INVESTIGATING DIFFUSIVITY OF VIRTUAL DIFFUSE FIELD ACOUSTIC TEST (DFAT) USING BOUNDARY ELEMENT MODELING AND WAVENUMBER-FREQUENCY ANALYSIS

Alexis Castel (1), Bryce Gardner (2), Chadwyck Musser (3), Augusto Medeiros (4), Luca Alimonti (5)

(1) ESI NA, 32605 W 12 Mile Road, Suite 350, Farmington Hills, MI 48334, USA, alexis.castel@esi-group.com
(2) ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, bryce.gardner@esi-group.com
(3) ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, chad.musser@esi-group.com
(4) ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, augusto.medeiros@esi-group.com
(5) ESI US R&D, 12555 High Bluff Drive, Suite 175, San Diego, CA 92130, USA, luca.alimonti@esi-group.com

ABSTRACT

In an ongoing effort to complement or replace expensive, time-consuming and potentially damaging (due to transportation) acoustic qualification testing of aerospace systems in reverberant chambers, Direct Field Acoustic Testing® (DFAT®) is an alternative that has been examined more closely in recent years. In DFAT testing, the structure to be tested is positioned in the center of a set of speaker stacks which commonly have several input channels that can be independently controlled to obtain an acoustic field that is as uniform as possible. A set of control microphones is used to indicate diffusivity (through levels and cross-correlation) and to provide inputs to the control system to actively adapt the speaker inputs to optimize diffusivity. However, these control microphones can only define the field characteristics at a limited number of points which are generally not sufficient to be able to evaluate the overall diffusivity inside the testing volume. To more thoroughly investigate the field diffusivity at significantly more points of interest in the test volume, the test setup may be modeled using numerical methods, particularly the Boundary Elements Method (BEM). BEM models offer flexibility for exploring the effect of different speaker configurations and inputs and for probing the acoustic field at multiple locations to check for "hot spots" or "cancellation" regions. It is of particular interest to identify DFAT "cancellation" regions where, in contrast to the reverberant chamber testing, the assumed fully diffuse acoustic field is not present and therefore the assumed incident acoustic energy from a range of angles that may cause strong structural excitation is not present. Potentially missing acoustic energy from important incident angles is one of the principal shortcomings of DFAT testing versus using a reverberant chamber and being able to predict and improve this is key to being able to use a DFAT test with confidence. In this paper, a methodology is proposed for looking at the diffusivity characteristics of representative DFAT configurations using Wavenumber-Frequency Spectra (WFS) computed from a BEM-simulated acoustic field at several planes inside the volume enclosed by the speakers. For different excitation configurations, resulting WFS are compared to the ideal diffuse acoustic field WFS and to other WFS including propagating waves to gather insights from the predicted acoustic field at different angles of orientation. Simulations are also carried out including a test specimen to investigate the influence of the structure on the acoustic field.

1. INTRODUCTION

The evolution of control system technology has allowed active control loop to precisely handle complex systems to higher frequencies. Originally used for active noise cancellation, the same technique can be used to control an acoustic field in an open space, constraining measured locations to precise levels, phase or even relative coherence. This is a key enabler for the Direct Field Acoustic Testing (DFAT) technology and allows for a portable high-intensity acoustic test system for the qualification of aerospace systems which can replace the traditional reverberant chamber tests. For this test approach, stacks of speakers are placed around the test article and a controller produces a sound field based on the levels measured by control microphones. Additional monitor microphones are usually also placed around the structure in order to ensure required levels are met at a larger number of locations around the structure (as opposed to simply monitoring at locations of the control microphones). The method is described in [1] and has been accepted and used in the structural qualification process by multiple spacecraft and launch vehicle manufacturers. Recent DFAT tests include the Orion E-STA module and the Boeing SLS/EUS Path Finder.

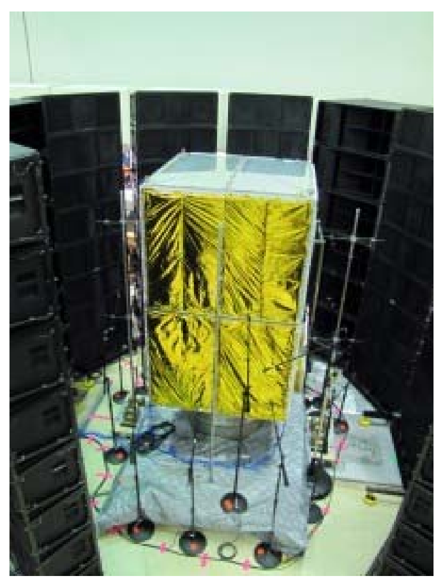

Figure 1. DFAT setup (image credit: msi-dfat.com)

However, simulation methods have not until recently provided a definite and validated technique to model the sound field from a DFAT test. A Diffuse Acoustic Field (DAF) can easily be emulated by a sum of incoherent plane waves impacting the structure from all directions and this is the standard modeling method to simulate reverberant room test acoustic fields (subject to some low-frequency assumptions related to room size and characteristics). However, this simplified representation is not appropriate for modeling the more complex acoustic field created by the speaker stacks around the structure and the control loop. Indeed, one can expect additional reflections and standing waves produced by the stacks of speakers and some incidence angles have more or less acoustic power in a more or less direct path from the source depending on the relative speaker positions in the test. As the Boundary Element Method (BEM) is usually the method of choice to model a reverberant field in a large and / or unbounded volume, over recent years multiple studies have shown promising abilities of BEM to model the DFAT field [2] [3] [4] [5].

Moreover, simulation can play an important role for DFAT; in addition to predicting structural response, it can also be used to either optimize the test setup or to ensure the acoustic field will possess the right characteristics such as amplitude and/or diffusivity as well as avoiding hot spots or cancellation regions. In this paper, a methodology to establish the sound field characteristics is proposed by using BEM simulation and then computing Wavenumber-Frequency Spectra (WFS) in the DFAT sound field. First the methodology, describing the transformation of field pressure cross-spectra to WFS, is presented. Then a study showing the key differences between the idealized DAF and the more complex DFAT field is presented. Finally, a test specimen is introduced into the model and a comparison of the two different acoustic fields is repeated when a structure influences the acoustic field.

2. OBTAINING WFS FROM DFAT SIMULATION

For modelling high-intensity acoustic qualification tests, BEM is traditionally used with the acoustic load modeled as a DAF represented as a sum of incoherent plane waves and a cross-spectral equation is often employed to model the system. Considering the cross-spectral excitation written as a matrix $[S_{ww}]$, the cross-spectral nodal structural response $[S_{nn}]$ and the matrix of the assembled transfer functions between each plane wave and each node on the structure $[H_{nw}]$, one can write:

$$[S_{nn}] = [H_{nw}][S_{ww}][H_{nw}]^H \qquad (1)$$

For this, $[H_{nw}]$ depends on both the behavior of the acoustic domain and the dynamic stiffness matrix of the structure. Here, $[\blacksquare]^H$ represents the conjugate transpose or Hermitian transpose of the matrix. As all the plane waves are incoherent, $[S_{ww}]$ is a diagonal matrix with the squared amplitude of each plane wave on the diagonal of the matrix. As $[H_{nw}]$ is obtained from the combination of the BEM calculation and the structural dynamic stiffness matrix, it can be fully populated and complex. It is also expected that $[S_{nn}]$ is also fully populated with the squared amplitude of the response at each node on the diagonal and the cross-spectral amplitude between each node for the off-diagonal terms. Generally, one focuses on response amplitude and discards off-diagonal terms.

A similar equation can also be written to provide a relationship between the excitation $[S_{ww}]$ and pressure in the acoustic field $\left[S_{pp}\right]$, giving the amplitude and cross spectra of the pressures in the acoustic field:

$$\left[S_{pp}\right] = \left[H_{pw}\right][S_{ww}]\left[H_{pw}\right]^H \qquad (2)$$

Perfectly diffuse acoustic fields possess a known cross-correlation for any two positions separated by a distance r that is given by:

$$S_{pp}(r) = A\frac{\sin(k_0 r)}{k_0 r} \qquad (3)$$

where k_0 is the acoustic wavenumber. Therefore, for a uniform DAF, $\left[S_{pp}\right]$ is known.

Given a Space-Frequency correlation on a plane, one can perform a 2-D Fourier Transform in the two spatial directions to obtain the WFS:

$$S_{pp}(\mathbf{k},\omega) = \mathrm{FFT}(\left[S_{pp}(\mathbf{x},\omega)\right]) \qquad (4)$$

where $\mathbf{k}$ is the 2D wavenumber, ω is the angular frequency and $\mathbf{x}$ is the 2D spatial coordinate. As $\left[S_{pp}(\mathbf{x},\omega)\right]$ is known for a uniform DAF, $S_{pp}(\mathbf{k},\omega)$ possesses an analytical formulation for the same field:

$$S_{pp}(\mathbf{k},\omega) = \frac{2\pi}{k_0^2}\frac{1}{\sqrt{1-|\mathbf{k}|^2/k_0^2}}, |\mathbf{k}| < k_0 \qquad (5)$$

This can be represented by the WFS presented in Figure 2 for a perfectly diffuse acoustic field, where one can see the well-known and expected acoustic circle showing that all acoustic energy is contained between the wavenumbers from 0 to k_0.

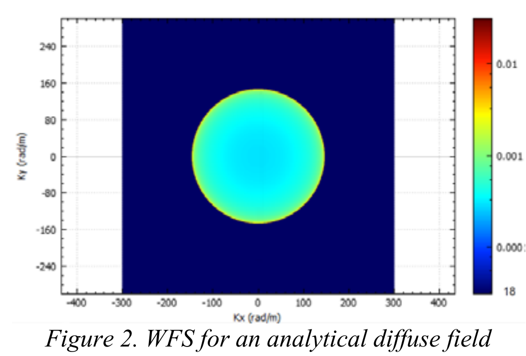

Figure 2. WFS for an analytical diffuse field

Generally, it is accepted that when applying a set of incoherent plane waves, $[S_{pp}]$ and generally the WFS for points in the far field (away from the test article and its influence on the acoustic field) have the characteristics of a DAF. As one can recover the pressure and $[S_{pp}]$ in a DFAT BEM simulation for any arbitrary acoustic field, the corresponding WFS from a more complex acoustic field can be used to evaluate the similarities and differences between the DAF and DFAT sound field in terms of diffusivity and indicate if a proposed speaker stack configuration is close to the ideal acoustic diffusivity for a given frequency or not.

3. DFAT MODEL CONSTRUCTION

As explained in the introduction, in order to construct a DFAT model, the speaker dimensions and local impedance need to be represented. In a representative VA One^{TM} BEM model simulating a DFAT setup, faces represent each correlated stack and a velocity constraint is applied to each face. To increase the accuracy of the model, the measured area impedance of each stack is placed on each face.

As the speakers are all fully correlated over the z direction, one should expect a reasonable amount of diffusivity in the XY plane but little diffusivity over the z direction. In fact, this relatively low expected diffusivity over the z direction is one of the principal concerns regarding differences in acoustic field between DFAT testing and reverberant room testing.

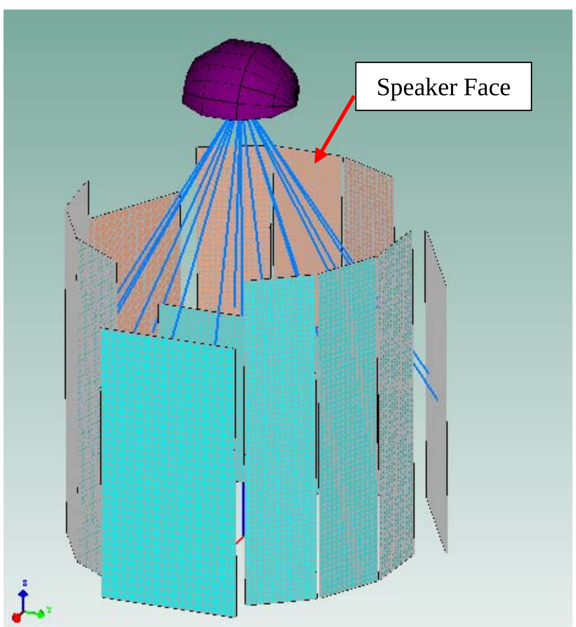

Figure 3. Representative DFAT Model using BEM

The most usual BEM modeling approaches are either fully correlated (deterministic) or fully uncorrelated (random) loads. The closer of these two options to the typical DFAT test is the random (fully uncorrelated) load. In this case the excitation matrix defining the velocity constraints is called $[S_{vv}]$ and all of its terms are optimized to provide an acoustic field that is as diffuse as possible based on responses at 24 chosen locations representing control microphones in the physical system (shown in Figure 7).

Two different types of speakers are used: six subwoofer stacks with the capability to provide efficient excitation up to 240 Hz and nine mid-frequency range speaker stacks where efficient excitation begins at 200 Hz. Therefore, only in the 200 – 240 Hz frequency range is there notable overlap and effective contribution to the acoustic field from all 15 speakers.

4. OPEN FIELD STUDY

One of the first simulation investigations was to study the diffusivity of a DFAT model without any structure present. A simple BEM fluid with a sum of 200 incoherent plane waves ($[S_{ww}]$ is then diagonal) was created with a data recovery plane where $[S_{pp}]$ can be recovered. A visual representation of this model is presented in Figure 4. The calculation is performed in 12th octave bands between 31.5 Hz and 420.25 Hz and the corresponding wavenumber-frequency spectrum is calculated. As the amplitude of the pressure is known from the analytical formulation, the quality of the model is mostly dependent on the number of plane waves present in the model. As frequency increases, one can see in Figure 5 the shape of the acoustic circle on the data recovery plane (parallel to the ground and in an orientation where good diffusivity is expected) begins to diverge due to discretization effects from the analytical shape of the acoustic circle presented in Figure 2. It is expected that increasing the number of plane waves in the model should improve diffusivity of the model if needed for good acoustic field high-frequency representation.

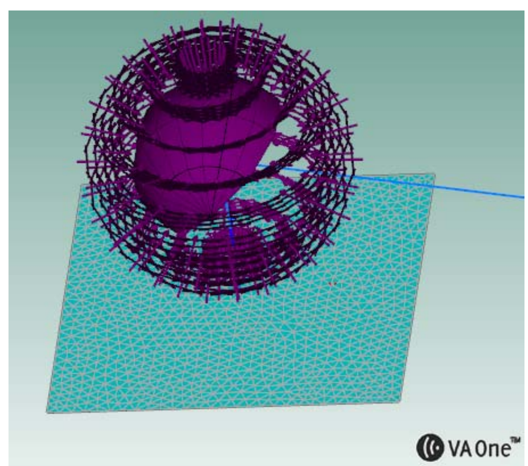

Figure 4. BEM model setup showing the set of incoherent plane waves

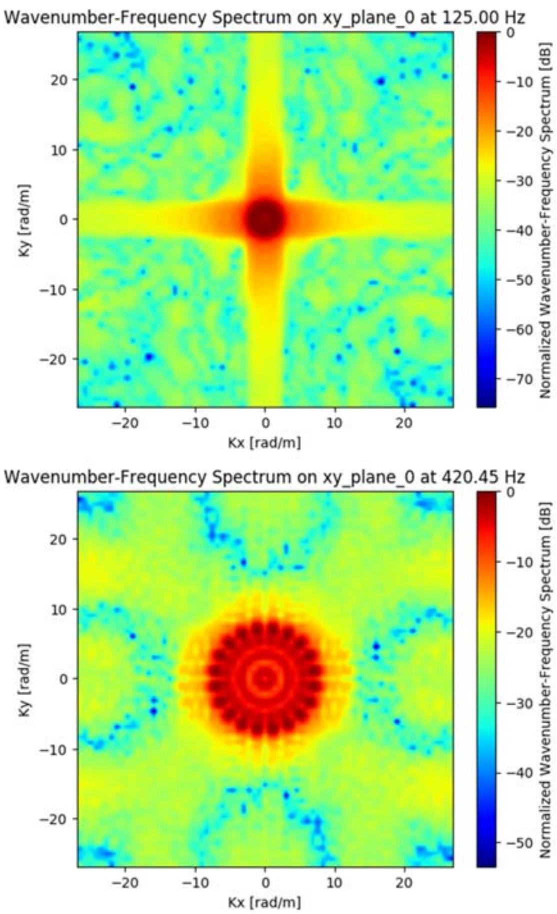

Figure 5. WFS for sum of plane waves at 125 Hz and 420.25 Hz

The second part of the open field study was a simulation of the DFAT setup consisting of a stack of speakers with two data recovery planes: one on the XY plane (parallel to the ground) and one on the YZ plane (normal to the ground) whose average pressure levels are presented in Figure 6 relative to a desired target.

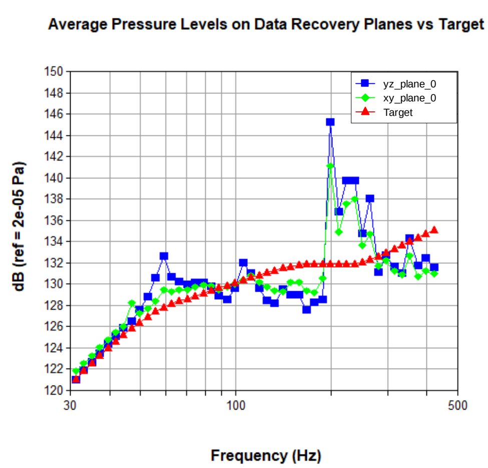

Figure 6. Average Sound Pressure levels on the data recovery planes vs Target

The figure above shows the difference between the sound pressure level target and the average sound pressure on both data recovery planes. The peak pressure at 200 Hz corresponds to a choice of the control microphones locations that are insufficiently random to be able to generate good diffusivity over a wider range of locations at this frequency. Indeed, at this frequency, although the average sound pressure level is well above target, the monitor microphones show a correct level due to the insufficiently random choice of location. This is shown in Figure 7 and can be interpreted as a cancellation region present at the control microphones. The bottom part of Figure 7 clearly demonstrates that in this case the average response around 200 Hz is too high relative to target even though no individual control microphones shows a level exceeding the target. We can understand that the simulated positioning of the control microphones (which does not reflect a real test setup) in this particular simulated case is too regular and not adequate for this setup and should be avoided for a physical test. This is one of the advantages that simulation can provide in designing an efficient and error-free testing setup.

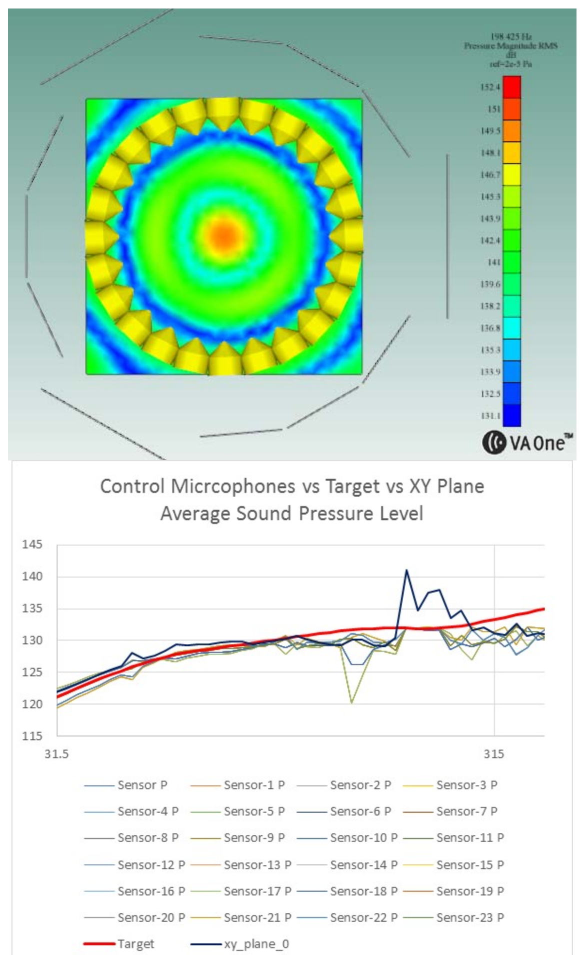

Figure 7. Top: Contour plot of the sound pressure level at 200Hz. Control Microphones are shown in yellow. Bottom: Average Sound Pressure level on XY data recovery plane vs control microphones and vs target

The WFS on the XY plane (parallel to the ground) for the DFAT simulation with speakers are presented in Figure 8 at the same two representative frequencies of 125 Hz and 420.25 Hz; both WFS show similarities with the analytical WFS of Figure 2, indicating that this setup produces a result approximating a diffuse field for this particular data recovery location. We can also see that for the lower frequency of 125 Hz, probably due to the large wavelength and the distribution of the subwoofers at only six discrete locations, the circle shows some irregularities compared to the ideal DAF. These irregularities are far less prominent at 420.25 Hz where smaller wavelength and larger number of mid-frequency speakers create an acoustic field with a characteristic closer to a DAF.

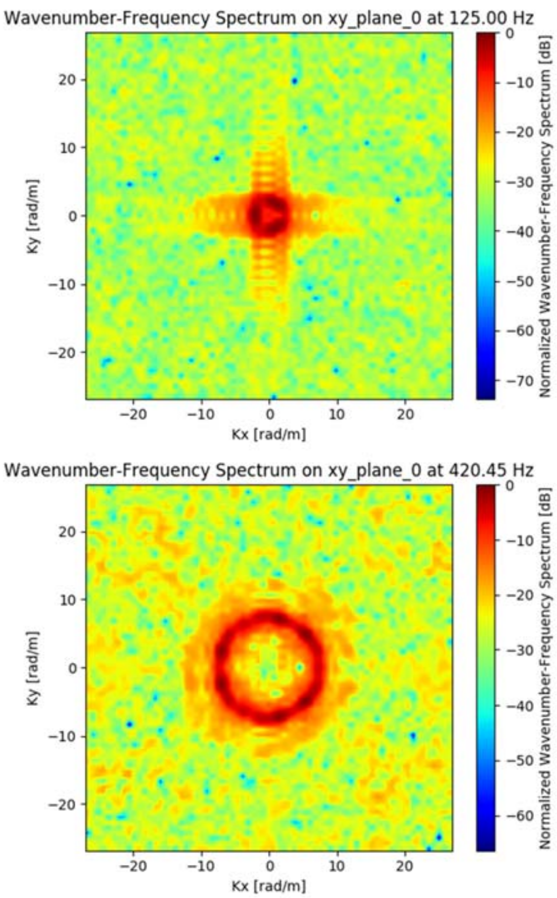

Figure 8. WFS on the XY plane for a DFAT setup with no structure at 125 Hz and 420.25 Hz

Figure 9 shows the corresponding WFS on the YZ plane (normal to the ground) for the same DFAT speaker simulation; here, a clear lack of diffusivity is present. This is likely due to the choice of having uniformly correlated stacks and can easily be remedied in a real DFAT test setup by splitting the stacks into different channels. Indeed, simulation indicates that further optimization of speakers is required (and can be supported by additional simulation studies) if diffusivity of the acoustic field in all directions is to be achieved.

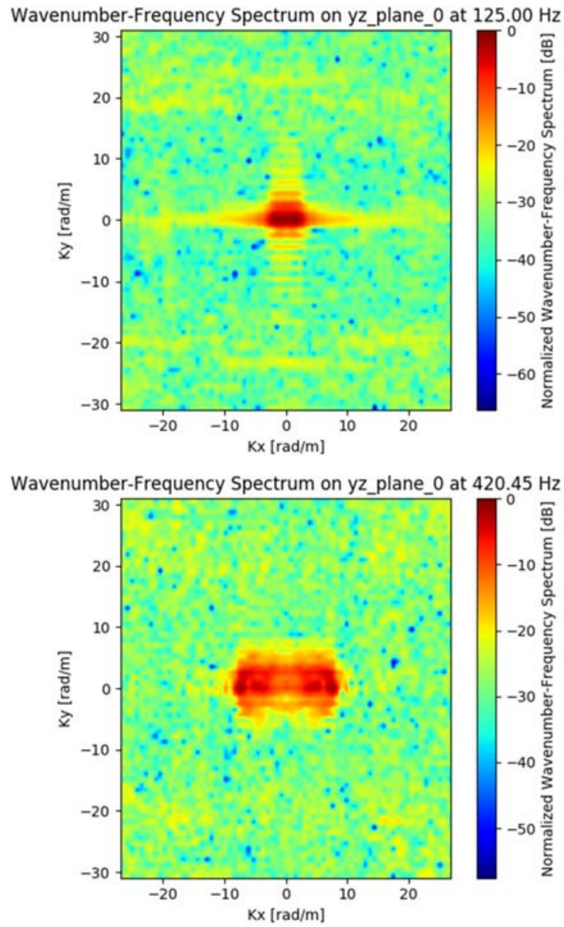

Figure 9. WFS on the YZ plane for a DFAT setup with no structure at 125 Hz and 420.25 Hz (Note that on this plot, Kx corresponds to the Y axis and Ky to the Z axis.)

5. STRUCTURAL TEST ARTICLE STUDY

To further the study, a simplified structure representative of a satellite is placed at the center of the speaker stacks in the BEM model as presented in Figure 10. Multiple data recovery planes, represented in yellow in the figure, are placed around the structure. For simplicity, this paper only shows the results to the XY plane parallel to the reflector (and also parallel to the ground).

Figure 11 shows a similar trend for the acoustic field of DFAT model to the one observed in Figure 6 and demonstrates that in this simulated case the presence of the structure does not introduce enough scattering to eliminate the peak at around 200 Hz. As previously mentioned, a better distributed set of control microphone will likely improve this behavior. The diffusivity patterns in Figure 12 are also very similar to those presented in Figure 8. This shows that the algorithm, which optimizes for a diffuse field $\left[S_{pp}\right]$ performs well. It is a key use of this simulation approach to be able to calculate the diffusivity not only in an empty space but in the presence of a test structure and interacting with it in a coupled structural-acoustic system.

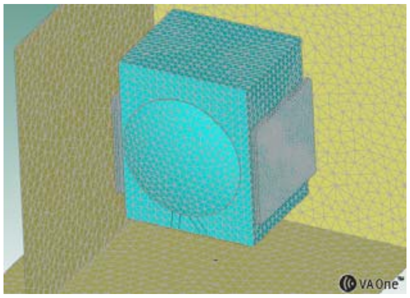

Figure 10. Simplified test structure in the center of the speaker stacks

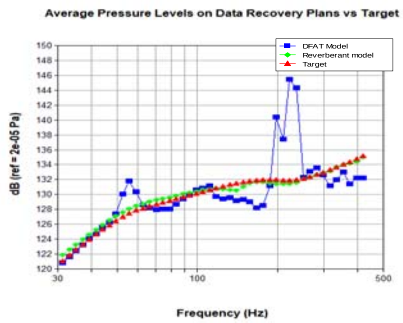

Figure 11. Average Pressure Levels on Data Recovery Plans vs Target

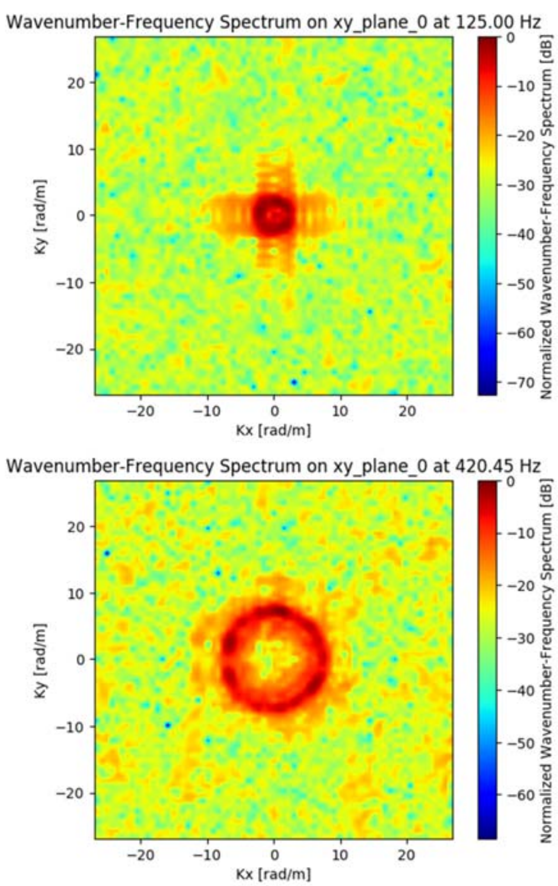

Figure 12. WFS on the XY plane for a DFAT setup with test structure at 125 Hz and 420.25 Hz

6. CONCLUSIONS

Virtual Direct Field Acoustic Testing allows for additional post processing that is not achievable using test for the same spatial resolution or number of sampling points. This allows comprehensive acoustic field results showing the degree of diffusivity obtained through the whole range of locations and frequencies from the simulated results in a straightforward process.

This paper shows a method to estimate acoustic field diffusivity in addition to the usual control of the acoustic levels. Simulation examples were provided and showed similar behavior in terms of control of sound pressure level and acoustic field diffusivity. For this study, the presence of a test structure minimally affected the acoustic field. However, it was shown that the location of the monitor microphone is also important as regular placement patterns can cause overdriving the structure if all control microphones are in a cancellation region.

Using this simulation method one can predict structural behavior under DFAT testing while looking for potential issues such as lack of diffusivity or overdriving due to an incorrect placement of the control microphones and iterate through simulated parameters to optimize setup.

Further studies may examine more closely differences in structural response between DFAT testing, reverberant room testing and idealized diffuse field and also compare the DFAT acoustic field characteristic against the reverberant room acoustic field characteristic which in many cases is assumed to be ideally diffuse.

7. ACKNOWLEDGEMENTS

Direct Acoustic Field Testing® and DFAT® are registered trademarks of Maryland Sound International.

VA One is a registered trademark of ESI Group.

8. Bibliography

[1] NASA, "NASA-HDBK-7010: DIRECT FIELD ACOUSTIC TESTING (DFAT)," NASA Techical Handbook, 2016.

[2] C. Fabries, B. Bertrand, S. Clamagirand, "Direct Field Testing Simulation for Subsystem Acoustic Qualification," in *Proceedings of 2016 ECSSMET Conference*, Toulouse, France, 2016.

[3] B. Gardner, V. Cotoni and A. Kolaini, "Investigation of Direct Field Acoustic Testing with BEM," in *SCLV*, El Segundo, CA, 2012.

[4] B. Gardner, "Investigating DFAT Diffusivity Using Wavenumber-Frequency Analysis with Boundary Element Models," in *SCLV*, El Segundo, CA, 2017.

[5] I. Dandaroy, "Analytical Tool for Numerically Simulating a Direct Field Acoustic Test," in *SCLV*, El Segundo, CA, 2017.