Chapter 1
Modal Survey Testing Using Combined Acoustic and Conventional Excitation Techniques

Kevin Napolitano, Dr. Michael Yang, Dale Schick, and David Kimpton

Abstract There is increasing interest in the aerospace community to reduce testing cost, risk, and schedule impacts by combining as many structure-related tests as practicable into a single test setup. This paper presents a method to perform modal survey testing in a direct field acoustic (DFA) test setup by using DFA inputs to excite acoustically sensitive structural modes and base inputs to excite high effective mass modes. While both input methods are able to excite many of the same modes of a test article, the combination of excitation methods allows for excitation of all modes that will be excited during launch. Furthermore, test data from both excitation methods can be combined with fixed base correction techniques to remove the effects of uncertain boundary conditions that are typically present when performing DFA testing.

Keywords Signal processing · Modal testing · Environmental testing · Direct field acoustic testing · Fixed base correction

Introduction

There is an increasing desire within the aerospace community to develop and deploy vehicles at an increasing pace, and one potential way of reducing development time is to perform as many different tests in as few testing configurations as possible [1], [2]. One way to do this is to perform a high-quality modal survey test to validate an analysis model while the test article is configured for an acoustic qualification test. The main challenge with this approach is not the use of acoustics as a source of excitation, but rather that the test article is usually mounted to a transportation cart that is oftentimes poorly modeled and dynamically active over the typical frequency range of a modal survey test.

This paper presents a method to perform modal survey testing in a direct field acoustic (DFA) test setup by using acoustic sources to excite acoustically sensitive structural modes and base inputs using conventional excitation techniques, such as shakers or impact devices, to excite modes sensitive to base excitation. While both input methods are able to excite many of the same modes of a test article, the combination of excitation methods allows for excitation of all modes that will be excited during launch. Furthermore, test data from both excitation methods can be combined with a fixed base correction (FBC) technique to remove the effects of uncertain boundary conditions that are typically present when performing DFA testing.

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Review of Modal Survey Tests Using Acoustic Excitation

Programs can save cost and schedule by performing DFA testing at a customer's facility in lieu of performing traditional acoustic testing at remote facilities. Fig. 1 presents a typical DFA test setup using Acoustic Research Systems' (ARS) Neutron^{TM} acoustic exciters. The test article is surrounded by a large number of independent acoustic sources while it is mounted on a either a transportation cart or another boundary condition—perhaps mounted directly to a seismic mass suitable for modal survey tests. Each acoustic exciter is similar to a typical electrodynamic modal shaker in that they are both driven by magnetic voice coil actuators. The difference is how the force is transmitted to a test article. The force generated by a modal shaker is transmitted directly to a test article through a stinger rod and is directly measured with a load cell, whereas the pressure from an acoustic exciter is transmitted to the test article through air and cannot be directly measured. Further savings can be realized if modal survey tests can be performed while a test article is configured for a DFA test.

Acoustic excitation is beneficial in exciting acoustically sensitive modes; and some acoustic devices like the Neutron^{TM} exciters are capable of a wider bandwidth, especially in the lower frequencies, than is typical. Two major factors that contribute to this capability are:

1. High initial efficiency through acoustic impedance matching (horn loading) and drivers with very high field strength to coil resistance ratios, and

2. Low mechanical losses through extremely robust construction – any flexure in the structure of the loudspeaker will be somewhat parasitic to the output unless the construction is very rigid.

The second point provides the added benefit of allowing their use for low-frequency modal testing above 2 Hz.

As such, recent research has been performed to explore how modal parameters (shape, frequency, damping) can be extracted from either test-measured or frequency response function (FRF)-synthesized cross-spectrum matrices that were created using acoustic excitation [3]–[6].

The main challenge with in situ acoustic modal testing is that the boundary condition, which is typically a transportation cart, is oftentimes dynamically active and not well modeled. A secondary challenge is that not all target modes may be excited well by acoustic excitation alone, which may lead to poorly extracted modes. The inability of a given exciter to not excite all modes is typical of any modal excitation technique and is oftentimes overcome by performing additional tests with exciters at different locations on the test article.

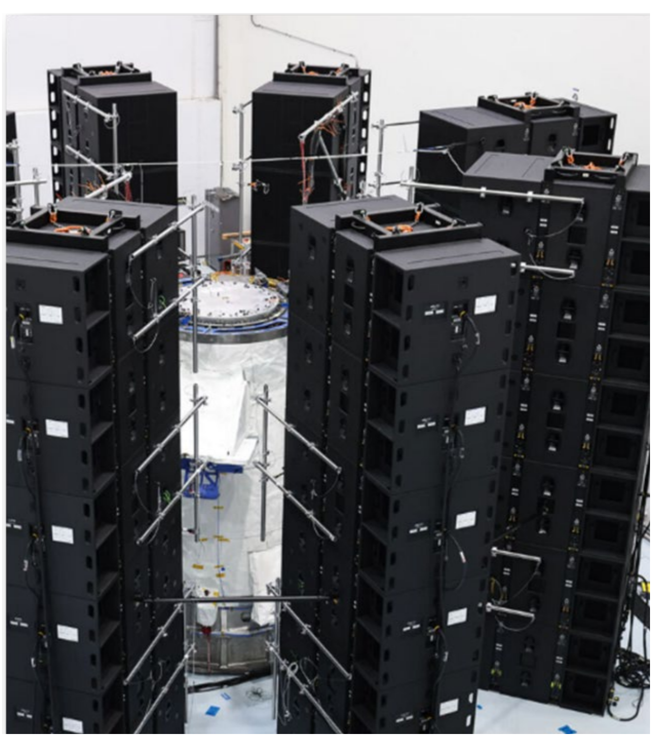

Fig. 1 Typical acoustic qualification test setup

Review of Fixed Base Correction

One way to address the boundary condition challenge is to mount the test article on a well-modeled support that can be inserted into the analysis model and incorporated in the model updating effort. Another way to address both the uncertain boundary condition and the excitation of all the target modes in a modal survey test is to supplement the acoustic test with conventional excitation sources, such as modal shakers and impact testing, and use the FBC technique [7] to measure FRFs associated with the boundary fixed.

FBC exploits the fact that when using drive point accelerations as references, mode shapes associated with the resulting FRFs are associated with those same acceleration degrees of freedom (DOF) fixed. The method has been used to measure fixed base modes on a variety of dynamically active boundary conditions including six-DOF base shake systems [8], shaker tables [7], and static testing fixtures [9].

In order to implement the method on a transportation cart, the number of shaker or impact locations used to excite the cart must be equal to or greater than the number of dynamically active shapes of the transportation cart over the frequency range of interest. The exciters must also be able to activate the dynamically active shapes.

Combining Acoustic Excitation and Fixed Base Correction

The straightforward way to implement FBC with acoustic excitation is to run all the exciters simultaneously including both the numerous acoustic excitation sources and the modal shakers mounted to the base, and then use both the acoustic sources and the base acceleration sources as references when calculating FRFs. The resulting FRFs, including the acoustic excitation sources, will be associated with those acceleration reference DOFs fixed.

There, however, may be future scenarios where a very large number of independent acoustic references, on the order of 80 or more, may be employed that could make calculating FRFs difficult and time-consuming. As such, this section presents an alternative approach that estimates modes from the fixed base corrected output cross-spectral matrix using FRFs from a separate test where only the accelerations of the boundary are used as references to remove motion from the base. The approach follows a Master's thesis by L.M. Elias [10] that separated responses due to disturbance sources from disturbances due to dynamically active boundaries.

The FRF equation using acoustic sources and boundary accelerations as references can be written as

$$\{A\} = \begin{bmatrix} H_{Ap} & H_{AB} \end{bmatrix} \begin{Bmatrix} P \\ A_B \end{Bmatrix} \tag{1}$$

where $\{A\}$ are measured responses such as accelerations, $\{A_B\}$ are the boundary accelerations and can be generalized coordinates such as constraint shapes, $\{P\}$ are the acoustic sources, $[H_{Ap}]$ is the FRF matrix associated with the acoustic sources {P} activated while holding the base accelerations $\{A_B\}$ equal to zero, and $[H_{AB}]$ is the test-measured FRF matrix due to exciting the boundary directly while holding the acoustic sources equal to zero. In practice, it is straightforward to generate the matrix $[H_{AB}]$ directly by exciting the base directly with conventional exciters while not turning on the acoustic sources. The matrix $[H_{Ap}]$, however, cannot be measured if the base is not excited directly because it is not possible to hold the base accelerations equal to zero while the acoustic sources are activated. Instead, the matrix must be generated from test data where all of the conventional base exciters and each acoustic source are activated.

To remove the requirement of calculating the matrix $[H_{Ap}]$ directly, a first test that measures the matrix $[H_{AB}]$ directly is performed by exciting the boundary directly while the acoustic sources are turned off; i.e., {P}={0}. Thus,

$$\{A\} = [H_{AB}]\{A_B\} \tag{2}$$

Equation (1) is expanded to $\{A\} = [H_{Ap}]\{P\} + [H_{AB}]\{A_B\}$, where $[H_{Ap}]\{P\}$ and $[H_{AB}]\{A_B\}$ are the response of the system due to the acoustic sources assuming the base accelerations are equal to zero and the response due to the base accelerations assuming the acoustic sources are equal to zero, respectively. This equation can be rewritten to solve for $[H_{Ap}]\{P\}$ as

$$\{\overline{A}\} = [H_{Ap}]\{P\} = \{A\} - [H_{AB}]\{A_B\} \tag{3}$$

where $\{\overline{A}\}$ is the response of the acoustic inputs holding the base accelerations fixed. Since $\{A\}$ and $\{A_B\}$ are measured and $[H_{AB}]$ is known, the product $\{\overline{A}\}$ can be calculated for each frame of data to calculate the output cross-spectrum $[S_{\overline{AA}}]$ as

$$[S_{\overline{AA}}] = \{\overline{A}\}\{\overline{A}\}^H \tag{4}$$

The frames are then averaged together to calculate the total response cross-spectrum due to acoustic inputs holding the base motion equal to zero. The resulting cross-spectrum matrix is then used to estimate modal parameters using operational modal analysis techniques.

Experimental Example

A previous presentation [5] documents the results of combining FRFs associated with acoustic sources with FRFs using conventional shaker excitation.

In this example, response cross-spectrum data from the same test article is calculated for two sets of tests: acoustic random input, and base impact test data. The impact test data is then used to calculate FRFs associated with the base accelerations as references. Then, Equation (4) is used to generate response cross-spectrum due to acoustic sources while holding the base accelerations fixed.

The test article in Fig. 2, a satellite mass model provided by Northrop Grumman Corporation, is mounted to its transportation cart, which is a typical testing configuration for acoustic qualification testing. For this test, however, the transportation cart was supported on isolators used to regularize and isolate the transfer of loading from the cart to the ground. A total of 24 Neutron$^{\mathrm{TM}}$ acoustic sources were used in an eight-stack configuration with three sources per stack. Control microphones placed in front of each source were used to set voltage levels for its corresponding source. ATA Engineering (ATA)-owned modal shakers were used to excite the base of the test article as well, but this paper presents the results using impact testing on the base to generate the base FRFs.

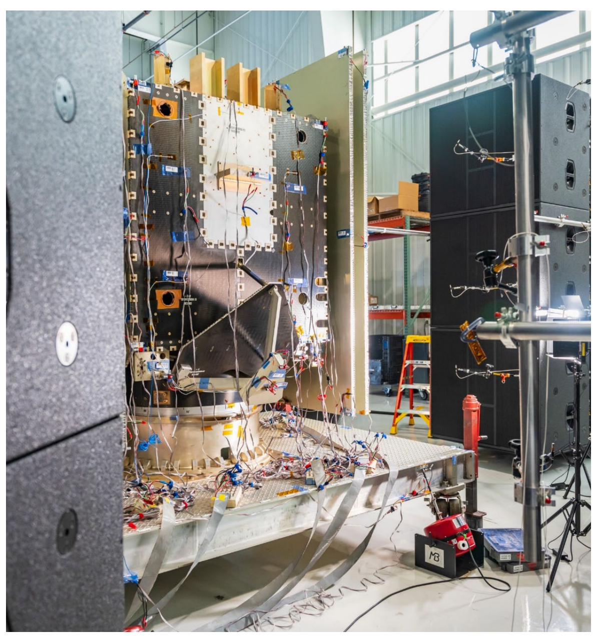

Fig. 2 Test article

A test display model is presented in Fig. 3. A total of 151 response accelerometers were mounted to the test article including twelve seismic accelerometers, which were mounted to observe the six rigid body modes of the transportation cart, the primary twist mode of the cart, and the three out-of-plane deformations (two roll and one vertical) of the center connection.

Impacts were performed using an uninstrumented mallet with a soft eraser bonded to the impact face to shape the frequency content of the impact to lower frequencies. Approximately five to eight impacts were performed near each of the twelve seismic accelerometers mounted on the transportation cart. The impacts were spaced greater than 8 seconds apart so that 8-second frames could be used to calculate FRFs. Ten transportation acceleration constraint shapes were used as references when calculating FRFs. The six rigid body modes of the transportation cart were supplemented with outer perimeter twist. Three additional constraint shapes were added: the of overall inner square rigid body RX, and RY, and Z motion out of phase with outer perimeter rigid body RX, RY, and RZ motion, respectively.

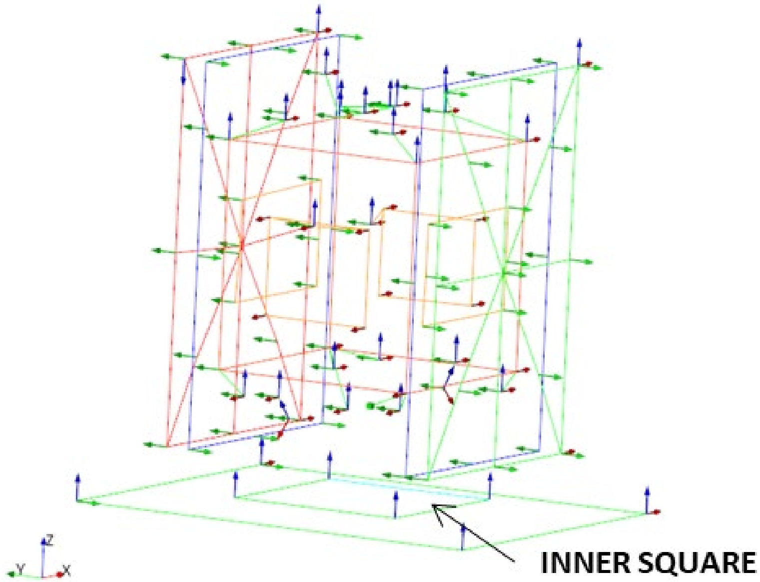

Fig. 3 Test article and accelerometer locations

For ten minutes, independent random signals from 0–200 Hz were input into each of the 24 acoustic sources. Overlap processing with a Hanning window was performed on 8-second frames of data to ensure that the frequency spacing for the acoustic sources was the same as for the impact tests.

Fig. 4 presents the first three singular values of the full 151-by-151 acceleration cross-spectrum matrix due to acoustic and impact inputs. Note that while many of the modal frequencies are the same, the acoustic exciters emphasize acoustically sensitive modes while the base impacts excite modes sensitive to base input. This is consistent with any source of excitation for modal tests, and maximizing the quality of the mode-shape fit is most often based on how distinct its peak is in the test data.

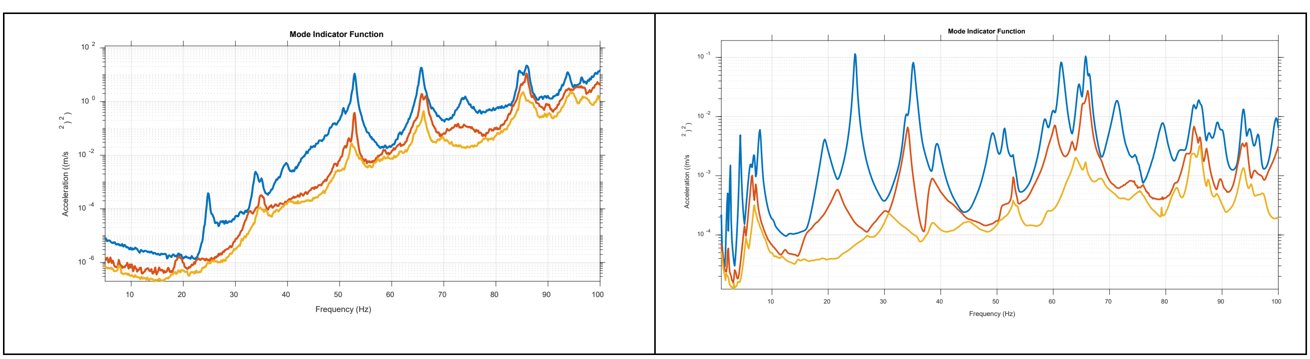

Fig. 4 First three singular values of natural acoustic (left) and impact test (right) cross-spectrum matrices

Note that the response cross-spectrum from the impact hammer can be used because the input spectrum was smooth; i.e., no frames of data with double hits were processed. Also note that the previous presentation [5] presents a case not examined in this paper where the acoustic sources were injected with a Multi-Sine excitation at low frequency to excite five of the six low-frequency rigid body modes of the test article.

Examples of three modes extracted from the acoustic test data are presented in Fig. 5.

The cross-spectrum matrix of the acoustic sources while holding the base fixed is calculated using Equation (4). The first three singular values of both cross-spectrum matrices are presented in Fig. 6, along with the first three singular values of the FRF matrix associated with base accelerations as references. Note that the peaks in the fixed base corrected cross-spectrum matrix match those of the fixed base corrected FRFs for many frequencies, including the two primary modes. However, not all peaks are present in both sets because the FRFs associated with the base accelerations emphasize high effective mass modes while the cross-spectrum matrix from the acoustic sources emphasize acoustically sensitive modes.

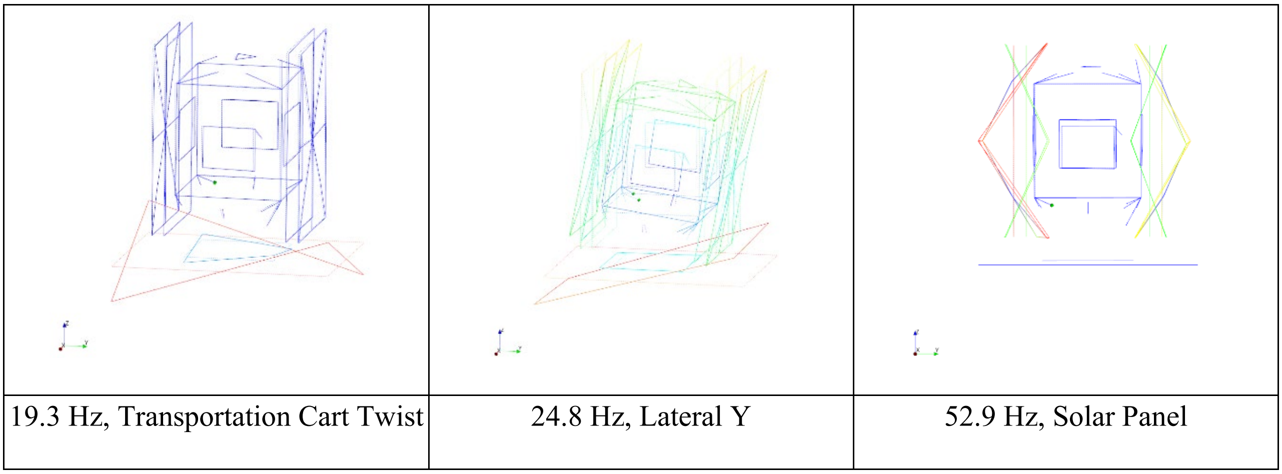

Fig. 5 Example of test-measured natural modes from the acoustic source cross-spectrum matrix

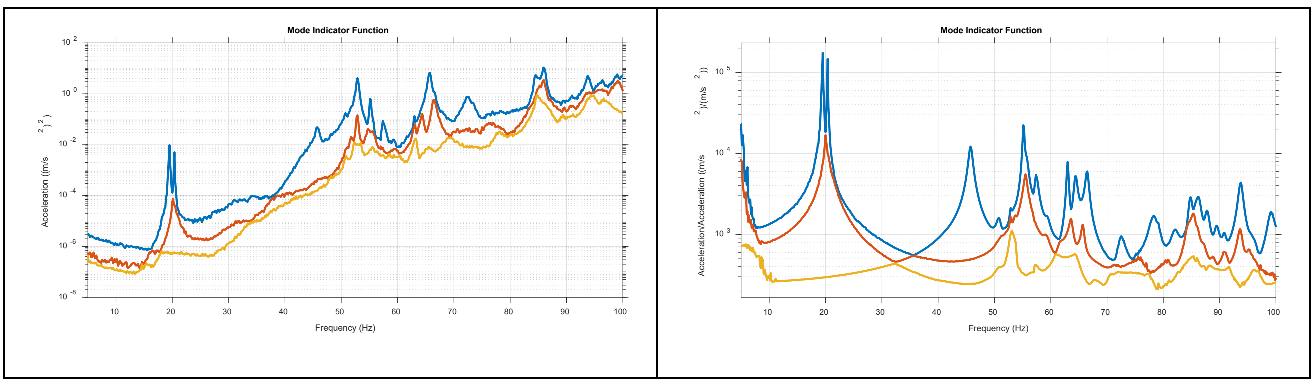

Fig. 6 First three singular values of acoustic corrected cross-spectrum matrix (left), and base acceleration FRF matrix (right)

In order to verify fixity, mode shapes were extracted from the fixed base corrected cross-spectrum matrix using the OPOLY parameter estimation tool in ATA's MATLAB-based IMAT$^{\mathrm{TM}}$ software [11]. Three of these modes are presented in Fig. 7, and the transportation cart does not move.

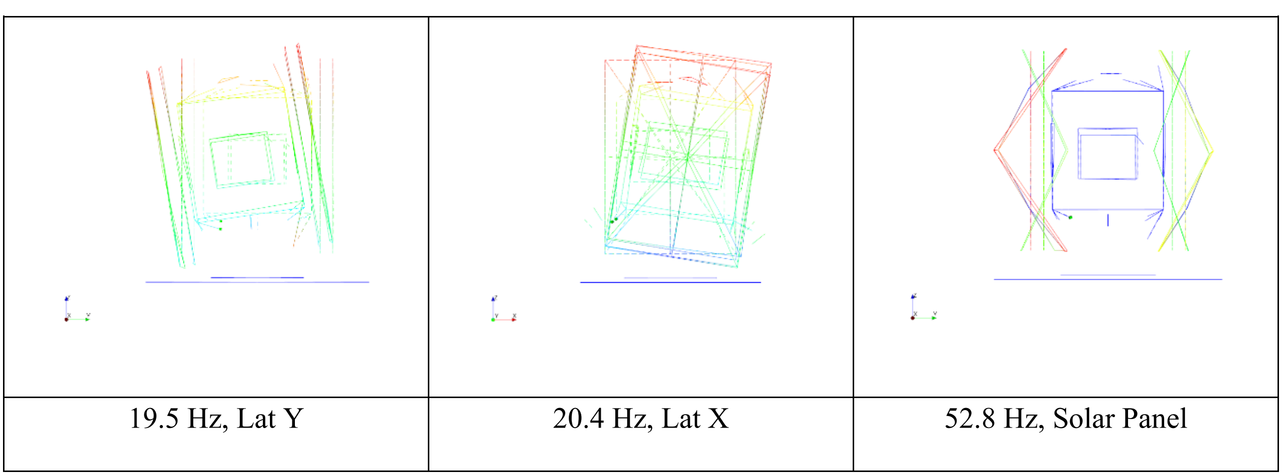

Fig. 7 Example of test-measured fixed base modes

As with almost every modal survey test that is conducted, some modes of interest may not be well excited because the location and orientation of the excitation source is not positioned properly. In these cases, it is oftentimes beneficial to excite the test article in a way that will emphasize a mode in question with whatever means is most expedient. For example, if the primary torsion mode of the test article were not well excited, perhaps the acoustic sources could be rotated so that they could provide both radial and rotational inputs instead of providing a purely radial input.

Summary and Observations

This paper verifies that data from acoustic sources can be combined with conventional sources for modal survey tests, and also presents a method to process acoustic test data when the number of independent sources becomes very large.

Acoustic excitation is beneficial in exciting acoustically sensitive modes. Acoustic sources are also ideal for cases where the modal test is performed in an acoustic qualification test configuration if only for the fact that they are already assembled and available.

If the boundary such as a transportation cart is well modeled, then the test results from the acoustic sources, either from calculated FRFs or from response cross-spectra, and the FRFs associated with conventional excitation techniques can be used directly to update an analysis model. In addition, FBC works with acoustic sources, which is important for cases when performing a modal survey test in a DFA test configuration is desirable and when well-modeled boundary conditions are not available. The additional benefit of combining FBC with acoustic excitation is that all high effective mass modes and acoustically sensitive modes are well excited and can be extracted.

References

1. Cross, K., Melendez, G., Arnold, F., Brenner, K., Throneberry, G., and Soine, D., "Combining Pyroshock with MIMO Vibration," *Proceedings of the 34th Aerospace Testing Seminar*, Los Angeles, CA, April 2025.
2. Throneberry, G., Melendez, G., and Cross, K., "Developments on Combined Thermal-Vibration MIMO Testing," *Proceedings of the 34th Aerospace Testing Seminar*, Los Angeles, CA, April 2025.
3. Schick, D., Hayes, D., Napolitano, K., Kerrian, P., Yang, M., Fogt, V., and Goit, M., "Modal Testing of the NASA VIPER Spacecraft Using Acoustic Excitation," *Proceedings of the 34th Aerospace Testing Seminar*, Los Angeles, CA, April 2025.
4. Napolitano, K., Yang, M., Friedlander, E., and Schick, D., "Mode Shape Extraction Using Direct Field Acoustic Noise Test Data," *Proceedings of the 43rd International Modal Analysis Conference*, Orlando, FL, February 2025.
5. Napolitano, K., Yang, M., Schick, D., Hayes, D., and Kimpton, D., "Experimental Modal Analysis Using Acoustic Excitation," *Proceedings of the Spacecraft and Launch Vehicles Dynamic Environments Workshop*, El Segundo, CA, June 2025.
6. Peeters, B., Alvarez Blanco, M., Musella, U., Waimer, S., Di Lorenzo, E., and Carrella, A., "Identifying the Structural Behaviour of a Specimen During Spacecraft Acoustic Testing by Operational Modal Analysis," *Proceedings of the 7th International Operational Modal Analysis Conference*, Ingolstadt, Germany, May 2017.
7. Napolitano, K., "Fixed Base Modal Testing of the SWFO Sensor Platform on an Environmental Shaker," *Proceedings of the Spacecraft and Launch Vehicle Dynamic Environments Workshop*, El Segundo, CA, June 2023.
8. Napolitano, K., Staab, L., Winkel, J., Akers, J., and Suarez, V., "Fixed Base Modal Survey of the Orion European Service Module Structural Test Article (E STA)," *Proceedings of the Spacecraft and Launch Vehicle Dynamic Environments Workshop*, El Segundo, CA, June 2017.
9. Spivey, N., Saltzman, R., Wieseman, C., Napolitano, K., and Smith, B., "Passive Aeroelastic Tailored Wing Modal Test Using the Fixed Base Correction Method," *Proceedings of the 38th International Modal Analysis Conference*, Houston, TX, February 2020.
10. Elias, L.M., "A Structurally Coupled Disturbance Analysis Method Using Dynamic Mass Measurement Techniques, with Application to Spacecraft-Reaction Wheel Systems," Masters of Science in Aeronautics and Astronautics Thesis, Massachusetts Institute of Technology, 2001.
11. Hensley, D., Antoun, G., Fladung, B., and Napolitano, K., "Using the IMAT Toolbox in the Modal Test Process," *Sound and Vibration* 47(6), pp. 6–12, June 2013.