SAND2018-12060C

Predicting System Response at Unmeasured Locations

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

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

1) Abstract

It is known that component tests in a single axis cannot simulate the field environment of the component in the system. Even if the control matches one measured accelerometer response perfectly there are substantial errors for several reasons. One is that the component connection response has at least three translations and three rotations which must be simulated for correct response. Typically, this minimum set is never measured or simulated. Here we demonstrate a method of measuring the system environment responses with a relatively small set of accelerometers. Responses at unmeasured component degrees of freedom can then be estimated. The approach extracts generalized modal degree of freedom response using the measurement accelerometers and a validated finite element model. The finite element model is used to extend the modal responses to unmeasured degrees of freedom. A test article known as the Modal Analysis Test Vehicle (MATV) was excited by acoustic testing to provide the field environment. The described method was used to simulate responses at 14 degrees of freedom (known as "truth responses") which were not used to extract the modal response. The simulated acceleration spectral densities are compared against the truth acceleration measurements of the acoustic environment. One method to minimize the required number of measurement accelerometers is given. In this case the method provided reasonable results using significantly fewer accelerometers than modes in the bandwidth.

Keywords – Flight Environments, Flight Accelerations, Modal Accelerations, Modal Filter

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 that measured on the system at the component connection point. The acceleration measurements from the system environment are often made at different locations than the component connection point, so are nominally wrong at the outset. In addition, the connection response has three translations and three rotations, some of which are completely ignored. Thus, the specification has a great deal of uncertainty. The specification is generally considered conservative, but no one knows how conservative, or if it is truly conservative. Several examples have been shown for certain specified acceleration spectral densities that were not conservative for all frequencies of interest. We recognize that it is unfeasible to measure every degree of freedom of response that is needed to generate a complete description of a specification for a certain system environment. In many systems, an accelerometer could not be mounted at

* Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

the connection points of the component to a system, and in most systems, there may not be the capability to record all the required connection degrees of freedom even if one could mount all the translation and rotation sensors that were desired. This generates the motivation. Is there a way to obtain a good estimate of the translation and rotation acceleration spectral densities from a system test without a measurement at those critical degrees of freedom? Then one could add some conservatism to the measured specification, and know how much conservatism had been added. This work demonstrates proof of concept of a proposed approach to estimate the true acceleration spectral densities at locations of interest by measuring generalized modal responses of a system environment.

The approach was described as the SEREP method [1] by O'Callahan et al., based on the modal substitution, that is

$$\begin{Bmatrix} \ddot{\boldsymbol{x}}_m \\ \ddot{\boldsymbol{x}}_u \end{Bmatrix} \approx \begin{bmatrix} \boldsymbol{\Phi}_m \\ \boldsymbol{\Phi}_u \end{bmatrix} \{\ddot{\boldsymbol{q}}\} \tag{1}$$

where $\boldsymbol{x}$ is the vector of physical response, $\boldsymbol{\Phi}$ is a truncated mode shape matrix from an analytical model for a certain frequency band and $\boldsymbol{q}$ is the generalized modal degree of freedom response from the model. Subscript m is for measured accelerations during a system test. Subscript u is for unmeasured accelerations at locations where we wish to produce an estimated acceleration spectral density for use in specifications (either translation or rotation). If eqn (1) holds, the upper partition can be used with measured accelerations from a system environment to estimate $\boldsymbol{q}$ with a modal filter as

$$\{\ddot{\boldsymbol{q}}\} = \boldsymbol{\Phi}_m^{+}\{\ddot{\boldsymbol{x}}_m\} \tag{2}$$

where the superscript + represents the pseudo-inverse. This requires more accelerometers than modal dof and proper placement of the translation measurement accelerometers. Once $\boldsymbol{q}$ has been extracted from the environment, the unmeasured dof, including rotations, can be estimated using the lower partition of eqn (1). This is the basic theory for obtaining estimates of acceleration responses that are not actually measured in an environment. This approach was implemented using research hardware known as the Modal Analysis Test Vehicle (MATV) developed at the Atomic Weapons Establishment. Several accelerometers were mounted in 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 was to attempt to simulate the truth measurements, in the form of acceleration spectral densities, for u dof using the FE model and $\boldsymbol{q}$ 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) Consulting at University of Southampton provided the environment and facility.

3) MATV Hardware, Instrumentation and Testing

A cutaway of the MATV finite element 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). Sixty-nine accelerometer channels were available for instrumenting MATV. These were used in a modal test for model updating, 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 dedicated to 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. Three triaxial accelerometers were 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, 5 channels on the RC cross beam were "truth" accelerometer (u) dof. This left 54 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 to uniquely identify the finite element mode shapes up to 2000 Hz, the m dof were at various locations on the cone, pipe, component plate, cover plate and RC.

4) Finite Element Model Calibration and Modal Test

The finite element model had over 70 modes that were considered in the frequency bandwidth of 2000 Hz. A shaker modal test with three shakers operating simultaneously was conducted using burst random excitation. The first axial mode, two bending modes and the first torsion mode were used to adjust the FE model parameters to improve frequency correlation to within five percent. The focus was on the first axial, torsion and bending modes of MATV and 3 RC component modes. All ovaling modes of the shell were within five percent with the initial model, so they were not adjusted. Modes above 1100 Hz were not used in adjustment due to project time constraints.

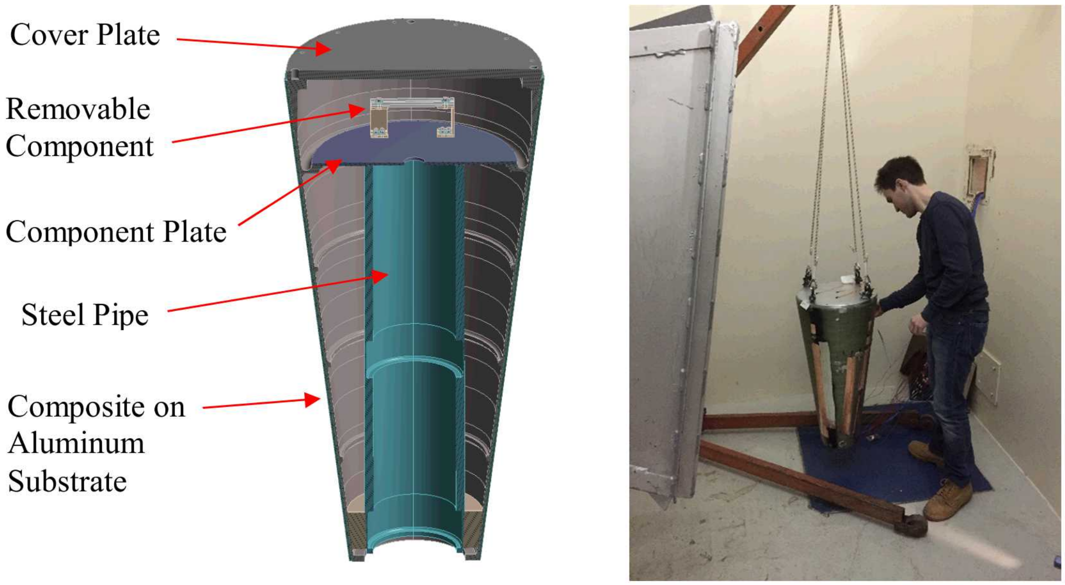
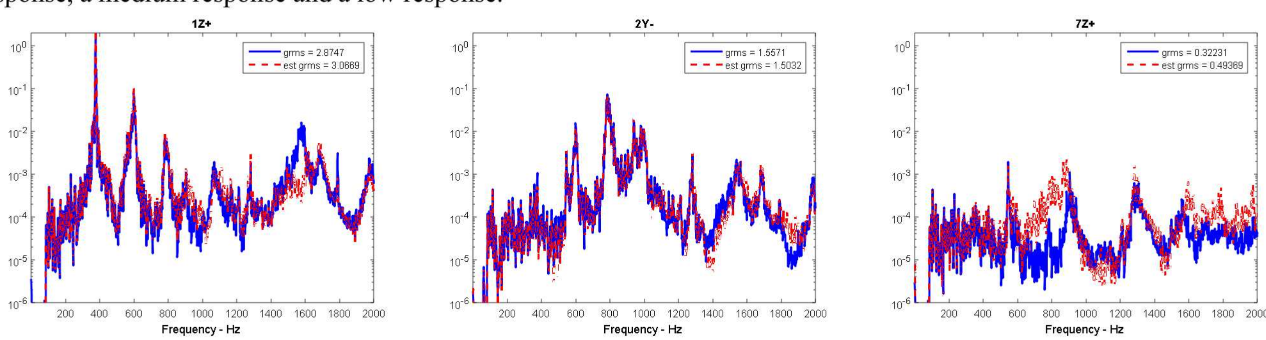


Figure 1 – MATV FE Model Cutaway (Left) and Acoustic Test Setup (Right)

5) Results of Predictions of Acoustic Test Truth Responses

The 2000 Hz frequency bandwidth was divided into five bands. Each band was analyzed separately. Only the largest contributing modes to the dynamic system response in a particular band were used in eqn (1) and (2). An algorithm was developed to choose accelerometers to minimize the sum of the condition numbers for the mode shapes from each of the five bands. This algorithm reduced the number of *m* accelerometers to 35 from the initial available 55. Eqn (1) and (2) were manipulated to produce cross spectra in the frequency domain. Figure 2 shows the comparison of the estimated response (red) and the measured acceleration spectral densities (blue) for three of the 14 "truth" gages. These show the largest response, a medium response and a low response.



High Level Medium Level Low Level

Figure 2 – Estimated (red) and Measured (blue) "Truth" Acceleration Spectral Densities

6) Conclusions

Our conclusion is that this process is effective if the FE mode shapes span the space of the actual motion. The results using the initial finite element model mode shapes were much worse, and the updating improved the mode shapes spanning the space of the test article motion. From the left curve of Figure 2, one can see at about 1600 Hz, the FE model mode shapes did not adequately capture the motion well in that band on the RC. Larger amplitude responses were generally estimated with more accuracy (in the dB error sense) than smaller amplitude responses. By dividing the response into five bands, the number of accelerometers required to modal filter was reduced from the classical 70 + (a minimum of one accelerometer per mode) to a lesser number, here 35.

Notice: This manuscript has been authored by National Technology and Engineering Solutions of Sandia, LLC. under Contract No. DE-NA0003525 with the U.S. Department of Energy/National Nuclear Security Administration. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

7) References

1 O'Callahan, John, Avitabile, Peter and Reimer, Robert, "System Equivalent Reduction Expansion Process (SEREP)", *Proceedings of the 7th International Modal Analysis Conference*, Las Vegas, NV, January 1989, pp. 29-37.