accelerations from a field acoustic environment. The optimization was focused on minimizing required amplifier output voltage, but one can minimize any quantity of interest, such as required shaker force, current, or control error.

Keywords – Ground Test Simulation, Impedance Matching, Multi-Axis Testing, Multi-Shaker Control, Vibration Control

2) Motivation and Approach

The Impedance-Matched Multi-Axis Test [1] has been shown to provide much higher quality random vibration simulations than the traditional attachment to a single degree of freedom (dof) shaker. One class of problem is the free flight of a test structure in which aerodynamic forces produce random vibration. Here we propose a new approach to optimize a multi-shaker IMMAT ground test to reproduce the random environment of a system test. Although the IMMAT technique has been used with some success [1,2], there is significant uncertainty in how to set up the test to ensure its success. Some questions are: 1. Do my shakers and amplifiers have the capability to generate the required forces, displacements, voltage and current? 2. How many shakers are required? 3. Where do I attach the shakers to the test article? 4. What will be the error in the control? Here we propose to model the IMMAT testing process by coupling substructure models of the shaker/amplifier system to a

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modal model (derived from a finite element model) of a test structure. The process is utilized to design and execute an IMMAT test of a test structure to reproduce experimental target acceleration spectral densities (ASDs) of the test structure in an acoustic environment. The research test structure is the Modal Analysis Test Vehicle (MATV) developed at the Atomic Weapons Establishment. This structure had 14 internal accelerometers chosen as control accelerometers. It was excited to 147 dB by an acoustic horn in a reverberant chamber at the Institute of Sound and Vibration Research Consulting facility at the University of Southampton. The responses of the 14 accelerometers were the target spectra for the IMMAT test. A four dof electro-mechanical model was developed for a shaker/amplifier and calibrated with test data. Since there was a finite element model of the MATV, it could be combined through substructuring with any combination of shaker/amplifiers attached to chosen dof. Optimization could be applied to minimize a function of required responses (e.g. amplifier output current, voltage, shaker force, control error).

3) MATV Hardware, Shaker/Amplifier Hardware and Models

A cutaway of the MATV finite element model, a picture of the MATV suspended in the acoustic chamber and the final IMMAT test setup are shown in Figure 1. The MATV hardware is about a meter long and weighs about 47 kg. It has an external composite conical shell, aluminum large end cover plate, aluminum internal flat component plate, a steel pipe bolted to the internal flat component plate (representing a large internal component) and a bracket called the removable component (RC) bolted to the internal flat component plate (representing a small component). The finite element (FE) model was updated to match (within five percent) all the natural frequencies of a burst random modal test up to 1100 Hz. The shaker/amplifier pairs were Data Physics LE-LS70 315 N force modal shakers with BEAK BAA 1000 V2 amplifiers capable of 1200 VA output. A shaker/amplifier modeling scheme from Lang and Snyder [3] was modified to provide a four dof model. Three dof were associated with displacement of the force gage, armature and shaker body, and one dof was associated with the current in the Kirchoff voltage loop of the amplifier and shaker. The parameters of this model were taken from shaker specifications or calibrated from free and blocked force tests of the shaker/amplifier. A minor update to the 4 dof model was obtained from a single shaker test of the MATV.

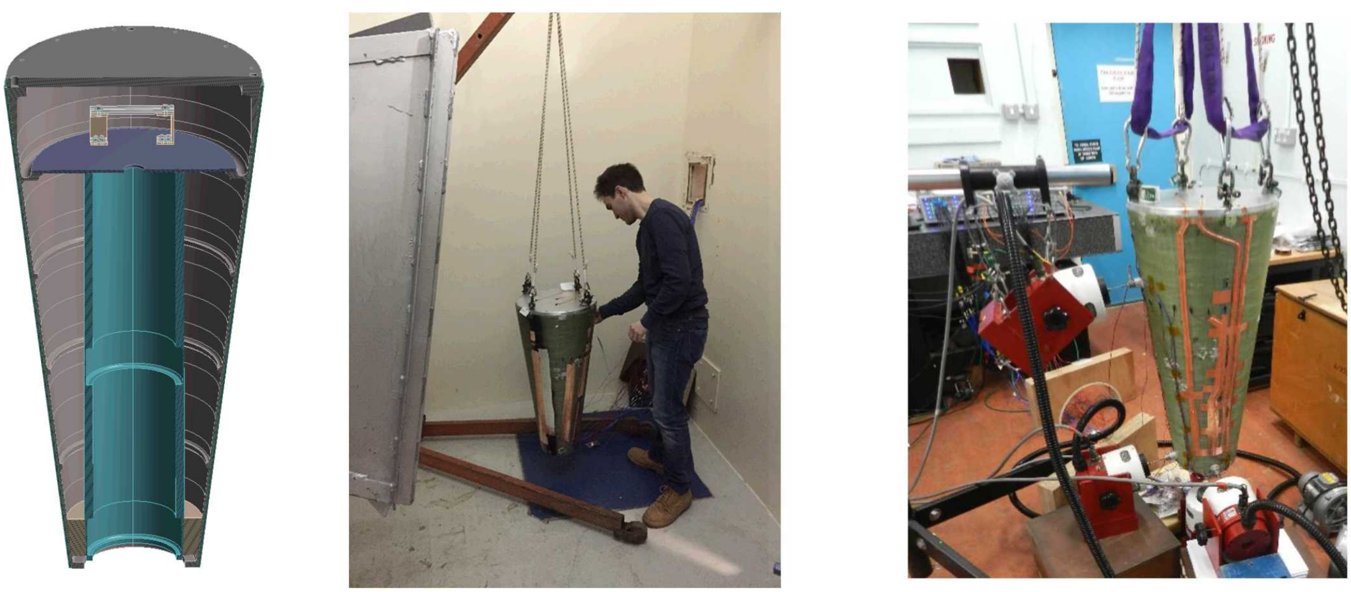

Figure 1 – MATV FE Model Cutaway (Left), Acoustic Test Setup (Center), IMMAT Test Setup (Right)

4) Optimization

14 accelerometer channels recorded in the acoustic test provided the target ASDs against which the IMMAT responses could be compared. The center picture of Figure 1 shows the acoustic test setup. The target accelerometers were at component

locations of interest on the large end cone wall, flat component plate and RC. The relation to derive the amplifier output voltage required is

$$\ddot{S}_{xx}(\omega) = H_{xE}(\omega) S_{EE}(\omega) H_{xE}^{*}(\omega) \tag{1}$$

where $\ddot{S}_{xx}$ is the 14 x 14 ASD matrix that was derived from the acoustic test, H_{xE} is the acceleration to voltage frequency response function matrix, * superscript indicates the conjugate transpose, S_{EE} is the amplifier voltage cross spectral density matrix (that needs to be calculated) and (ω) indicates that each matrix is a function of the frequency line. H_{xE} for a specific shaker setup is obtained by substructuring the 4 dof shaker amplifier models with the MATV modal model by constraining the shaker force gage dof to the appropriate MATV attachment dof.

Thirty-four possible shaker locations were considered for the optimization. There were a couple of axial locations considered on each end and five axial stations along the cone with six circumferential angles at each station. Attachment was normal to the cone surface. Optimization was focused to minimize required amplifier output voltage associated with S_{EE} in eqn (1). All 34 shaker positions were run through eqn (1) and the one with the lowest rms output voltage was chosen as the first shaker. In the second pass, the remaining 33 shakers were each paired with the first shaker, and the shaker which provided the minimum sum of the two rms output voltages was chosen as shaker two. This continued until four shakers had been chosen, which appeared to be able to physically accomplish the test and achieve reasonable dB control error. Resulting force and amplifier current were also checked. The right-hand photo of Figure 1 shows the testing configuration.

4) Results

The $\ddot{S}_{xx}$ matrix was input to the Siemens LMS multi-input multi-output shaker control software as the control target. Controlled random vibration tests were initially run at -3dB and then 0dB levels. Finally, a run was made at +3dB for which results are shown in Figure 2. The leftmost figure shows the comparison based on the sum of all 14 ASDs out to 2000 Hz, with the blue being the acoustic test target and red being the achieved response in the IMMAT test. The center figure is the best control achieved, and the right figure is the worst control achieved on one individual accelerometer. It shows that the four shakers could not quite simulate the low frequency rigid body motion. The model slightly over-predicted the required amplifier output voltage for three of the shakers. It over-predicted the required output voltage for the upper shaker shown in Figure 2 by a factor of two. On further investigation, this was because of modal truncation, because the modal model only had modes out to about 2000 Hz. Modes beyond 2000 Hz had residual effects that were significant.

5) Conclusions

The simple sub-optimal approach applied to the substructured MATV modal and shaker/amplifier models provided excellent guidance for the number and location of shakers to achieve the target response. Amplifier voltage estimates from the model were slightly conservative for three shakers, since the FE model was not a perfect estimate for the real system. The fourth shaker voltage estimate was very conservative due to modal truncation of the modal model. The lesson learned is to include enough modes beyond the bandwidth to address the residual effects of out-of-band modes. The key to this approach is having a calibrated electro-mechanical model of the shaker/amplifier system and test article.

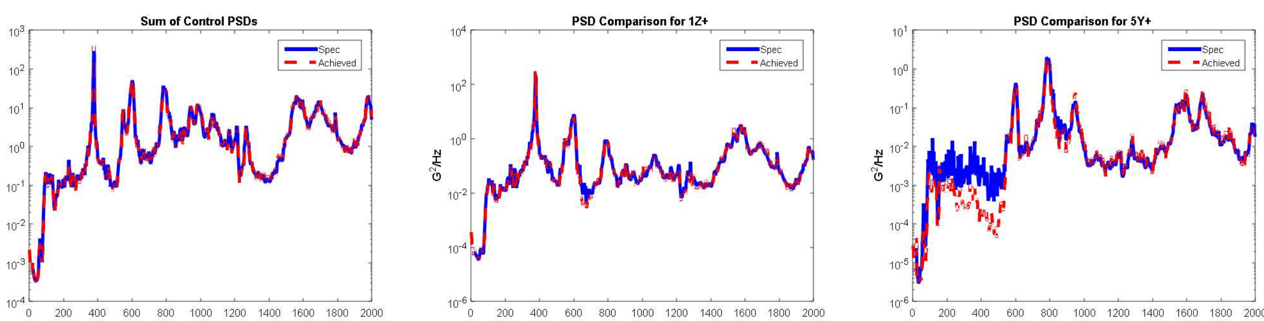

Figure 2 – IMMAT (red) and Target (blue) ASDs – Sum of 14 ASDs (left), Best Control ASD (center), Worst Control ASD (Right)

5) References

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