Chapter 4
Mode Shape Extraction Using Direct Field Acoustic Noise Test Data

Kevin Napolitano, Dr. Michael Yang, Eric Friedlander, and Dale Schick

Abstract Direct field acoustic noise (DFAN) testing involves the placement of loudspeakers around a structure for acoustic qualification tests. It is becoming more prevalent because it allows the testing to be performed in situ, which reduces or eliminates the test article transportation costs that arise from testing in an acoustic reverberation chamber. DFAN testing could provide an even greater value proposition if it could be used as a source of excitation for modal survey tests. This paper describes DFAN testing and how it can be used for modal survey tests and then uses DFAN test data from a demonstration test article to extract modes using operational modal analysis methods with measured, output-only cross spectra and cross spectra generated from frequency response functions to remove the time-delay-induced phase shift.

Keywords Modal testing · Parameter estimation · Direct field acoustic noise

Introduction

Direct field acoustic noise (DFAN) testing is increasingly used as the preferred method for performing acoustic tests because it is less expensive than traditional reverberant chamber tests. The value proposition associated with DFAN testing systems could be further enhanced if the DFAN speakers could also be used as sources for modal survey tests, especially for exciting acoustically active modes.

A DFAN system developed by Acoustic Research Systems (ARS) generates a diffuse acoustic field by ensuring that all acoustic devices in the test setup are driven by true random sources that are independent of each other. The amplitude of each speaker is set independently based on the test requirements placed on the microphone that controls it. The control microphones are placed such that each speaker has a microphone that is significantly closer than the other microphones, thereby ensuring that the response of each control microphone is dominated by a single speaker.

The fact that each source is truly independent is advantageous for modal testing because the sound pressure levels can be set such that they mostly satisfy the assumptions associated with operational modal testing (i.e., they are independent and constant over the frequency range of interest [1]). Furthermore, acoustic excitation techniques have been used to extract modes of a flat disk [3].

This paper demonstrates the feasibility of using a DFAN system to conduct a modal survey test on a demonstration test article using both output-only cross-spectra test data as well as cross spectra generated from frequency response functions (FRFs) with control microphones as references. It gives a background of DFAN testing and then describes how the equipment was used as sources for exciting the test article, how the resulting data was processed, and how the processed data was analyzed to extract modal parameters (shapes, frequency, and damping). Finally, the test results are presented and discussed.

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Background of DFAN Testing

The history of DFAN testing began with the use of concert loudspeakers available in the late 1990s and early 2000s, which were designed to carry acoustic energy long distances with several band-pass filters. This type of testing required separate subwoofers, midrange, and high-frequency speakers. Using multiple loudspeaker drivers worked well for live sound but caused many challenges when trying to reproduce the intense energy propagated by the fairing of a large launch vehicle. DFAN technology has since evolved to mitigate these challenges and simplify the overall design into a more efficient test system. The system utilized for this study was the first to be designed specifically for the purpose of DFAN testing, its development and qualification having been discussed in previously published literature [1]. With the development of an acoustic device that can operate safely and efficiently at extremely high output levels, without the need for drive signal manipulation or integration of various discrete band-pass devices, uniform and highly repeatable acoustic field conditions can now be easily created. For the purpose of modal extraction, this acoustic generation system enables the creation of an acoustic field that is highly predictable and can be sustained at a high level for long periods of time with stability, and it has the advantage of adequately exciting the test article while extending the number of measurement averages to reveal modes in the infrasonic frequency range. The consistency of the DFAN system also allows for modal surveys to be run at different sound pressure levels, which can reveal nonlinearities in the structural response that can often occur with complex structures.

Another advantage to this type of system is scalability. The creation of a somewhat diffuse field requires only three devices, and incorporating additional devices fed with stochastic sources only increases the quality of diffusivity and spatial uniformity [1]. Currently, systems have been scaled from three to ninety units with adequate structural excitation in all configurations.

In traditional modal testing, the excitation is imparted to the structure using shakers and/or impact hammers, both of which require access to and contact with the structure. A third method of excitation, the focus of this paper, is a noncontact method of excitation. By exciting the entire structure with an acoustic field, components that could otherwise be damaged by contact-driven excitation or which are out of reach can be energized. An optical lens, for instance, may shatter with local excitation or lack response when traditional localized methods are used. Acoustic energy, on the other hand, will not only safely energize the spacecraft structure, but also the local fixturing of the optical lens as well as the lens itself. This benefit can also be extended to solar arrays, reflectors, antennas, and other spacecraft components.

For traditional structural components, which are less sensitive to impact and shaker excitation, there is still some benefit with the acoustic excitation method. First, impacts can be difficult to repeat in terms of amplitude consistency. Since many impacts are necessary to create clean FRFs for processing, the repeatability of the acoustic energy from one average to the next, along with the sheer number of them, has an advantage over the hammer method. Second, shakers require bonding of long, flexible rods (known as stingers) to the structure to adequately transfer the energy. Mounting the shaker and bonding the stinger provide added complexity and risk to the structure. The acoustic method, however, oftentimes only needs to be rolled up next to the test article, and the air already surrounding the test article is used to transmit vibration energy to the test article.

One key aspect of acoustic testing is that it typically focuses on the audible frequency range, about 20 Hz to 20 kHz. The ARS Neutron acoustic device (Fig. 1) utilized for this study, as designed for typical DFAN testing applications, has an operating frequency range that is optimized for testing from 20 Hz to 10 kHz. When utilizing a DFAN test system for modal extraction, it is important to consider how the system might excite modes that fall below the typical audible frequency range. From the standpoint of DFAN system design, the generation of infrasonic frequencies to an amplitude of significance requires not only special considerations to be made in the design and construction of the acoustic device but also a complete signal chain from sound generation source to microphone capture that supports the generation and acquisition of infrasonic frequencies.

While it is possible to address these challenges, one advantage of utilizing a purpose-built full-range acoustic device for in situ modal extraction is that the inherent efficiency of the acoustic device in the very-low-frequency (VLF) range allows it to generate significant and stable acoustic excitation, even as the frequency range of interest approaches the lower extension of the optimal operating bandwidth. This efficiency combined with a long acoustic exposure time allows the acoustic device utilized for this study to provide adequate excitation of modes in the infrasonic range, without the need to employ exotic methodologies.

Fig. 2 compares the low-frequency section of an ARS Neutron to the low-frequency section of a typical front-radiating concert subwoofer. The higher acoustic efficiency allows the device to more easily couple the excitation of the drivers to the air surrounding the test article, which, in turn, provides more energy for longer durations of time and with more incoherent sources to approximate a diffuse acoustic field. Note that regardless of approach, the efficiency of acoustic devices as they near infrasonic frequencies tends to decline.

Fig. 1 ARS Neutrons configured in six stacks of two (6 × 2).

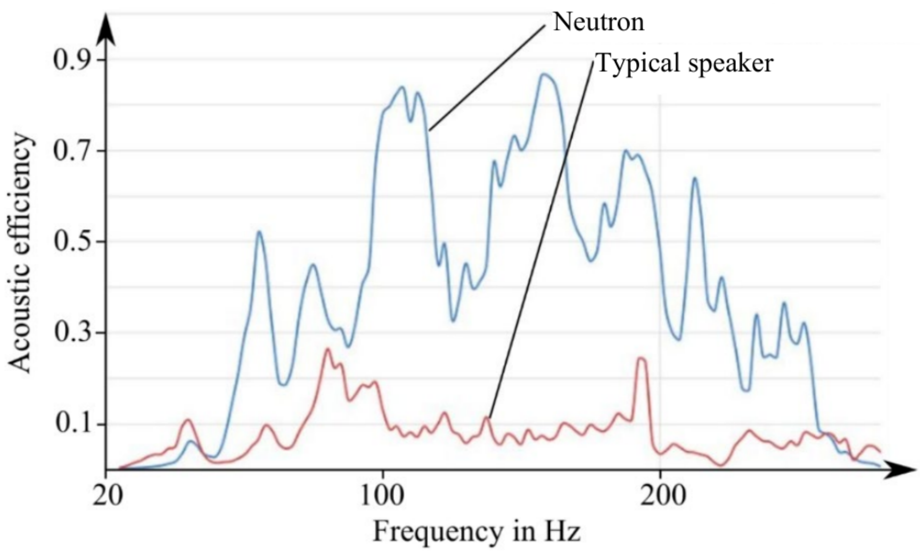

Fig. 2 Low-frequency acoustic efficiency of Neutron vs. typical front-radiating loudspeaker.

Test Article and Data Collection

A test article was designed, fabricated, and tested to demonstrate that both acoustic and modal testing can be performed while the test article is in one configuration, which is ideally on a head expander of an environmental shaker [4]. The test article, shown in Fig. 3, is a loose representation of a satellite bus with acoustically active panels mounted on a base plate that represents a head expander of an environmental shaker. The test article is mounted on four rubber mounts that rest on two portable sawhorses. The number of accelerometers mounted to the test article was minimized to make the test article as easily deployable as practicable but still observe primary bending, torsion, axial, and panel modes.

A total of 34 accelerometers were mounted on the test article. The accelerometers were placed in such a way as to measure the rigid body motion of the base, the rigid body motion of the upper box, and the relative motion between the

Fig. 3 Test article (left) and test display model with accelerometer measurement degrees of freedom (right).

bottom of the box and the base. Two accelerometers per surface were mounted in order to measure the out-of-plane motion of the four side panels and the top panel. Motion of unmeasured degrees of freedom (DOFs) in the test display model were estimated assuming that the base and the box move as independent rigid bodies.

One limitation of using data from environmental tests is that the total testing time is often short compared to the data collection time involved with a traditional modal survey [5].The short testing time forces the engineer to either not have enough frames of data to generate smooth frequency-domain data or not have a tight enough frequency resolution to adequately observe resonant peaks. Since the objective of this effort is to use acoustic speakers as sources for a modal survey test, data was collected for a total of 10 minutes at a low acoustic input level.

Data Processing

After the 10 minutes of random data was collected, the time-history data was processed into acceleration cross spectra and microphone sound pressure to acceleration FRFs using 20 s frames with an associated frequency spacing of 0.05 Hz, a Hanning window, and 95% overlap. Frequency-domain functions were calculated from 0 to 1.6 kHz. The full cross-spectra matrix was 34 accelerometers by 34 accelerometers, and the FRF matrix was 34 accelerometers by 12 microphones.

An overlay of the first two singular values of the accelerometer cross-spectra matrix vs. the singular values of a cross-spectra matrix generated from the FRF assuming unit microphone inputs is presented in Fig. 4. The peaks in the singular values are the observable modes. Generally, the singular values of the FRF-generated cross-spectra matrix are cleaner but

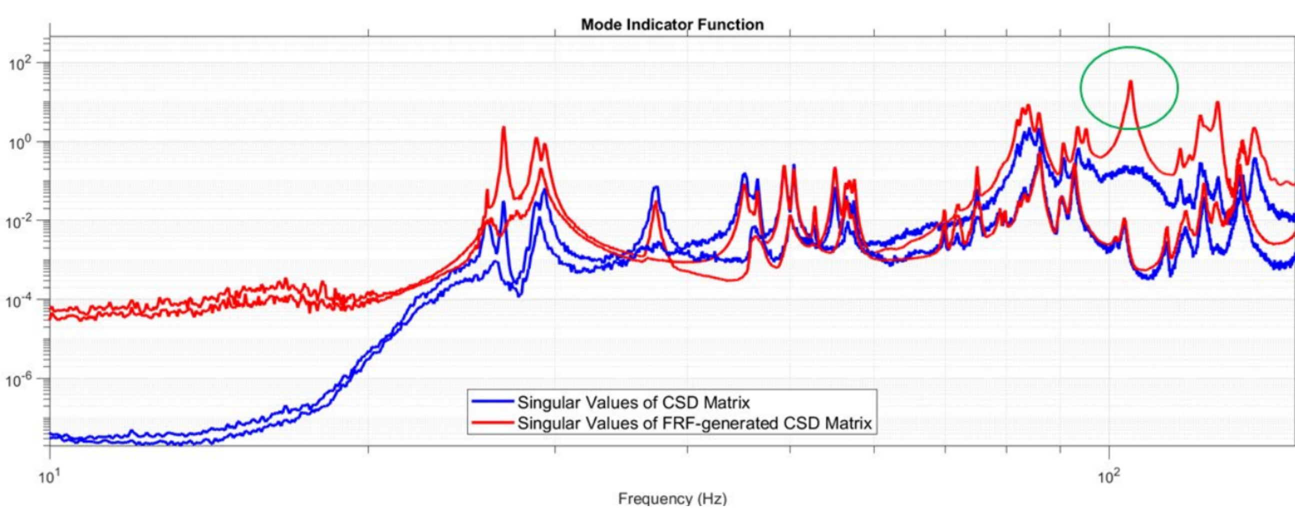

Fig. 4 Comparison of singular values of accelerometer cross-spectra matrix (CSD) vs. singular values of FRF-generated cross-spectra matrix.

most modes are observable from both sets. There is one mode near 104 Hz that is observable in the FRF-generated cross-spectra singular values but not as observable in the accelerometer cross-spectra singular values. The discrepancy could have been due to being a fictitious mode where there is cross talk between the speakers and the control microphones that causes a notch in the source-to-microphone FRF [6] or it could have been a mode where the impedance does not allow the microphone pressure to fully apply to the structure, leading to the mode not being fully observable in the cross spectra. This feedback effect is typical of many modal survey tests with shakers where the force spectra dips at a resonant frequency because the structure is too flexible to accept the full shaker load. Subsequent tap testing verified that the mode was real.

Modal Extraction from Acoustic Test: Operational Modal Analysis

The baseline assumption in operational modal analysis (OMA) is that the input cross-spectra matrix is constant over the frequency range of interest for which modes are extracted. With this assumption in place, several frequency- and time-domain methods have been proposed to extract modal parameters by manipulating the cross-spectra density matrix [2]. Since the DFAN system used in this effort controls the sound pressure of microphones mounted directly in front of the acoustic excitation sources, this assumption mostly holds true. Fig. 5 shows the power spectral density (PSD) functions for

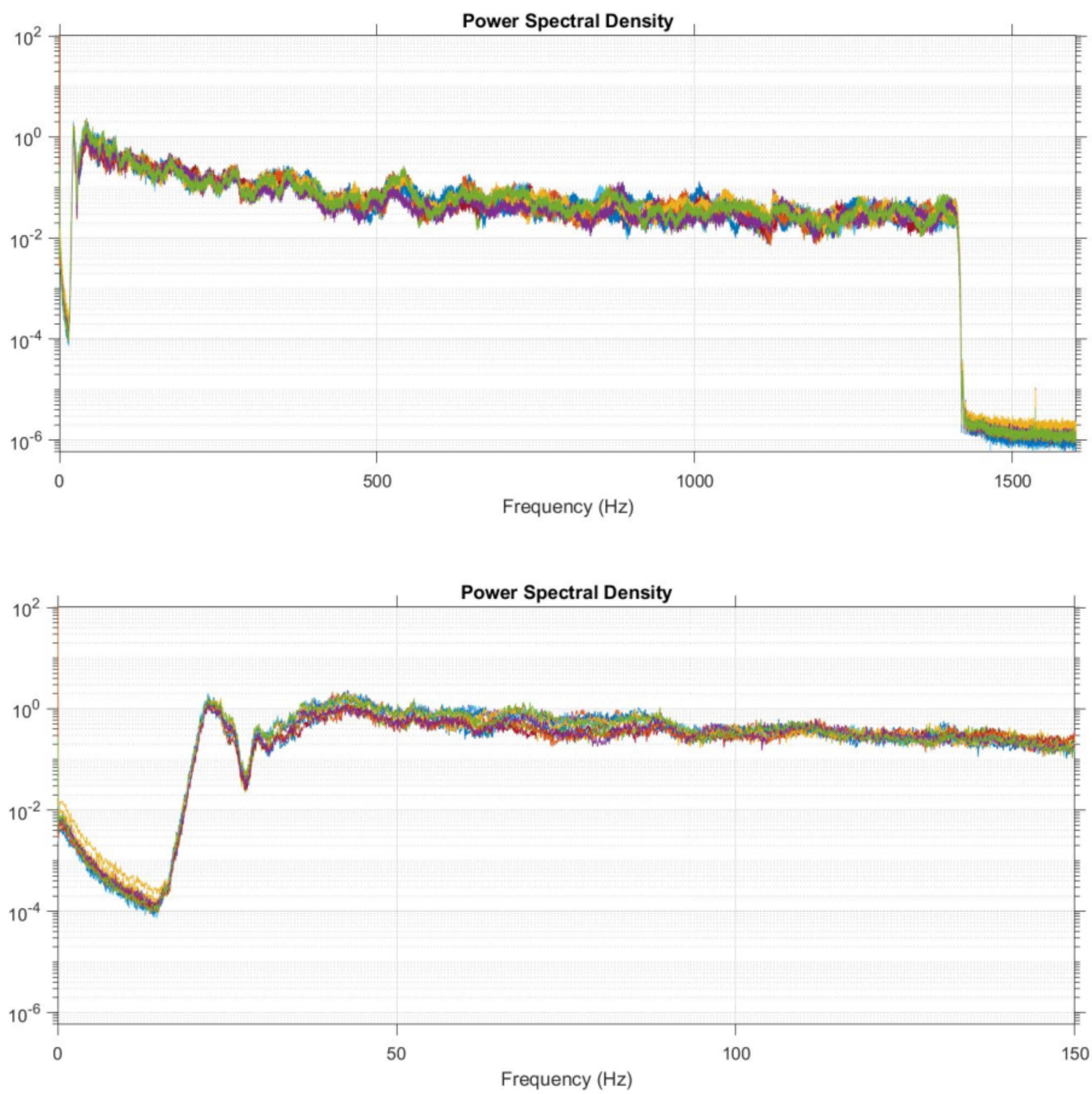

Fig. 5 PSDs of all control microphones. Full frequency range (top) and 0–150 Hz (bottom).

all six control microphones. For this test, the low-frequency power was boosted as high as practicable in order to excite the lower-frequency modes below 30 Hz as much as possible. The singular values of the control microphone cross-spectra density matrix (Fig. 6) shows that, while the control sound pressure is consistent over all frequencies, there is some feedback from the structure at around 104 Hz and 125 Hz such that the sound pressure is not fully independent at all frequencies.

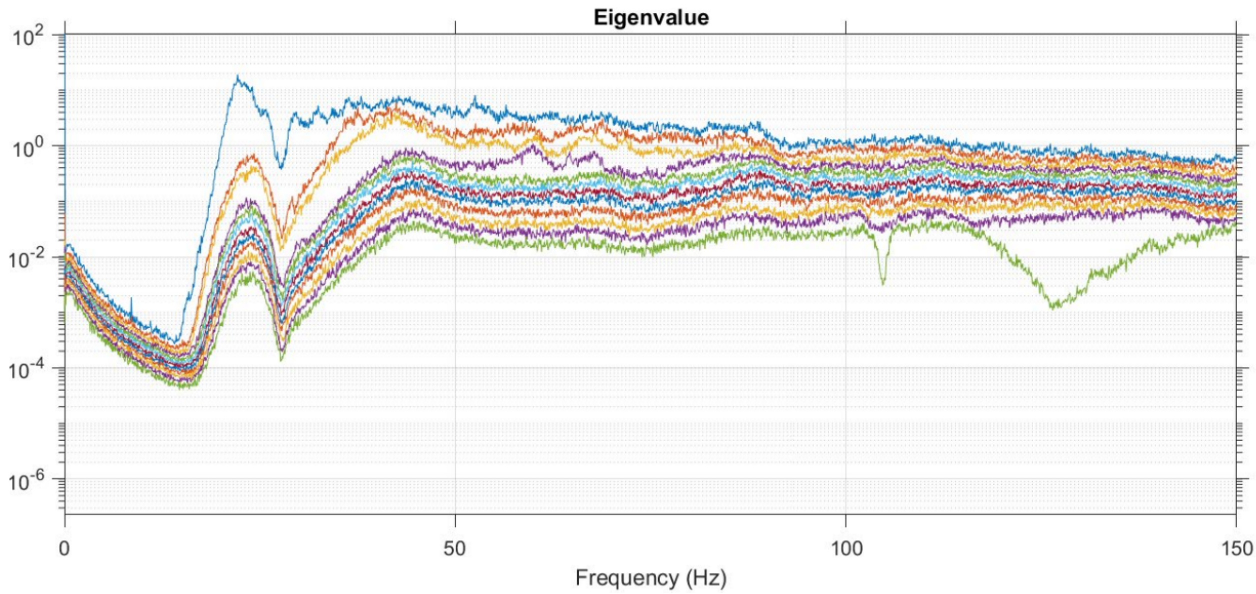

Fig. 6 Singular values of all control microphones.

Modes were extracted from the test data using a standard frequency-domain modal analysis tool by exploiting the fact that, as shown in Fig. 7, there are four complementary poles (two with positive damping and two with negative damping) when analyzing cross spectra instead of just two (both with positive damping) when analyzing FRF [7].

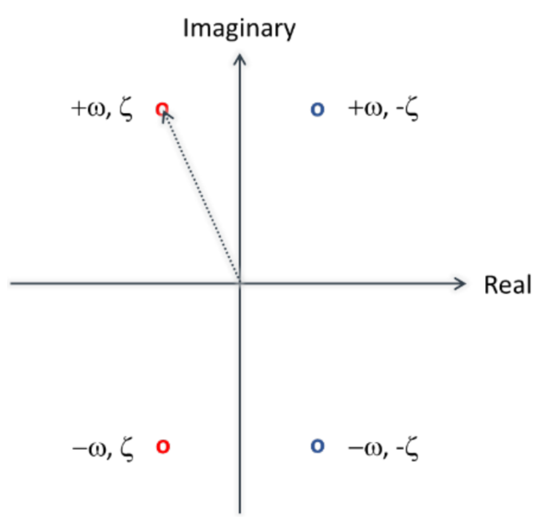

Fig. 7 Poles associated with cross spectra (blue and red) and FRFs (red).

The full 34 × 34 acceleration cross-spectra matrix was calculated, and then a coordinate transformation was applied to the DOFs associated with the columns using the first seven singular vectors from a concatenated array containing the cross-spectra matrices from 20 to 150 Hz. The resulting 34 × 7 cross-spectra matrix was then analyzed to extract mode shapes. A narrowband fit of each resonant frequency or set of closely spaced frequencies was then performed to extract modal parameters, including shape, frequency, and damping. The modal parameters were verified by overlaying the power spectrum mode indicator function of the cross-spectra matrix to the power spectrum mode indicator function of the cross-spectra matrix synthesized from the modal parameters. An overlay of the test vs. synthesized functions is presented in Fig. 8.

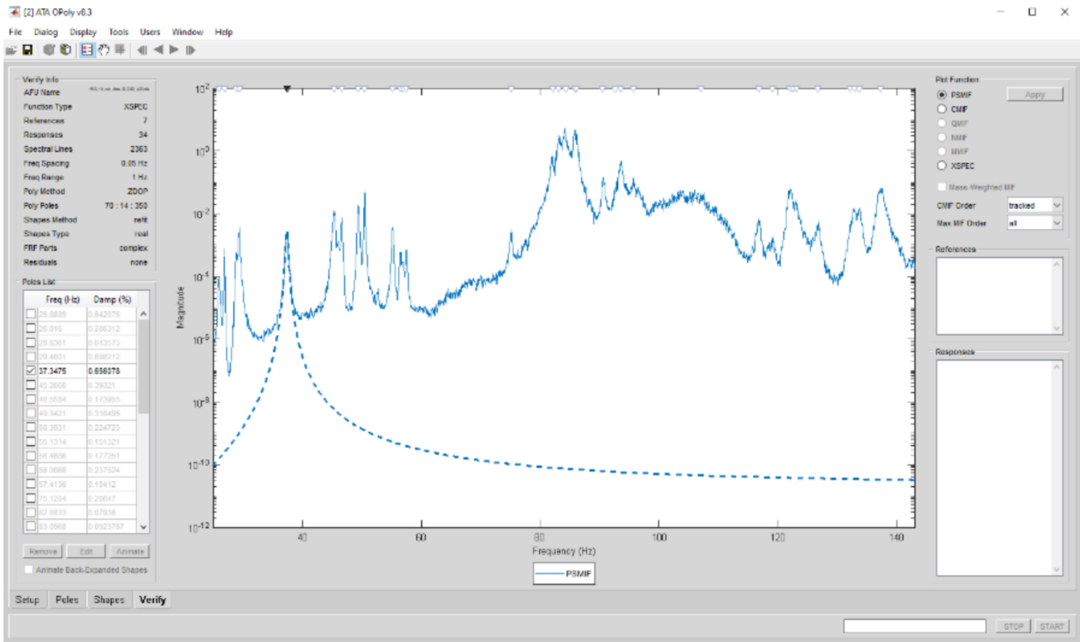

Fig. 8 Overlay of test vs. synthesized cross-spectra power spectrum mode indicator function verifies modal parameter extraction.

It was also noticed that low-order modes from 5.7 to 17.6 Hz of the test article resting on the rubber mounts and sawhorses were observable in some of the acceleration PSDs (Fig. 9). Note that the base and test article are moving in and out of phase for the rigid body vertical and first vertical modes, respectively. Each set of cross spectra was used to extract the observable mode using a single DOF.

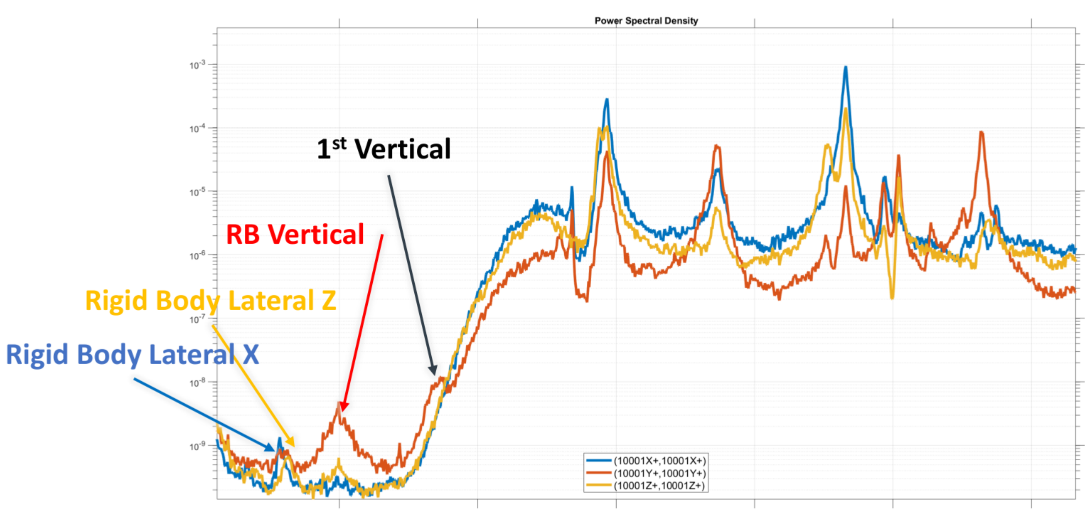

Fig. 9 Low-frequency lateral and vertical rigid body (RB) modes and first vertical modes observable in PSD data.

Modal Extraction from Acoustic Test: FRFs

The acoustically excited FRFs have a phase that varies linearly as a function of frequency associated with a time delay of the sound pressure traveling from the source to the test article (Fig. 10).

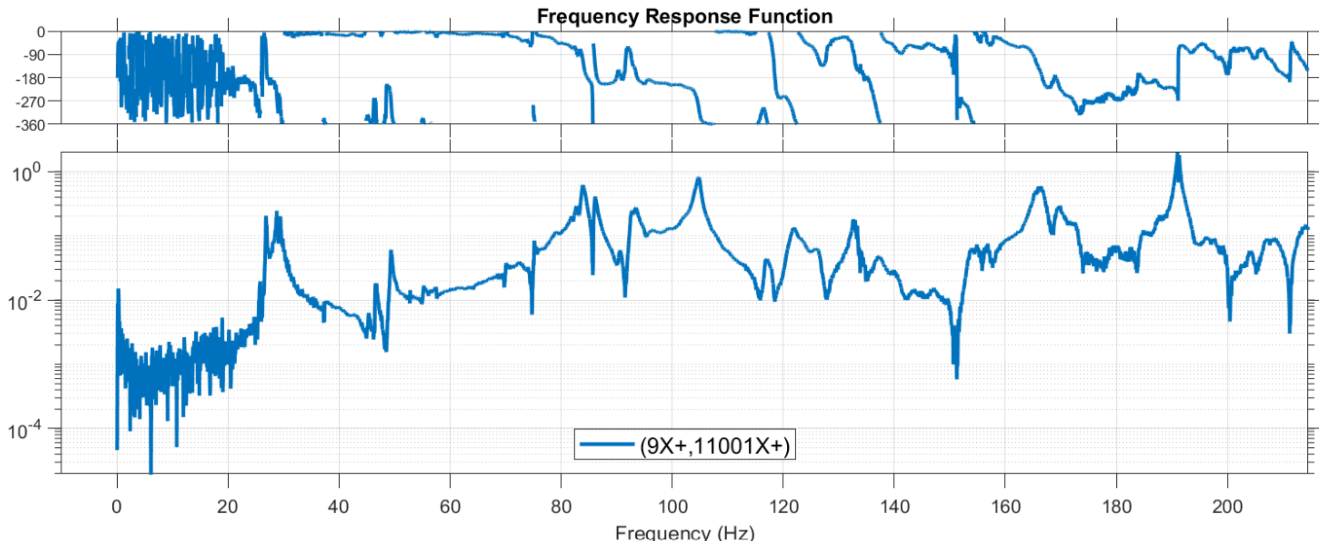

Fig. 10 Example FRF from microphones to response accelerometers showing linearly varying phase as a function of frequency.

While these FRF can still be used to extract complex modes to a reasonable degree, this paper uses the same OMA as above to calculate real modes directly. In this case, the FRFs were used to generate a full acceleration cross-spectra matrix by assuming that the reference autospectrum matrix for the microphones was equal to the identity matrix at all frequencies. Essentially,

$$[S_{YY}] = [H_{YX}]\,[S_{XX}]\,[H_{YX}]^H = [H_{YX}]\,[I]\,[H_{YX}]^H = [H_{YX}]\,[H_{YX}]^H, \tag{1}$$

where Y is associated with outputs, X is associated with microphone inputs, $[S_{YY}]$ is the FRF-generated output cross-spectra matrix, $[H_{YX}]$ is the FRF matrix from the inputs to the outputs, and $[S_{XX}]$ is the input cross-spectra matrix.

In doing so, the phase variation in the FRF is removed, since the phasing relationship of the accelerometers should be mostly real at resonance. An example of the FRF-generated cross spectra for several DOFs is presented in Fig. 11.

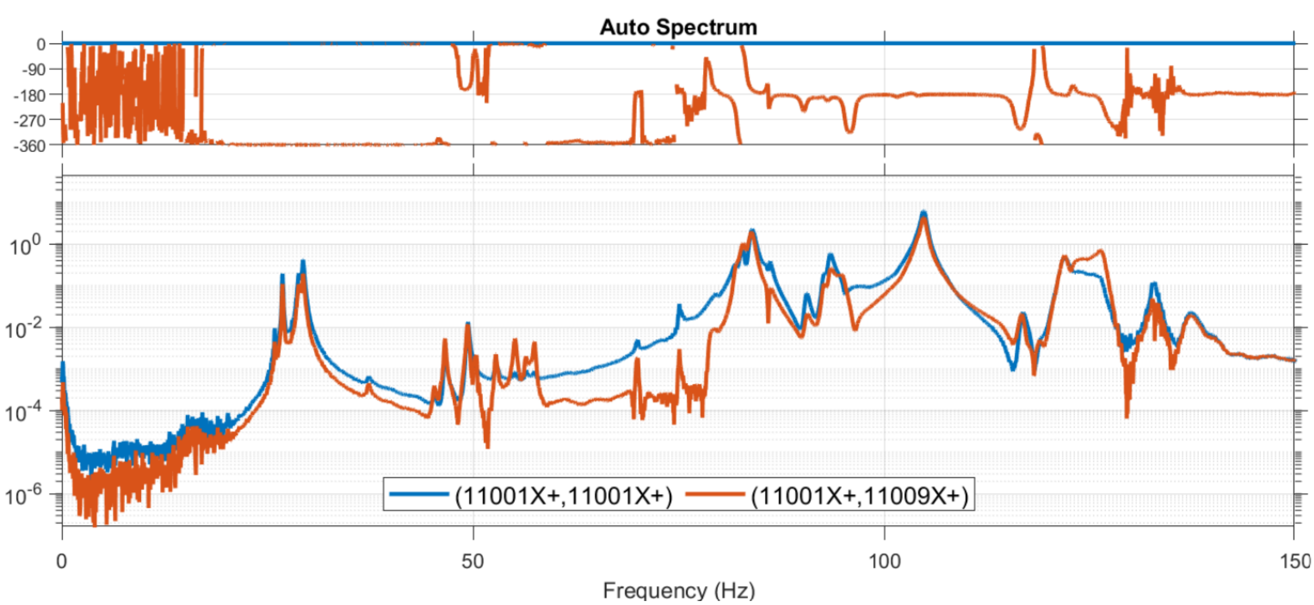

Fig. 11 Example FRF-generated cross-spectra matrix. Note that response is mostly real at resonant frequencies.

Once the data has been converted to the acceleration cross-spectra format, the same process as described in the OMA section was used.

Modal Extraction Results

Table 1 presents modal analysis results from using measured acceleration cross-spectra data and FRF-generated cross spectra for modes from 25 to 60 Hz as well as the 105 Hz mode. The 105 Hz mode is an actual mode that was verified through tap testing. Overall, both methods worked well for cases where the modes were well observed in the functions. There was one discrepancy in the cross-MAC at the low-observable 52 Hz mode, and for most cases the damping predictions were higher for the cross-spectra data than for the FRF-generated data.

Table 1 Modal extraction results: acceleration cross spectra vs. FRF-generated cross spectra.

Mode Number	Acceleration Cross Spectra		FRF-Generated Cross Spectra		Ratio		Cross MAC
	Frequency Hz	Damping %Crit	Frequency Hz	Damping %Crit	OMA/FRF Frequency	OMA/FRF Damping	
1	25.89	0.64	25.93	0.43	1.00	1.49	97
2	26.82	0.29	26.84	0.21	1.00	1.40	100
3	28.84	0.64	28.81	0.50	1.00	1.28	100
4	29.40	0.70	29.35	0.52	1.00	1.33	99
5	37.35	0.66	37.40	0.50	1.00	1.32	100
6	45.30	0.45	45.29	0.53	1.00	0.84	100
7	46.54	0.21	46.58	0.25	1.00	0.87	99
8	49.37	0.32	49.37	0.30	1.00	1.05	99
9	50.39	0.22	50.41	0.26	1.00	0.85	99
10	52.62	0.38	52.76	0.13	1.00	2.88	78
11	55.13	0.29	55.12	0.31	1.00	0.94	100
12	56.41	0.30	56.44	0.30	1.00	1.00	97
13	56.89	0.38	56.88	0.37	1.00	1.02	98
14	57.46	0.28	57.48	0.28	1.00	0.98	100
15	106.01	3.04	104.74	0.50	1.01	6.08	98

Plots of the first four modes are presented in Fig. 12. The first two modes are the primary modes of the side panels. The fifth mode is the primary mode of the top panel, and the fifteenth mode is the 104 Hz mode.

Additionally, low-frequency lateral and vertical modes of the test article on isolators extracted from the acceleration cross-spectra data are presented in Table 2. The relatively high damping values are likely due to the interaction between the primary modes and the heavily damped rubber mounts. The first lateral rocking mode is shown in Fig. 13.

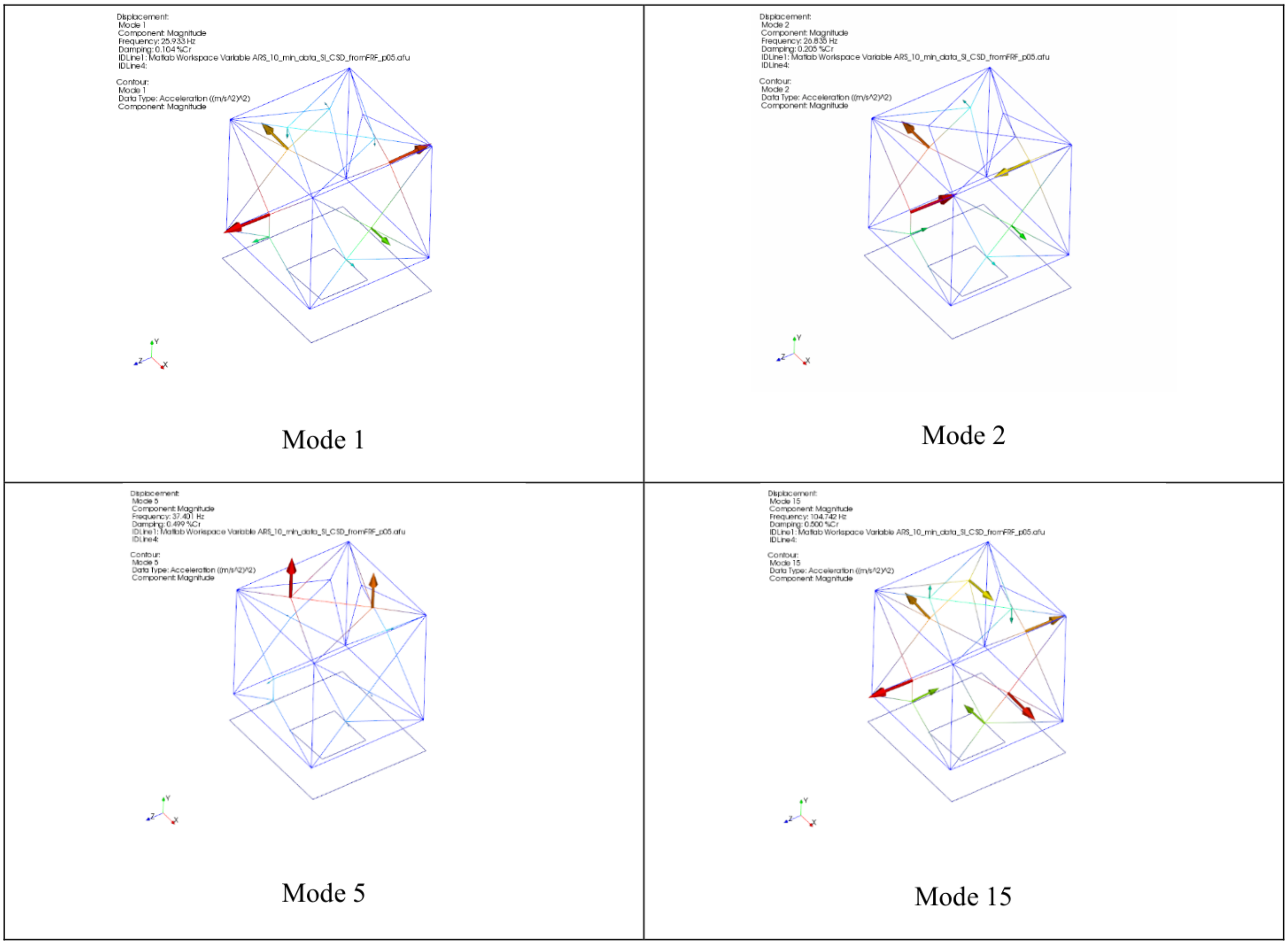

Fig. 12 Example back-expanded plots for modes 1, 2, 5, and 15.

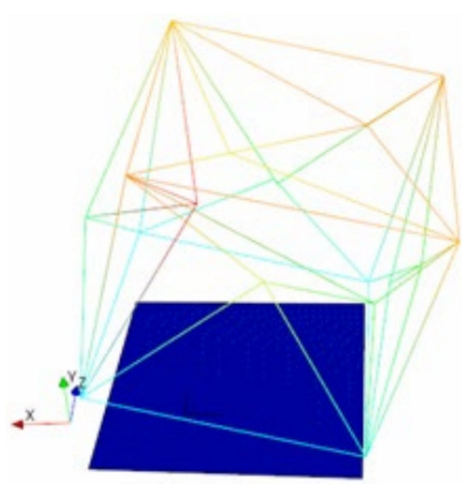

Fig. 13 First low-frequency mode – primary lateral X.

Table 2 Low-frequency OMA results.

Mode Number	Frequency Hz	Damping %Crit
1	5.76	3.06
2	6.24	5.58
3	9.92	1.67
4	17.1	1.62

Summary and Observations

This paper verifies the feasibility of extracting mode shapes from accelerometers excited by DFAN acoustic noise. In addition to using OMA on measured acceleration cross-spectra matrices, FRF-generated cross-spectra matrices were used to extract modal parameters. While both methods were able to extract many modes, the FRFs better characterize a poorly excited mode near 52 Hz and better estimate damping of a mode near 104 Hz. Likewise, OMA was able to extract estimates of mode shapes at low frequencies where the input sound pressure was not active.

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