EXPERIMENTAL CORRELATION OF DFAT® SIMULATION

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ABSTRACT

Spacecraft vibroacoustic qualification testing is traditionally done in reverberation chambers. A Direct Field Acoustic Test® (DFAT®) is an alternative test approach. It is desirable to model the test in detail to have confidence that the test will not damage the flight hardware and will be a reasonable equivalent to a reverberant field or other desired sound field characteristic with principal differences visible and planned for. In this paper, a simulation of the DFAT test will be demonstrated. This paper introduces a new optimization algorithm allowing the prioritization of sound field level versus diffusivity. General concepts and comparisons to previous methods are presented. This new implementation is then used to perform a correlation study against test data on a flight article including measured sound pressure levels as well as structural responses and the influence of the test room ceiling on the DFAT microphone responses.

1. INTRODUCTION

Direct Field Acoustic Testing (DFAT®) is a practical and portable approach to creating high-level acoustic fields to test spacecraft hardware. Arrays of powerful speakers are placed surrounding the test article as an alternative to the customary reverberant room facility excited by speakers or horns to achieve a target acoustic pressure level with known or expected diffusivity throughout most of the frequency range. The DFAT method actually offers more flexibility than reverberant room testing as the number, type, location and correlation of the individual speakers and grouped speaker stacks can be reconfigured to simulate a wide range of correlated loads corresponding to single or combined propagating wavefields, turbulent boundary layers or diffuse acoustic fields in any desired or expected combination. In addition, DFAT offers the key advantage of being able to bring the test system to the test article instead of undertaking costly, time-consuming and risky transportation to a reverberant room facility whose scheduled use may also introduce a delay in the development time.

The value of the flexible types of sound fields that can be generated by DFAT testing, including a standard reverberant field, are enhanced by a simulation model, unique to each test article and DFAT configuration due to test article interaction with the sound field. The simulation model can confirm that the desired sound field and target levels are achieved or help design the test to come closest to the desired sound field characterization. In this modeling approach both the sound pressure field inside the speaker stacks and the structural response of the payload are predicted. While simulating complex acoustic environments such as DFAT, initial simulation algorithms did not offer the flexibility to prioritize acoustic levels vs. ensuring diffusivity. However, when performing a correlation study, amplitude at given microphones is often prioritized versus diffusivity and this can be explored and optimized in the simulation.

With a validated modeling approach, it is possible to investigate the characteristics of the sound field in ways that cannot be done in an experimental context alone, particularly since test microphones are too limited in number to be able to definitely measure the sound field correlation and variance within the sound field at all but the lowest frequencies – these are parameters which can reliably be simulated. The modeling provides a method to understand the consequences of the test both during the payload design process and during the test development. This provides a means to use the model to help design the most appropriate test plan and to increase confidence that the test will demonstrate suitability for the intended mission.

2. DIRECT FIELD ACOUSTIC TESTING

Spacecraft qualification testing is typically done in a reverberant chamber. These tests are intended to ensure that structures will not fail due to vibration introduced by acoustic loads encountered during operational use. The sound pressure levels for these tests are very high, usually representative of the levels experienced at launch. They are intended to test the high estimate of a statistical envelope of the sound pressure levels that the payload or test article is expected to experience during the entire mission including takeoff and any other extreme acoustic environment. These levels are sometimes reduced due to limitations of speaker systems and their maximum power and performance which often fall short of the same levels as actual launch condition acoustic levels. Also, low-frequency control of the sound field levels and reverberant character can be challenging or limited. But in short, these facilities are designed to be suitably loud.

Direct Field Acoustic Testing (DFAT) is a test method that can be brought to the test article and tested in a typical industrial facility. This has advantages in reducing travel risk of flight hardware. Avoiding the travel to an acoustic facility also saves time in the schedule. In addition, having a DFAT capability may replace the need for a dedicated acoustic reverberation room. The first DFAT test was conducted in 1998 on the NASA/JPL QUIKSCAT spacecraft [1]. The testing process has been under continuous refinement since that time and MSI-DFAT has performed 176 successful tests to date.

Figure 1: Typical DFAT Test Setup with near stacks removed (courtesy MSI-DFAT)

The DFAT test consists of surrounding the test article with many specially designed loudspeaker systems capable of required high acoustic output." A typical test setup is shown in Figure 1. Typically, the speakers are stacked in a circular pattern around the test article and stacked somewhat higher than the test article. Often there will be speaker boxes that are tuned for low frequency and speaker boxes for the mid and high frequencies. Driving the speakers to produce the sound pressure levels experienced by spacecraft and other payloads in launch vehicles takes many high output speakers, often over 100, and a corresponding amount of power. A large bank of amplifiers is required to drive the speakers.

A real-time control system drives the test. This control system is a multi-input, multi-output control system. There are several microphones providing the inputs to the controller. These are designated the control microphones. There are several output channels to drive the speakers. These are the control signals. There are typically about 12 to 16 output control signals. Because each speaker box may have several individual speaker cones and there are often well over 100 speaker boxes, there are not usually enough output signals to control each speaker box, let alone to independently control each speaker cone. The test setup links the control signals to groups of speaker boxes. Designing the optimal correlation of the groups of speakers requires experience and benefits from support and guiding information. A DFAT model can provide this insight into optimizing the distribution of the control signals by indicating its impact on the sound field and optimizing which correlation will give results closest to the target.

The control microphones feed sound field data back to the control system which takes the sound pressure levels as inputs and uses them to determine the output signals to drive the speakers. There are also monitor microphones to measure the sound field at other locations than the control microphone locations. In addition, there may be accelerometers or other transducers on the payload structure to monitor the structural response which is the critical parameter being studied and for which the entire test is designed.

The qualification of space flight hardware is well established through testing of flight hardware in acoustic reverberation rooms. The reverberation room is designed to provide a diffuse acoustic field inside the room. The qualification process is tuned to having diffuse acoustic fields. All acoustic environments the payload is expected to be subjected to during its mission will be boiled down to one environment that will be used to design the test environment. This test environment has traditionally been assumed to be diffuse. In practice this is suitably conservative as in a diffuse field there is no angle in which acoustic incident energy is not present and impinging on the test article, whose structural response sensitivity often has a strong reliance on angle of excitation.

The DFAT control system is typically given a target cost function so that it attempts to drive all control microphones to the target sound pressure level and to also drive the control microphones to experience a cross-correlation function of a perfectly diffuse field. Often the cross-correlation target is set to zero correlation. This should have the effect of minimizing the cross-correlation which results in the minimum physically available cross-correlation which is the perfectly diffuse field.

The control system starts with a measured model of the system (the relationship between the control signal and the control microphones). As the system runs, it updates both the model of the system and the control signals to attempt to move the control microphones to the desired conditions (the sound pressure level and the cross-spectral matrix between the control microphones).

The control system uses a standard, best-practice speaker setup and correlation which generally allows it to converge more quickly and stably to a configuration in which the target levels and correlation are met. The optimal setup, designed and confirmed by simulation, also ensures that the closest approach to the target levels and correlation are achieved as the extra efficiency from this optimization translates into the ability to reach the very high acoustic levels that are targeted but which are often not reached due to speaker power limitations combined with non-optimized test design including non-ideal correlation of groups of speakers in the control system.

3. MODELING THE DFAT TEST

A DFAT test has many moving parts. There are several aspects that must be considered in the modeling of a DFAT test. The main parts are the acoustic field, the payload, the speaker stacks, the electronics (speakers, power supplies, wiring, and connections), and the control system. The DFAT test is a complex, time-domain system that pumps a large amount of power into an acoustic space and controls it to a specific spatial / temporal acoustic field. This complexity poses significant challenges to modeling. The current model will assume that over a short period of time the control system will achieve a steady-state response near the desired acoustic properties and thus a frequency domain steady-state model is be developed at the target acoustic field.

3.1. Acoustic field

The acoustic field is the sound carried by the fluid, in this case air, surrounding the payload. Basically, the fluid in the room carries the sound and needs to be modeled. For practical reasons the air in the interior of the speaker stacks is the most important location for response calculation and is the focus of the model. There are several technologies that can be used to model this type of acoustic field such as Ray Tracing, Finite Element Analysis (FE), or Boundary Element Analysis (BEM). In this case, the Boundary Element Analysis method was chosen.

BEM is a deterministic numerical method that solves the wave equation in three-dimensional space. What sets BEM apart from most of the other approaches is that in the interior of the fluid an exact analytical expression is used. The surfaces that contain the fluid, called the boundary, are meshed. The surface meshes are discretized with elemental piecewise polynomials to approximate the acoustic pressure and surface velocity response in the fluid. The relationships between the acoustic pressures and the surface velocities on all boundary surfaces are computed by the BEM solver.

In the DFAT model, the boundary surfaces will include the speaker surfaces, and the surfaces of the payload. The floor of the test facility is usually put in as an analytical reflecting plane. Other surfaces in the test facility may be included in the model but are often omitted as their effects on the sound field near the payload are negligible.

BEM provides a highly accurate model of the acoustic field between the speakers and the payload. It only requires surface meshes of the large surfaces in the model. It can compute the sound pressure at any location such as the microphone locations in the test. It can also compute the sound pressure on a “data recovery surface” which provides a good indication of field character and correlation. It couples well to structural finite element models and modern solvers have good performance which have improved significantly over time and will continue to improve going forward.

3.2. Payload

The payload structure is modeled with Finite Element (FE) Analysis. This is the standard structural modeling method and a suitable FE model is always expected and available for use. The payload FE model is easily and simply coupled to the acoustic BEM model. The BEM model will apply the acoustic excitation to the FE structure and the structural response will be predicted at any point of interest, accounting for the interaction between the payload structure and the acoustic field.

3.3. Speaker stacks

The speaker surfaces are meshed as boundaries of the acoustical fluid in the BEM model. The speakers provide the acoustic input and inject sound power into the space between the speakers and the payload. This is often done by specifying a surface velocity to the speaker. However, this can be improved upon as, in this study, both the surface velocity and an impedance will be applied to the speaker surface. This is the equivalent to turning an “ideal” source into a “realistic” source in electrical circuits with either Norton’s or Thevenin’s theory. The speaker impedance should be obtained by measurement at the surface of the speaker. In the DFAT model, the speaker cone velocity response drives the BEM acoustic field including both the control and observation microphone locations. The BEM pressure field then drives the FE structural response in a coupled, interactive calculation.

3.4. Electronics – speakers, power supplies, wiring, and connectivity

The internal speaker voice coil and other components are dynamically coupled to the power supplies through the wiring and eventually connected to the control signal. There is a significant amount of electro-dynamics that is difficult to predict. Most high-fidelity models of speakers involve a lot of empirical tuning to get right. These items are difficult to model so that they can be used in a predictive sense.

Therefore, in the current modeling process, the dynamics of the electronics will be eliminated from the model. This will be discussed further in the next section. At this point, the speaker surface velocities are the entry point into the model.

3.5. Control System

The control system is a real-time optimization algorithm that adaptively builds a model of the system between the control inputs and the observation microphones. A control algorithm attempts to control the response towards a target (cost function) by continuously updating the model and adapting the control signals. This will continue until the cost function is satisfied at the control microphones. This should approach a steady-state solution where the cost function is satisfied as well as possible given the physical constraints and the noise at the sensors. The DFAT model is a steady-state frequency domain model and if the sensor measurement error is low, it should provide a good prediction of the stabilized version of the generated sound field.

Recall that the control system develops a measured model between the control signals and then uses this model to take the gap between the desired and observed response at the control microphones to compute the control inputs. In the DFAT model, the model is developed between the control microphones and the speaker surface velocities. If the same control strategy is applied to the DFAT model as is done in the DFAT test, the test can be well modeled except for any limitations to obtaining an ideal solution caused by the dynamics in the electronic portions of the system.

One final part of the model must be defined. That is how the control signals are connected to the velocities of each speaker. Since there are only a few control signals compared to the number of speakers in the test, each signal controls several speakers. This information about how the control signals are distributed to the speakers must be defined. This brings the number of independent inputs down from the number of speakers or speaker cones to the number of control signals. Now the number of input variables in the DFAT model is equal to the number of control signals. These are the inputs to the BEM analysis. However, this can be solved as an inverse problem – given the microphone pressure response, what control signal amplitude (and cross-spectra) could have caused this microphone response. This can be formulated as an optimization problem. It is not a difficult problem since there are at least as many control microphones as there are control signals. This is an over-determined system and will give the best solution to the problem. That is exactly what the control system in the test is trying to do. The physical test has a harder task as it is doing it in real-time and with noise. But tests have proven quite adept at achieving the given cost functions. So, the DFAT model should provide the best-case solution of velocity sources to make the closest possible match to the given cost function.

3.6. Final model

Putting all the previously discussed portions of the model together, a modeling approach to the DFAT test has been laid out and implemented. This has been applied to DFAT tests and the results are presented in the following sections. Because the result of the modeling approach provides the speaker velocities that give the desired pressure response at the microphones, these velocities can be used to predict the vibro-acoustic response at any location in the fluid region or on the payload structure. This provides rich information to understand the DFAT test in detail, to design better tests, and to tune the testing environment.

4. EXPERIMENTAL VALIDATIONS

Two validation cases will be presented. The first case is a DFAT test of a mockup satellite used to develop testing procedures without risking flight hardware. The mockup satellite is flight-like, but not flight hardware. This DFAT test was done several years ago but does give a good demonstration of the DFAT results. The second validation case is a test facility for testing panels in a DFAT context. This test was done recently and represents a more current testing process and equipment.

4.1. Satellite DFAT test

In this case a DFAT test was performed on a satellite-like structure. The structure was made to be similar to a satellite but constructed of materials from other space programs. A structural FE model of the test structure was available as this structure was used for various method development projects. As described in the previous section, a boundary element model was coupled to the structural FE model.

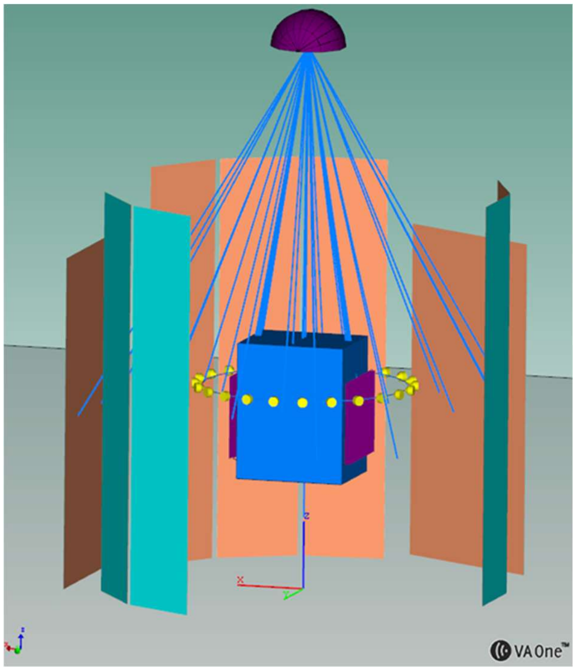

Figure 2. The BEM model of the satellite.

The BEM surface model can be seen in Figure 2. The tall rectangular surfaces represent the fronts of the speaker stacks. The stacks in front have been temporarily hidden in the model to be able to view the satellite. The peach color on the speaker stack signifies that a measured speaker impedance has been applied to that surface. It was found that modeling only the front of the speakers' boxes was adequate to get good predictions inside the ring of speaker stacks. The blue and purple box and panels inside the speaker stack ring represent the test article, a mocked-up satellite. The BEM fluid is represented by the purple hemisphere at the top of the model with lines that show connectivity to the surfaces in the BEM model. The floor of the space was included as an ideal reflecting surface to avoid adding another meshed surface. With this model, the control system response can be predicted as described in the modeling section. In addition, the pressure at any point in the model may be predicted as well as the structural response at any location in the FE model of the satellite.

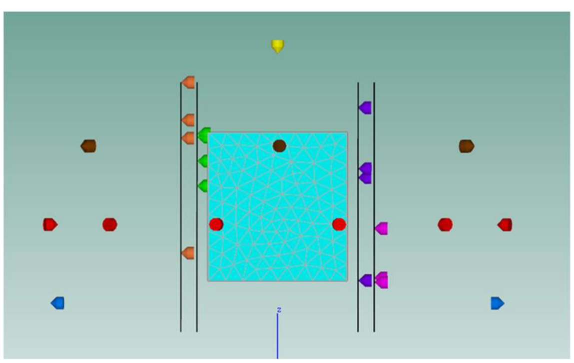

Figure 3. Control and Observer Microphones around the satellite.

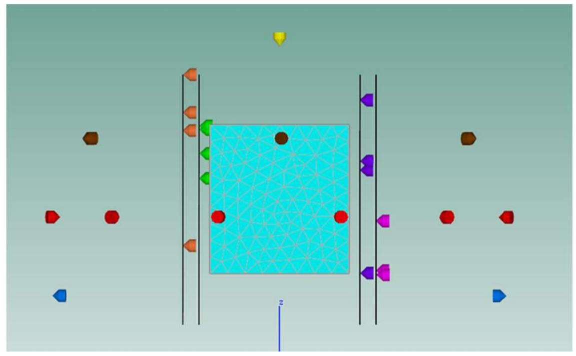

Figure 3 shows a closer view with the control microphones colored red, the observer microphones colored blue, brown, and yellow, and accelerometers on the solar panels of the satellite colored orange, green, purple, and pink.

The model was exercised as described in the modeling section. Each control signal was attached to the proper set of speakers. A target spectrum was given to the control microphones along with a target cross-spectral matrix, representing a diffuse field correlation. Then the best range of control signal velocities was identified. The sound pressure levels at the control microphones are shown in Figure 4 and Figure 5. It should be observed that both sets of microphones are clustered around the target pressure spectrum (in red). However, the model results provide a tighter cluster around the target. This isn't surprising considering that the test is performed in the presence of noise and is performed in real-time. In addition, the control algorithms have been improved and the tests are coming closer to the ideal.

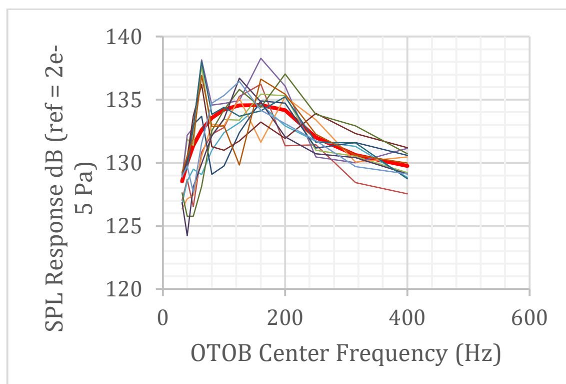

Figure 4. Control microphone data from the DFAT test.

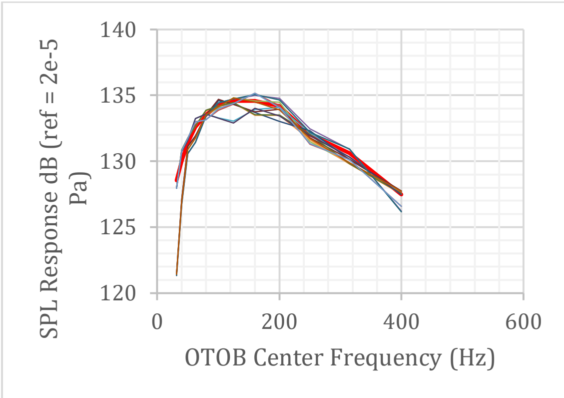

Figure 5. Control microphone data from the model.

It is also worth noting that the arrangement of the control microphones in a single ring has been shown to be problematic and make the convergence of the control system difficult (both in the model and the test). Current, updated testing process would instead scatter the control microphones at different heights and diameters from the center of the ring.

Figure 6 and Figure 7 show the observer microphone data from the test and the model. Interestingly, the observer microphone data looks to have a more similar character between that test and model than was observed with the control microphones. Also of interest is that both the test and model show the same microphone as the single highest outlier. This is particularly noticeable in the 63 Hz one-third octave band data.

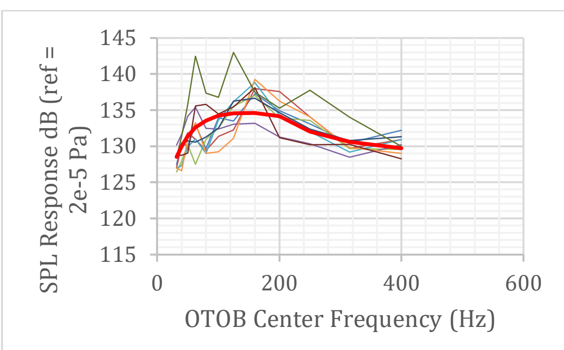

Figure 6. Observer microphone data from the DFAT test.

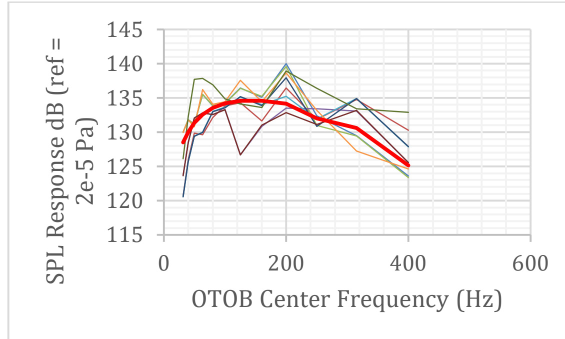

Figure 7. Observer microphone data from the model.

Six accelerometers had data available for comparison between the test and the model. These are shown in Figure 8 through Figure 13. Overall, the structural predictions compare well with the test data. This suggests the structural FE model is a good model for the structural behavior and that the acoustical model also does a good job of modeling the key physics correctly. This is particularly encouraging as it suggests that detailed models of the speaker and power supply dynamics are not necessary to capture the total system dynamics. Thus, the control system actively removes the impact of the electronics from the results. This should be true until the speakers are at max power or start to overheat and burn out the voice coil.

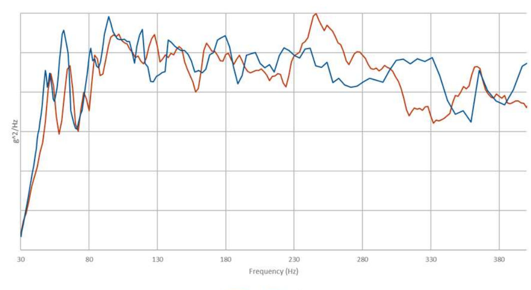

Figure 8. Accel 1 PSD (test--red, model--blue).

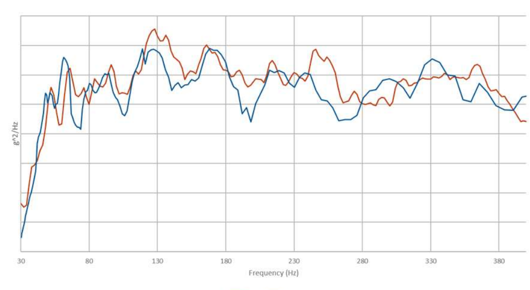

Figure 9. Accel 2 PSD (test--red, model--blue).

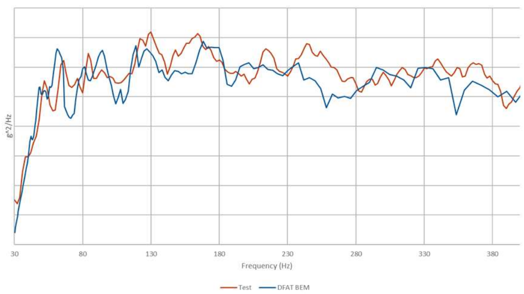

Figure 10. Accel 3 PSD (test--red, model--blue).

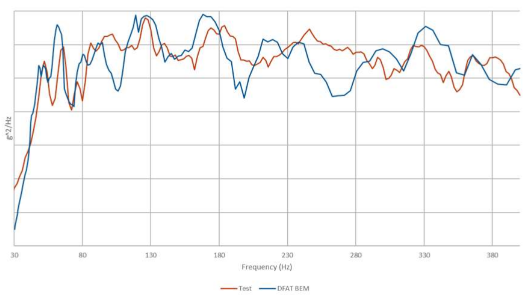

Figure 11. Accel 4 PSD (test--red, model--blue).

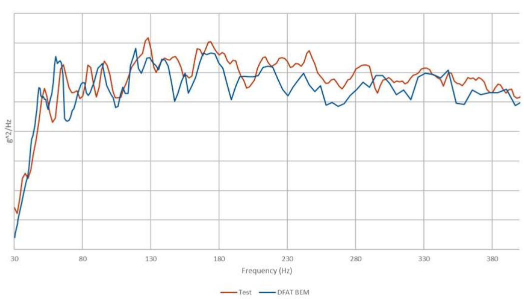

Figure 12. Accel 5 PSD (test--red, model--blue).

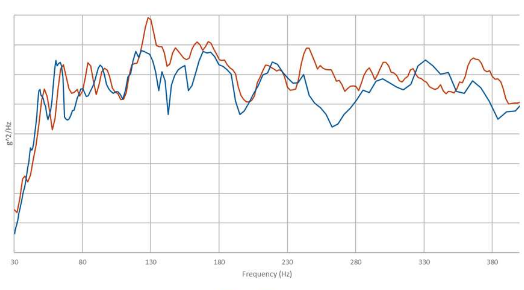

Figure 13. Accel 6 PSD (test--red, model--blue).

The model may be used to investigate the spatial nature of the sound field in greater detail than is possible in a test. An example of the predicted sound pressure field is shown in Figure 14. The pressures are plotted on surfaces where the data was requested from the model.

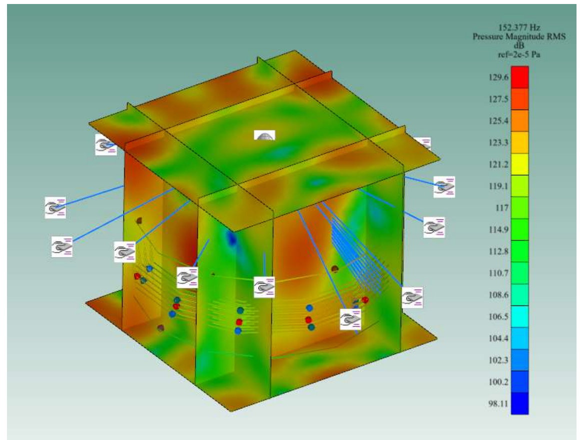

Figure 14. Predicted sound pressure distribution at 152 Hz.

The results from the model can give more insight by performing Fourier transforms of the pressure on these surfaces. This provides a wavenumber view of the data on a particular surface. The results of a wavenumber plot at 420 Hz in a reverberation chamber is shown in Figure 15 for a horizontal cross-section of the tested volume and shows a result consistent with a diffuse field.

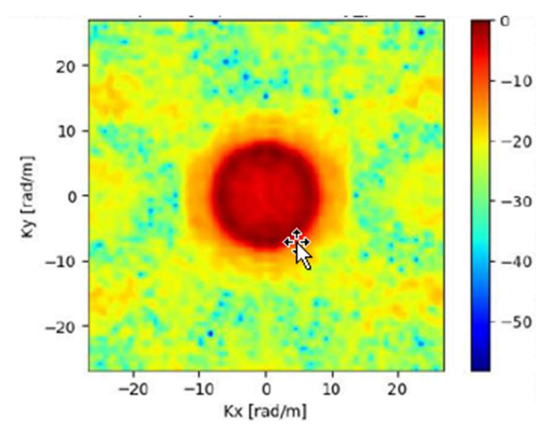

Figure 15. Normalized wavenumber spectra (k_x vs. k_y) of a reverberation chamber at 420 Hz.

The same data for the DFAT simulation result is shown in Figure 16 at a horizontal cross-section and in Figure 17 for a vertical cross-section of the same studied volume. It can be observed from the circular character of the acoustic energy that the field is significantly more diffuse in the horizontal direction than in the vertical direction which exhibits a concentration of acoustic energy less symmetrically distributed. This suggests that more acoustic energy has a more diffuse character in the horizontal direction than the vertical direction. This information from the model could be used to update or re-design the test. There is also the ability to design the ideal relationship between the control signals and the speakers to improve the diffuseness of the target sound fields.

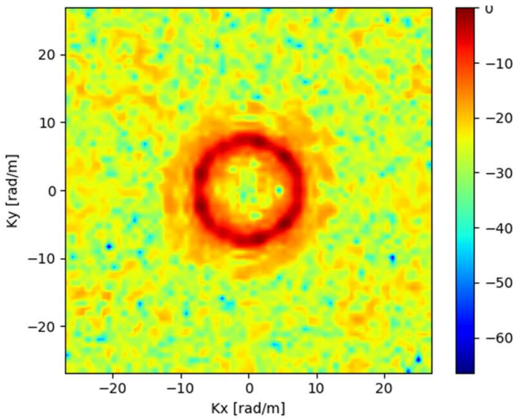

Figure 16.Normalized wavenumber spectra k_x vs. k_y) at 420 Hz for a horizontal plane.

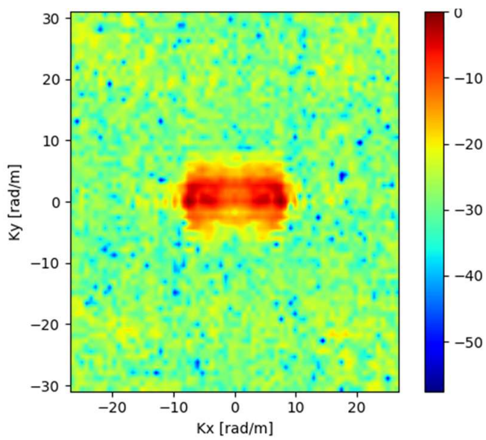

Figure 17. Normalized wavenumber spectra k_x vs. k_y) at 420 Hz for a vertical plane.

4.2. Panel DFAT test

A small DFAT test facility was used to investigate the ability of parallel banks of speakers to excite panels. A frame to hold the panels was built and banks of speakers were placed in both the front and rear of the panel structure. The frame was designed to hold 3 panels approximately 4 foot by 8 foot in size and can be seen in Figure 18. An FE model of the frame and panels was developed along with a BEM model. These are shown in Figure 19 along with the transducers used in the test.

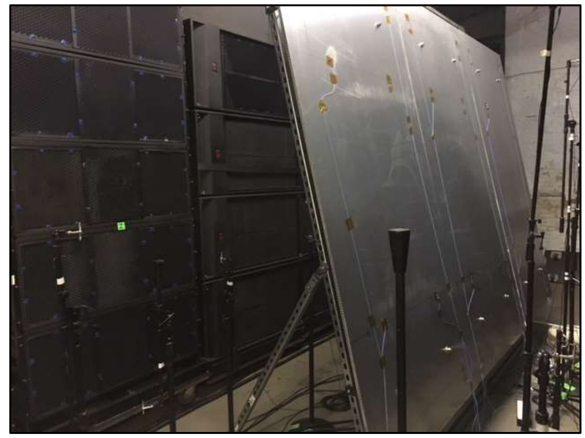

Figure 18. Frame of beams holding 3 panels in front of speaker stacks.

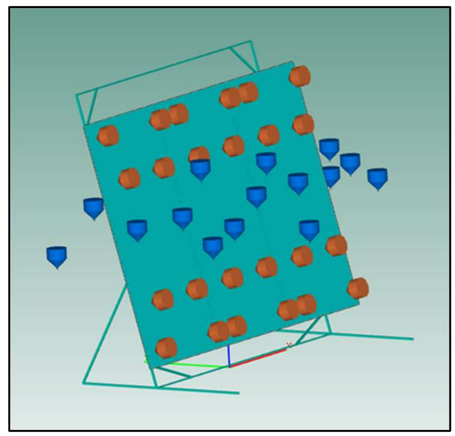

Figure 19. FE and BEM model of the test structure. The orange transducers are accelerometers (24) and the blue transducers are microphones (16 control and 8 observer).

Because this test was performed in a smaller space than a large high bay and the speakers were not arranged to close off the outer space, the BEM model was extended to cover the full extent of the room. The full BEM model can be seen in Figure 20. Otherwise the same modeling procedure was followed as presented above.

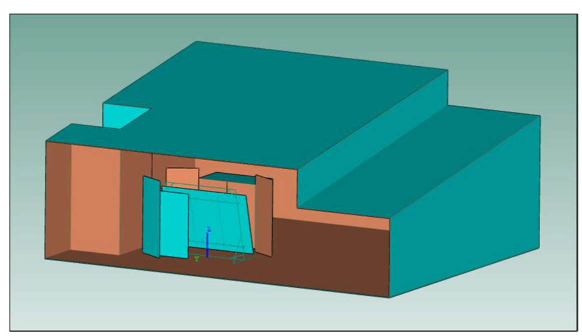

Figure 20. Full BEM model except the front wall and some speaker stacks were hidden for clarity.

The microphone data is shown below. Figure 21 shows the results from the control microphones and Figure 22 shows the results from the observer microphones. The overall acceleration of each accelerometer (test vs. model) is shown in Figure 23. The average accelerometer spectrum is shown in Figure 24. Note that accelerometer 2 was removed from the data. The microphone data looks similar except for a few frequencies where certain microphone results drop down. This implies that the BEM model is predicting a microphone is at a node line of a dominant mode. This behavior is also seen in the test, but not to the same level. Possibly the acoustic model has less damping than the room being tested or the theoretical pressure minima from the model are lower than the actual measured minima which take into account the discrete size effects and averaging on the microphone surface.

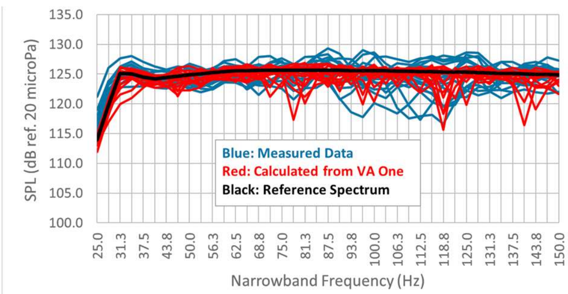

Figure 21. Control microphone comparison.

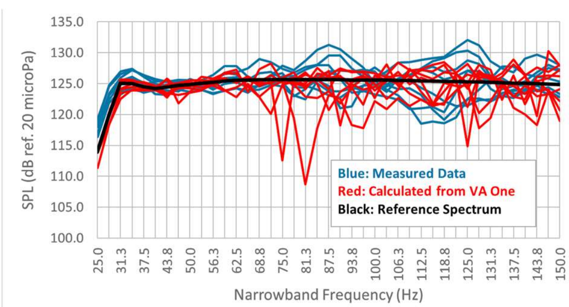

Figure 22. Observer microphone comparison.

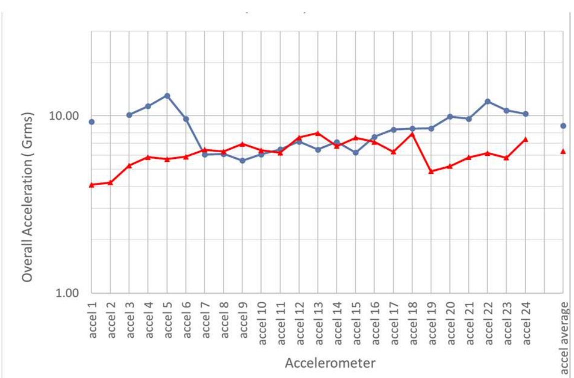

Figure 23. Overall accelerometer comparison. X-axis is accelerometer number.(test-blue,model-red)

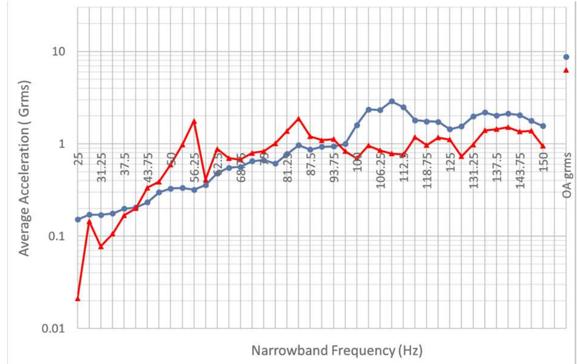

Figure 24. Comparison of the averages of all accelerometers. (test-blue,model-red)

The accuracy of the structural responses is encouraging, but the differences are interesting. It seems that the lowest- and the highest-numbered accelerometers systematically differ between the test and the model. On average the prediction is reasonably accurate over most of the spectrum, but the measured data is quite a bit higher in the region from 100-120 Hz. There is also an interesting peak at 56 Hz in the model data that is not reflected at all in the test data. It will be interesting to understand these details. Overall, this is a good example of modifying the normal DFAT process to do a variant study with a change in focus. This suggests that acoustic testing with speaker stacks can be used in other contexts than spacecraft qualification.

With the model, it is useful to investigate the uniformity of the sound pressure field. A contour plot of the region around the panels is presented at representative frequencies in Figure 25 and Figure 26. The corresponding structural response is shown in Figure 27 and Figure 28.

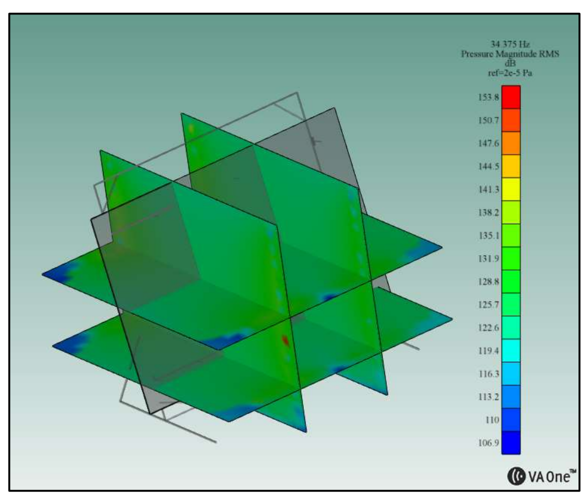

Figure 25. The sound pressure response around the panels at 34 Hz.

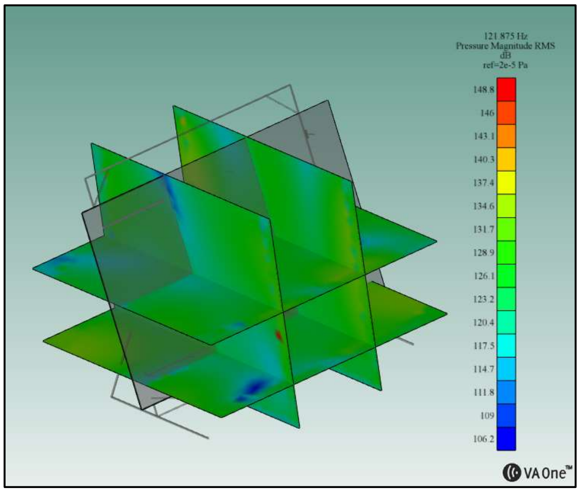

Figure 26. The sound pressure response around the panels at 122 Hz.

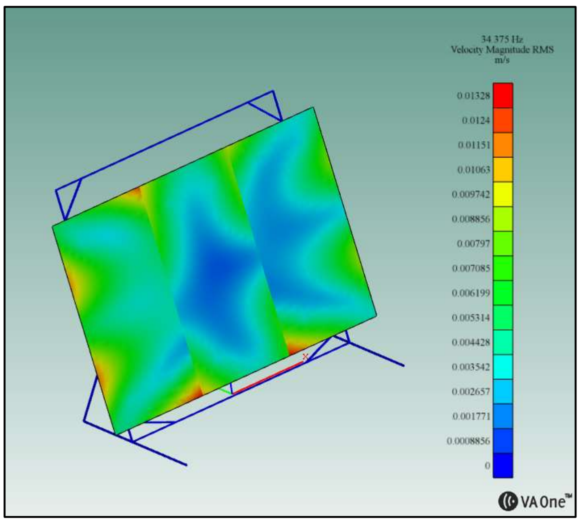

Figure 27. The panel velocity field at 34 Hz.

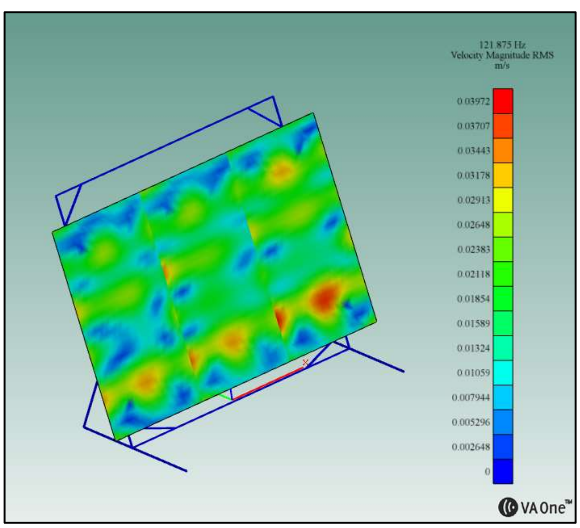

Figure 28. The panel velocity field at 122 Hz.

5. Investigations

The comparisons between test results and simulation illustrate some of the ways in which the simulation can be productively used to confirm the validity and optimization of the test, which is unique for every structural article tested due to the strong interactions between lightweight structure and surrounding sound field. It also shows some of the key results which can only be viewed and evaluated in the simulation due to the limited number of transducers that can ultimately be used to evaluate the response (and including the fact that the transducers themselves may influence the measurements at the higher frequencies).

In terms of supporting and confirming the test design and setup, the simulation can help to support and answer the following questions:

1. Are the targets theoretically achievable for a given speaker setup? Or will changes to max power levels, number of speakers or setup geometry be required?
2. Are the control microphones in the optimal place to drive an efficient control loop for the system? What are the ideal locations for the control microphones for optimum efficiency?
3. What are the better options for grouping speakers under the same control channel to reach max efficiency (highest levels and most diffuse field) given that there are many fewer channels than speakers and that the control loop isn't capable of moving speakers between different channels?

In terms of useful result evaluation to characterize and confirm the nature of the resultant sound field and its interaction with the test structure, the simulation can provide the following results which are nearly impossible to reliably obtain from a limited, discrete number of transducers:

1. Does the correlation detail of the sound field at all frequencies of interest look diffuse or else of the targeted character (specified as target correlation in the simulation input)? This can be seen qualitatively by looking at data recovery surface cross-sections in different orientations as illustrated in section 4.1.
2. Is the vertical plane diffusivity sufficient at and near the payload? It is often much less than the horizontal plane diffusivity and may be a challenge to achieve due to the speakers facing parallel to the floor (it is unusual to have top speakers facing down and never the case to have ground speakers facing up, although both are possible DFAT configurations).
3. Are there angles of incidence for the sound field interacting with the structure which inject significantly more or less acoustic power than the average over all angles (to be able to

consider and plan for regarding how this may overtest or undertest the structure?

These types of results related to each unique test setup can be used to build confidence in and adjust the test as well as to have some key results that impact structural qualification and design beyond what the very valuable but necessarily more limited physical test is able to provide due to a finite number of transducers. With the potential for DFAT to create test fields other than approximately diffuse, simulation of the field both pre and post-test would be even more important.

6. CONCLUSIONS

DFAT tests can be modeled with adequate accuracy. These models can be used to provide certainty that the payload will pass qualification and minimize schedule impact risk. They can also be used to design and optimize the test setup. They provide a wealth of information about the acoustic fields in the test which can be used to improve the test and testing process. As the fields in flight are better understood, this type of model can help design tests that move beyond just reverberant fields to be more like the actual flight environments.

7. ACKNOWLEDGEMENTS

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