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Predicting System Response at Unmeasured Locations using a Laboratory Pre-Test

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1) Abstract

One can estimate unmeasured acceleration spectral density responses of a structure utilizing measured responses from a relatively small number of accelerometers and the active mode shapes provided from a finite element model. The objective in this paper is to demonstrate a similar concept, but purely based on information from a laboratory pre-test. Response predictions can only be calculated at degrees of freedom that have been instrumented in the experimental pre-test, but greater accuracy may be possible than with a finite element-based expansion. A multi-reference set of frequency response functions is gathered in the laboratory pre-test of the field hardware. Two response instrumentation sets are included in the pre-test. One set corresponds to the measurements that will be taken in the field environment. The second set is the field responses that are of great interest but will not be measured in the field environment due to logistical constraints. For example, the second set would provide definition of the component field environment. A set of basis vectors is extracted from the pre-test experimental data in each of multiple frequency bands. Then the field environment is applied to the hardware and the data gathered from the field accelerometers. The basis vectors are then used to expand the response from the field accelerations to the other locations of interest. The proof of concept is provided with an acoustic test environment on the Modal Analysis Test Vehicle. Predicted acceleration spectral density simulations at 14 degrees of freedom (known as "truth responses") are compared against truth acceleration measurements collected for this work from the acoustic environment. Due to the segregated bandwidth analysis, the required number of field accelerometers to provide the simulation is much smaller than the number of modes in the entire frequency bandwidth.

Keywords – Flight Environments, Flight Accelerations, Expansion of Field Response

2) Motivation and Approach

The dynamic qualification of components requires a specification for testing the component. Often the specification is an acceleration spectral density that has undergone an "enveloping" and sanitization process such that the resulting flat profiled curve is not representative of the dynamics measured on the component in the system environment. The acceleration measurements from the system environment are often made at different locations than the component connection point, resulting in a great deal of uncertainty. The specification is generally considered conservative, without understanding how conservative, or if it is truly conservative. Examples have been shown when traditional specified single degree of freedom acceleration spectral densities were not conservative compared to the multi-degree of freedom field component response[1,2]. Generating a complete dynamic description of a component specification for a certain system environment is logistically unfeasible with traditional methods. In many systems, the required number of sensors cannot be mounted at the location connecting the component to the system for specification of base input. Often there are no sensors mounted on the component or subsystem in traditional field tests. This generates the motivation. Is there a way to obtain a good estimate of the component motion and, thus, to remove the uncertainty that traditionally exists in the system environment for that component motion? A finite element-based method was presented previously [3]. This work demonstrates proof of concept

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of an experiment-based approach to estimate the true acceleration spectral densities at enough component locations of interest to establish the component's environment in the system.

The approach is somewhat analogous to the SEREP method [4] by O'Callahan et al. Consider the approximation of acceleration motion as

$$\begin{Bmatrix} \ddot{\mathbf{x}}_m \\ \ddot{\mathbf{x}}_u \end{Bmatrix} \approx \begin{bmatrix} \mathbf{U}_m \\ \mathbf{U}_u \end{bmatrix} \{\ddot{\mathbf{p}}\} \tag{1}$$

where $\boldsymbol{x}$ is the vector of physical response, $\mathbf{U}$ is a shape matrix of orthogonal basis vectors derived from an experimental laboratory pre-test for a certain frequency band and $\boldsymbol{p}$ is the vector of generalized DoF responses for these basis vectors. Subscript m is for measured accelerations during a system test. Subscript u is for unmeasured system test accelerations at locations where we wish to produce an estimated acceleration spectral density for use in specifications. The **U** vectors are determined from a laboratory pre-test. Only the subscript m accelerations are recorded in the typical field test. If eqn (1) holds, the upper partition can be used with measured accelerations from the system environment to estimate **p** with a spatial filter as

$$\{\ddot{\mathbf{p}}\} = \mathbf{U}_m^{+}\{\ddot{\mathbf{x}}_m\} \tag{2}$$

where the superscript + represents the pseudo-inverse. The pseudo-inverse mitigates some experimental error when there are more accelerometers than generalized dof. A well-conditioned $\mathbf{U}_m$ matrix provides more accurate results, which comes from proper placement of the measurement accelerometers. Once **p** has been extracted from the system environment, the unmeasured dof characterized in the laboratory pre-test, can be estimated using the lower partition of eqn (1).

This experiment-based approach was implemented using research hardware known as the Modal Analysis Test Vehicle (MATV) developed at the Atomic Weapons Establishment (AWE). 67 accelerometers were mounted at various locations in MATV. Some of the accelerometers were used as measurement dof, and others were placed at locations of interest and were dubbed the truth accelerometers. The truth accelerometers correspond to the unmeasured u accelerations in eqn (1). The proof of concept attempts to simulate the truth measurements, in the form of acceleration spectral densities, for u dof using the laboratory measured **U** vectors and **p** derived from the measured m accelerations. The system environment was provided for MATV by suspending it from bungee cords in an acoustic chamber and exciting it with a random pressure loading from an acoustic horn. The Institute of Sound and Vibration Research (ISVR) at University of Southampton provided the environment and facility.

The experimental approach described here was an afterthought to a previous work [3]. A multi-shaker modal test had been performed by AWE on the MATV for finite element modal validation. After the finite element-based approach was tried, the authors posed the question, could basis vectors be extracted from the frequency response functions gathered for the modal test for use in predicting responses as described in eqns. (1,2). This extended abstract provides the overview of the work.

3) MATV Hardware, Instrumentation and Testing

A cutaway of the MATV solid model as well as a picture of the MATV suspended in the acoustic chamber are given in Figure 1. The MATV hardware is about a meter long and weighs about 47 kg. It has an external composite conical shell mounted on an aluminum substrate, 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). 67 accelerometer channels were available for instrumenting MATV. These were used in a laboratory pre-test, and the same accelerometers were also recorded in the system level acoustic test to provide the random vibration environment of interest. For the acoustic test, there were 14 channels selected as u dof as described in eqn (1). These were the "truth" accelerometers that would normally be unmeasured, u DoF, in a system environment. Here they were measured to provide acceleration spectral densities against which the predicted responses could be compared. Nine u channels came from three triaxial accelerometers mounted at potential locations for a component, one on the cone wall near the large end, and two at locations on the flat component mounting plate. In addition, 4 channels on the RC cross beam were "truth" accelerometer (u) dof. This left 53 candidate accelerometer channels for possible measurement (m) dof. None of the measurement dof were a repeat of any of the unmeasured dof. Based on engineering judgment the m dof were at various locations on the cone, pipe, component plate, cover plate and RC.

A multiple input multiple output (MIMO) shaker modal test with three shakers operating simultaneously was conducted to 2000 Hz using burst random excitation. The shaker arrangement for the test is shown in Figure 2.

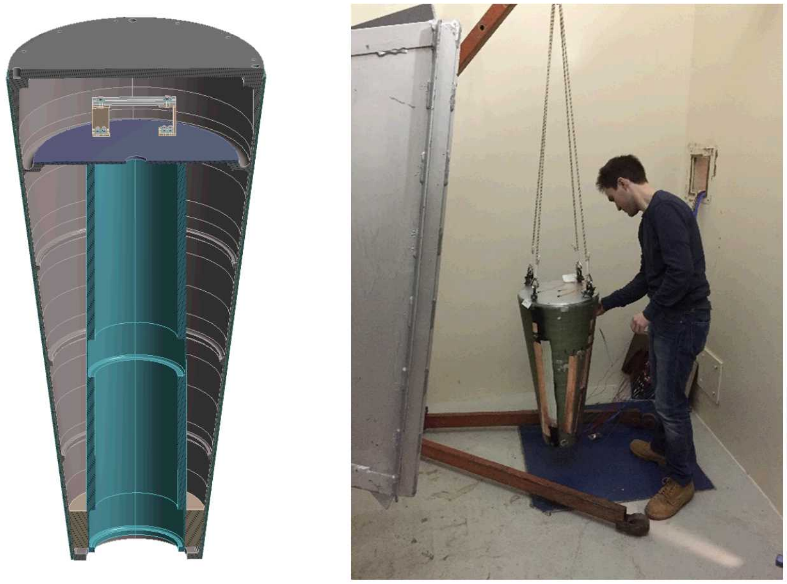

Figure 1 – MATV Solid Model Cutaway (Left) and Acoustic Test Setup (Right)

Figure 2 – MATV Modal Test Setup for Pre-Test

4) Predictions of Acoustic Test Truth Responses

The 2000 Hz frequency bandwidth was divided into 10 equal bands. Each band was analyzed separately. The real part of the FRF matrix and the imaginary part of the FRF matrix from the three reference shakers were stacked side by side. A singular value decomposition of these real numbers was calculated, and the first fifteen orthonormal shape vectors were saved as the **U** vectors for each band. Before the estimation process, an algorithm was developed to choose accelerometers to minimize the sum of the condition number for the ten $\mathbf{U}_m$ matrices. This algorithm reduced the number of m accelerometers to 30 from the initial available 53. Eqns (1) and (2) were manipulated to calculate cross spectra in the frequency domain. Figure 3 shows the comparison of the estimated response (red) and the measured acceleration spectral densities (blue) for the 14 "truth" gages.

5) Conclusions

From previous model validation work [3] it was known that there are at least 70 modes in the 2000 Hz bandwidth. By dividing into bands and using 15 shapes per band, a reasonable estimate of the 14 so called "unmeasured" acoustic test responses was obtained using an optimized set of 30 field measurement gages. Since this approach was an afterthought to the previous work, it is likely that the pre-test could have provided even better basis vectors by attaching more shakers to ensure exciting all possible modes. The advantage of this approach over the finite element approach is that there is great confidence in establishing the basis vectors applicable in each band by the singular value decomposition of the FRF matrix of the as-built system. The disadvantage of the experimental-based approach is that only responses instrumented in the pre-test may be predicted, as opposed to the finite element approach, which can at least attempt to predict unmeasured response at any DoF of the finite element model.

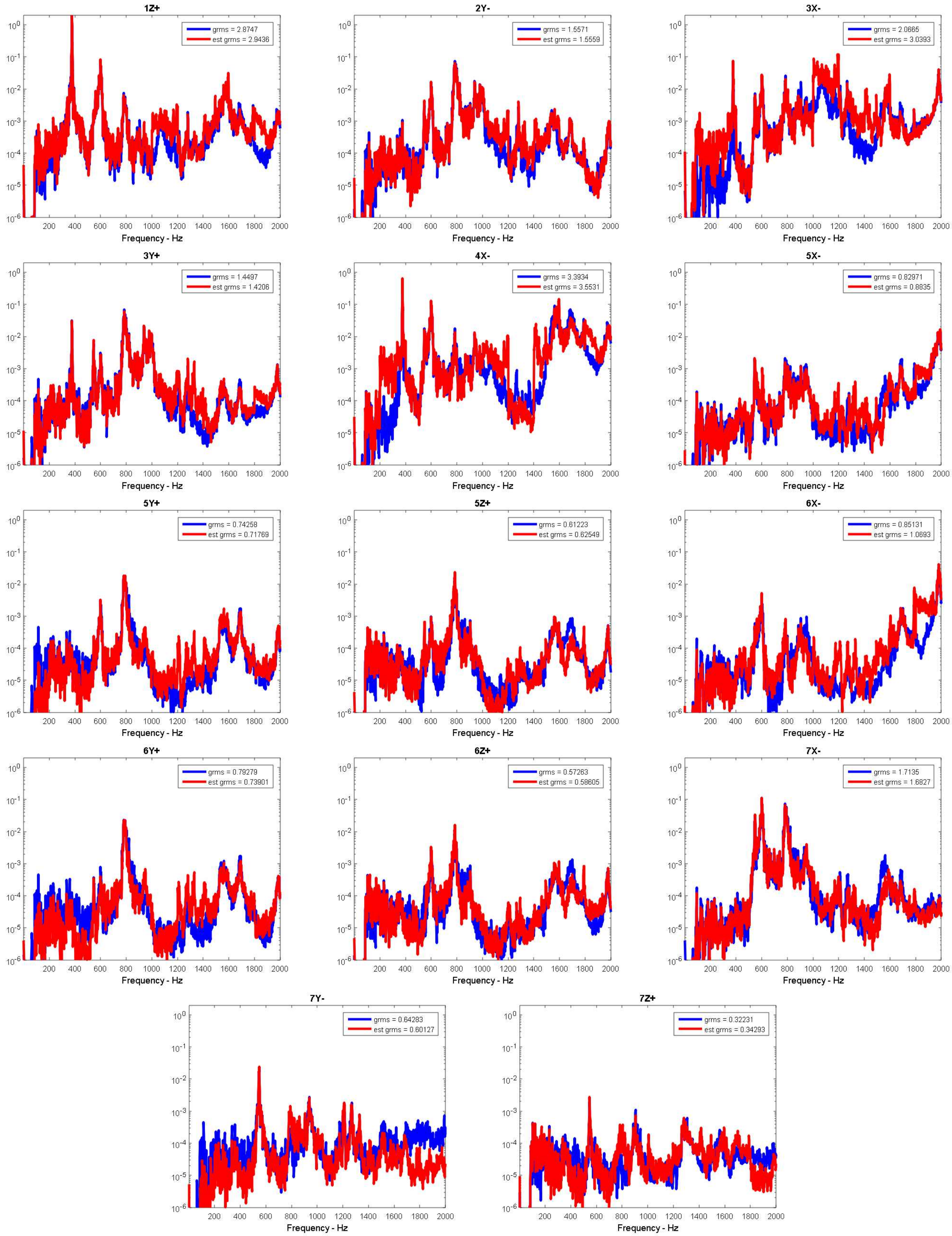

Figure 3 – Estimated (red) and Measured (blue) "Truth" Acceleration Spectral Densities

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