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Performing Direct-Field Acoustic Test Environments on a Sandia Flight System to Provide Data for Finite Element Simulation

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ABSTRACT

Aero-acoustic loading has been established as the primary source of excitation for a Flight System at Sandia National Laboratories. However, flight data of this system does not exist, limiting estimations of system or component response in this environment. Therefore, an experimental acoustic simulation was performed on a heavily-instrumented Flight System, using the direct-field acoustic test (DFAT) method with a multi-input multi-output (MIMO) control system. The combination of DFAT and MIMO resulted in attaining uniform and gradient acoustic fields as high as 127 dB OASPL. This paper will discuss the design of the test, the speaker and controller configurations, and the test results of this unique test method. Additionally, an overview of the method used to apply the measured test data to the pressure-loading finite element simulations of the Flight System will be discussed as well.

KEYWORDS

Direct-Field Acoustic Testing (DFAT), Multi-Input Multi-Output (MIMO) Control, Model Validation, Uniform/Gradient Field, Acoustic Finite Element Modeling

INTRODUCTION

At Sandia National Laboratories, response predictions are required of a Flight System under yet-to-be-flown aero-acoustic loading environments. These predictions are required to inform component designers of environment specifications in advance of future flight tests. Additionally, flight tests suffer from a lack of instrumentation and often do not explore the entire design envelope of the Flight System. As such, making response predictions with a high-fidelity finite element model is desirable.

The response predictions of the Flight System are performed using a structural dynamics (SD) model in a pressure-loading scenario. Typically, the SD models are calibrated/validated in single-axis, point force input cases. However, flight loads are a combination of vibration inputs from the aircraft/system interface *and* aeroacoustic loading from aircraft noise and flow-generated pressure fluctuations. An acoustic ground test was desired because it better replicates this loading scenario, more so than an experimental modal or random vibration test. Acoustic test results would provide both model assessment data as well as an experimentally derived model that could be used to estimate component responses based on acoustic pressures in the surrounding field.

The details of the acoustic ground tests are the primary focus of this paper, which includes the design of test, the acoustic excitation method, the closed-loop controller configurations, and the resulting acoustic fields achieved. The test technique used is fairly unique and deserves to be discussed in depth. The structural responses of the Flight System are only briefly discussed, as is the method used to apply the test data to the acoustic and structural dynamics models.

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DFAT WITH MIMO CONTROL

Direct-field acoustic testing (DFAT) is an acoustic test method that consists of exciting a test item the direct acoustic field—the portion of the field in which sound waves have not undergone any reflection—of a sound source. In practice, the direct field is created by surrounding a test article with a wall of specially modified concert-style loudspeakers, and placing multiple control microphones in-between the test article and speakers. A closed-loop control system uses the control microphone measurements to adjust the speaker outputs in order to obtain the desired test specification. Multiple response microphones are placed around the test item to better characterize the acoustic field [1].

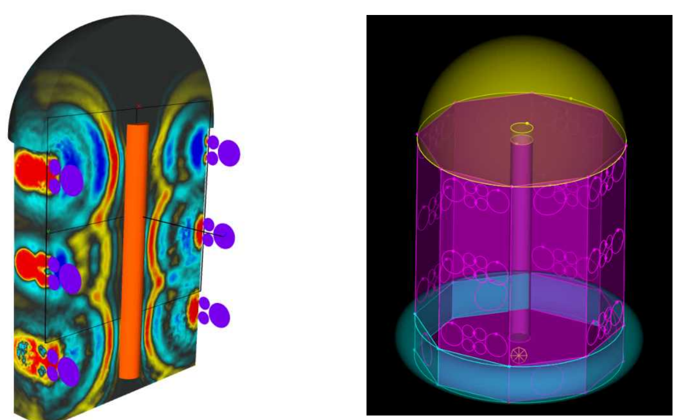
When applying multi-input multi-output (MIMO) control to DFAT, the multiple independent controls and corresponding drives of the control system allow for detailed tailoring of the resulting acoustic field. Since each control microphone has an independent test specification as well as a defined phase and coherence between them, it is possible to create both uniform acoustic fields and shaped acoustic fields, depending on the control parameters. The uncorrelated outputs used in MIMO control have also been shown, in analytical models and in experiments conducted in the industry, to reduce both standing waves and spatial variability in the resulting acoustic field, which is highly desirable for hardware safety and realistic acoustic environment simulation [2,3].

TEST DESIGN

Sandia's current acoustic test system consists of twelve MSI VT-99 speaker cabinets and six MSI VS-Q speaker cabinets. The VT-99 cabinets contain low, mid, and high frequency speakers and are driven by six acoustic amplifiers circuits; the VS-Q cabinets contain low frequency speakers and are driven by 3 acoustic amplifier circuits. In the large-scale Sandia reverberation chamber, this acoustic system is capable of achieving an overall sound pressure level (OASPL) of approximately 146 dB. Outside of the reverberation chamber in a DFAT configuration, levels of 136 dB OASPL have been achieved. While this DFAT level is much lower than the realistic acoustic loading environment, it was still a desirable test method due to the ability to obtain shaped acoustic fields, which is difficult to achieve in a reverberation chamber (due to acoustic reflections).

With the given number of speakers and independent drives available, analytical simulations were performed to determine the optimal test configuration. Vertical and horizontal test item orientations were examined as well as various speaker stack configurations. Simulation output data in the form of acoustic sound pressures levels (SPL) throughout the stack volume, as shown in

Figure **1**(a), was analyzed to assess any spatial dependence of sound pressure level. The final design, a vertical test article surrounded by an octagon of speaker stacks with reflective panels between speakers as illustrated in
Figure **1**(b), was chosen because this allowed for a fairly even field in the angular direction while allowing for a length-wise gradient by controlling the top speaker row to a different test specification than the bottom two speaker rows. Reflective panels on the sides of the octagonal stack increased the overall level inside the stack and provided some additional smoothing of the field in contrast to a design with open walls.



(a) **(b)**

Figure 1: (a) Pre-Test Analysis SPL and (b) Final Test Design

TEST SETUP

As discussed in the test design analysis results, the DFAT configuration consisted of suspending the Flight System vertically in the center of a 10-foot diameter octagon of speakers, 1 foot above the floor. Four towers of the VT-99 cabinets (low-mid-high frequencies) were stacked three high and placed 90-degrees apart, as shown in the simplified diagram of Figure 2. In order to provide more speaker coverage along the length of the Flight System, 2-foot long extension bars were installed in-between the short VT-99 cabinets, resulting in an 11-foot high stack. The six VS-Q subs (low frequency speakers) were stacked alternating one and two high, and were placed on the floor at the 45-degree locations (not shown in diagram). Analysis determined that the low frequency VS-Qs were not as location-dependent as the VT-99s. The reflective panels required by the test design were provided by ¾-inch thick plywood, installed in the open spaces of the speaker configuration, such as on the extension bars between the VT-99s, and the space above the VT-Qs. Adding panels between loudspeaker cabinets was predicted to increase the overall sound pressure, though the increase in reflection may affect the ability of the control system to achieve high spatial pressure gradients.

Figure 2: Sandia Flight System and Speaker Configuration

The Flight System was suspended using a specially-designed test fixture that incorporated a pivot joint near the center of gravity of the test item, when suspended by a strongback (shown in as purple in Figure 2). With this fixture, instrumentation could be attached to the Flight System in a horizontal configuration at a comfortable working height. Once ready for testing, an overhead crane was used to lift the entire assembly high enough to rotate the test unit into a vertical configuration, and place it at the center of the speaker stacks, 1 foot above the floor. Casters installed on the VT-99 speaker stacks allowed for easy opening and closing of the speaker enclosure.

Acoustic instrumentation for the Flight System DFAT consisted of a total of 18 microphones, located no closer than 3-ft to the speakers in order to measure a more uniform sound field, and no closer than 1-ft to the test article to reduce microphone distortion due to reflections and surface effects (per standard DFAT practices [1]). Microphone heights varied from 2-ft to 11-ft above the floor. The exact locations of the individual microphones, represented by the green squares, are shown in the top-view diagram of Figure 3 and listed in Table 1. Pre-polarized ¼-inch diameter pressure-field microphones were used for this test, with sensitivities ranging from 0.7 mV/Pa to 1.2 mV/Pa.

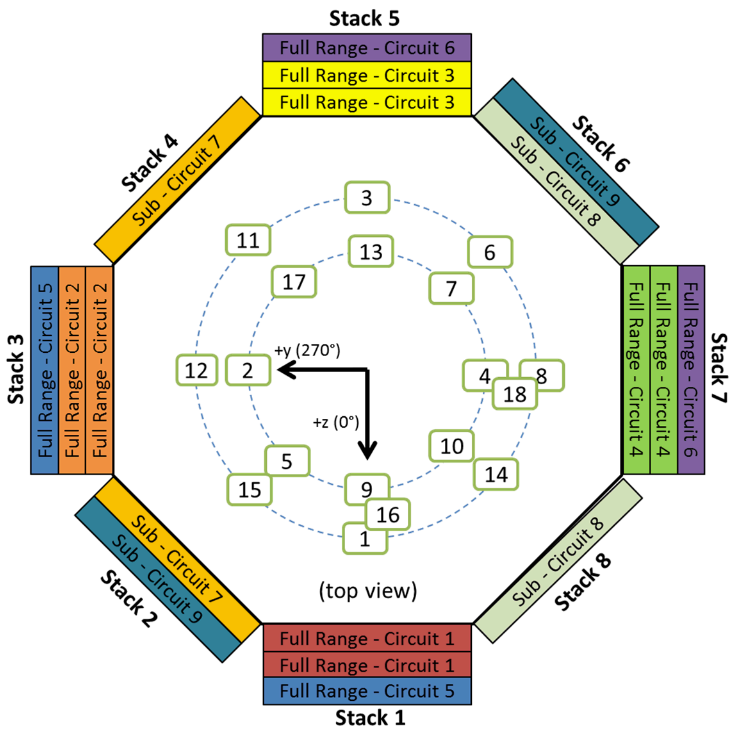


Figure 3: Microphone and Speaker Circuit Placement

Table 1: Microphone Coordinate Locations

Mic. (Ch #)	Radius (in)	Angle (deg.)	Height (feet)
1	24	0	3
2	18	270	5
3	24	180	4
4	18	90	7
5	18	315	10
6	24	135	11
7	18	135	6
8	24	90	9
9	18	0	8
10	18	45	6
11	24	225	7
12	24	270	10
13	18	180	8
14	24	45	11
15	24	315	4
16	21	0	5
17	18	225	7
18	21	90	2

The diagram of Figure 3 also displays the individual speaker cabinets that make up each speaker stack along with their corresponding amplifier circuits. In this diagram, Full Range cabinets represent the VT-99s which contain low-mid-high speakers, and the Sub cabinets represent the VS-Q low frequency speakers. The speakers are stacked as the radius increases out from the center—for example, Stack 1 consists of a Full Range - Circuit 1 cabinet on the bottom, a Full Range - Circuit 1 cabinet in the middle, and a Full Range - Circuit 5 cabinet on the top.

Each of these amplifier circuits was driven by an independent output from the MIMO control system which was determined by a corresponding control microphone placed nearby. If placed too far away, there was a potential of speaker damage due to the control system outputting more voltage than speaker could withstand in order to reach the desired specification. Therefore, as seen in the diagram, control microphones (Microphones #1-6) were placed near their associated speaker circuits and at various heights to aid in achieving the acoustic field gradient. The remaining response microphones (Microphones #7-18) were placed randomly in the field.

As mentioned previously, the test was designed with six independent speaker circuits/control system drives, which accounts for the twelve Full Range cabinets (two cabinets per circuit). In order to supplement the low frequency portion of the test specification, the six Sub cabinets driven by 3 additional independent speaker circuits, were integrated with the six main drive circuits using an acoustic mixer (Circuit 7 added to Circuit 1 and 3, Circuit 8 added to Circuit 2 and 4, and Circuit 9 added to Circuit 5 and 6).

Accelerometers were used to measure the structural response of the Flight System due to the simulated acoustic environment. A total of 84 internal and 75 external locations were instrumented with both uni-axial and tri-axial accelerometers, ranging in sensitivity from 100 mV/g to 100 mV/g. Twelve channel gather boxes were used to collect both the microphone and accelerometer data from the center of the speaker circle and transmit them to external signal conditioners. The completed test setup is shown in Figure 4; the external accelerometers (red cables), the microphones, the speaker stacks, the plywood panels, and the 12-channel gather boxes can all be seen in the photo.

Figure 4: Sandia Flight System DFAT Setup

TEST ENVIRONMENT

The test specification used in the laboratory ground tests to simulate the aero acoustic loads is shown as 1/6-octave bands in Figure 5. While the desired test environment was much larger in magnitude, acoustic test equipment limitations (speaker/amplifier output, number of speakers) resulted in scaling down this test specification to approximately 127 dB OASPL. In addition to the test specification, the coherence and phase values were defined in the MIMO control system as well. The defined coherence values determined how close the resulting phase was to the defined phase values. With a 0-degree phase for example, a high coherence test should result in phases very close to 0-degrees; alternately, a low coherence test should result in a random phase (not 0-degrees). With the test specification and various MIMO control parameter settings, four different acoustic fields were applied to the Flight System, defined as Truth Tests #1 – 4.

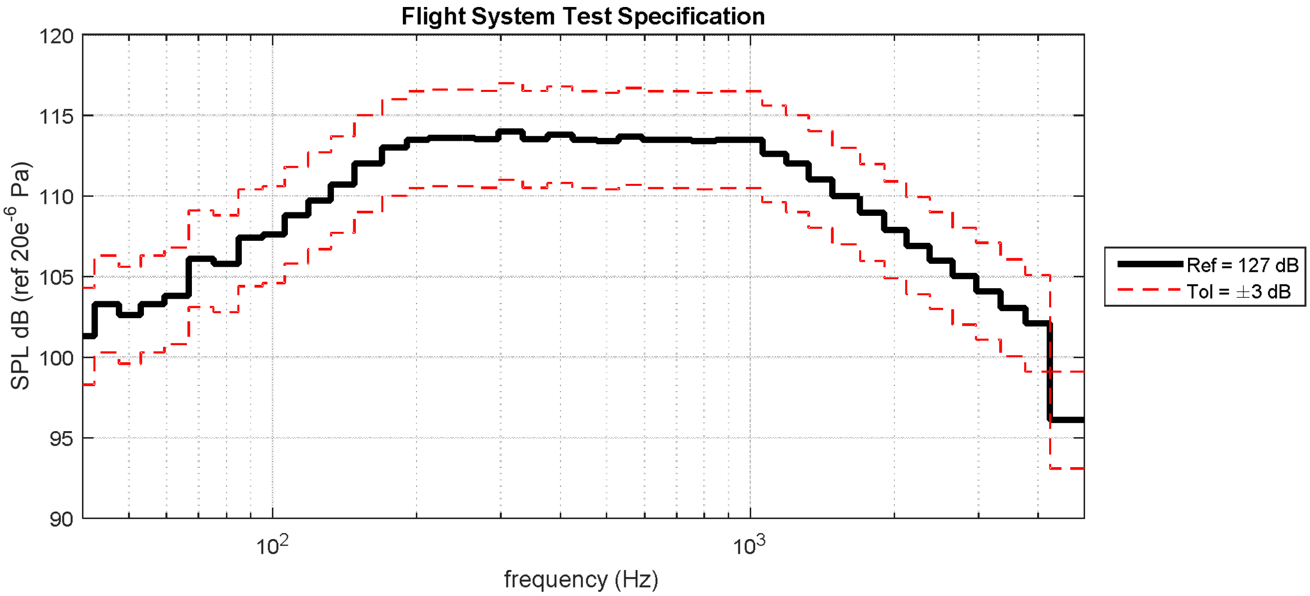


Figure 5: Sandia Flight System Acoustic Test Specification (127 dB OASPL)

The first two tests consisted of a uniform field, where the same test specification was used at each control location. The coherence between control locations was set with a high coherence (0.9) for Truth Test #1, and a low coherence (0.1) for Truth Test #2; the phase for both tests was set to 0-degrees. The goal of this test was to determine if the uncorrelated random phase, provided by the low coherence, would reduce spatial variability in the acoustic field. Past acoustic tests, performed with a single correlated (high coherence) drive exhibited strong positive and negative interference, resulting in very large spatial variability [4].

The next two tests attempted a gradient field, where the aft end of the Flight System would experience the test specification and the forward end would experience the test specification scaled down 6dB. This gradient was desirable, as it simulates a realistic acoustic loading scenario. To achieve this gradient with the MIMO control system, the nominal test specification was applied at the control locations/speaker circuits at the bottom of the speaker stack (Microphones #1-4); the nominal test specification scaled by -6dB was applied to the control locations/speaker circuits at the top of the speaker stack (Microphones #5-6). As with the first set of tests, both a high coherence (0.9) was used for Truth Test #3, and a low coherence (0.1) was used for Truth Test #4.

TEST RESULTS – TRUTH TEST #2

For the sake of brevity, this paper will plot only the acoustic field test results for Truth Test #2 (uniform field, low coherence) and Truth Test #4 (gradient field, low coherence), although comparisons to Truth Test #1 (uniform field, high coherence) and Truth Test #3 (gradient field, high coherence) will be discussed. Additionally, the structural response data will not be shown, as this paper is primarily focused on the unique DFAT MIMO test technique applied to the Flight System and the resulting acoustic fields.

Truth Test #2 consisted of a uniform field by applying the test specification at all the control microphone with a low coherence value (0.1) and phase of 0-degrees between control locations. The resulting 1/6th octave sound pressure levels for the six control microphones, along with the test specification (reference) and recommended ±3 dB tolerance, are shown in Figure **6**; the OASPL values are listed in the legend for each microphone. The control microphones were all within the frequency band tolerance except for Microphone #6, which was below tolerance up to 100 Hz (and above at 700 Hz). Microphone #5 was also low relative to the test specification at low frequencies. Also seen in Truth Test #1, the low SPL of these two microphones was thought to be due to their location (10-11 feet above the floor) relative to the VS-Q sub speaker cabinets placed on the floor. The OASPL levels for all control microphones are similar as well, with the two control microphones located at the top of the stack (Microphone #5 and #6) being slightly lower in magnitude.

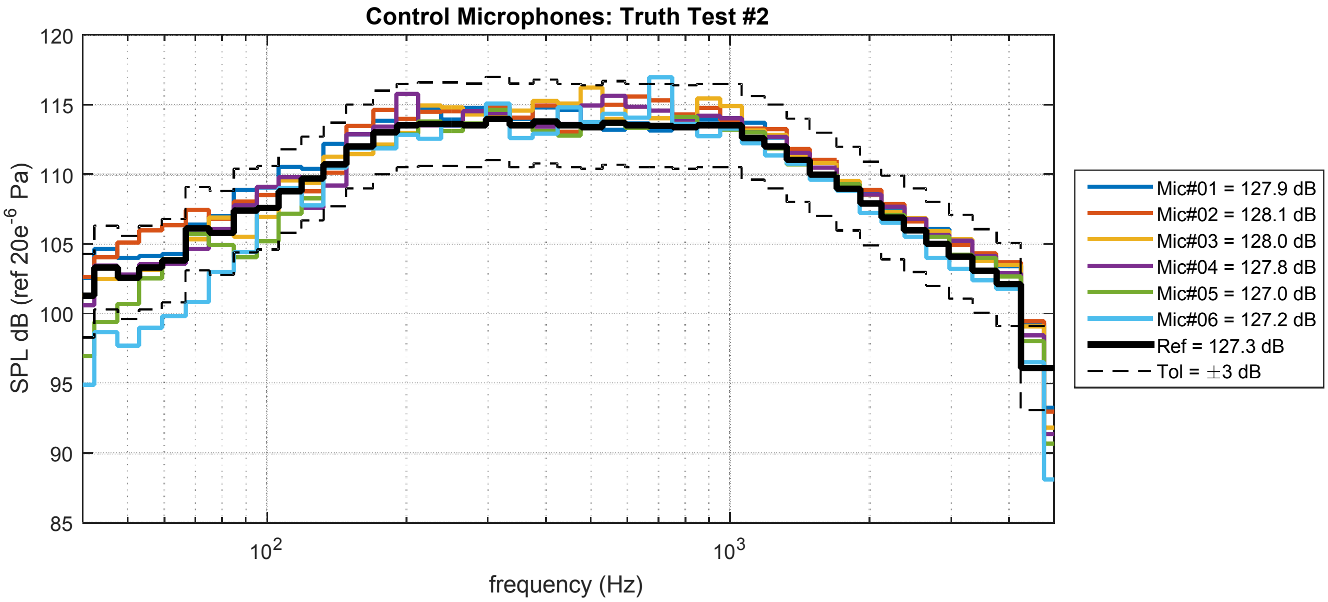


Figure 6: Truth Test #2 Control Microphone Sound Pressure Levels

The 1/6th octave SPL for the 12 response microphones are shown in
Figure **7**, along with the test specification (reference), the ±3 dB tolerance, and the OASPL values. The response microphones are larger in magnitude and vary much more than the control, especially for frequency bands 180 Hz and above. While some difference from the control specification was expected for these non-control locations, the general increase in level for all response microphones was interesting and will be discussed in a subsequent section. When compared to the response microphones of Truth Test #1 (high coherence), which were also larger in magnitude than the control, the low coherence control MIMO parameter setting did not seem to reduce the spatial variability as expected. This may be due to the physical speaker stack configuration or the lack of full speaker coverage in the stack; it may not be physically realizable to reduce the spatial variation in this configuration. Finally, when comparing the individual response microphone OASPL values, they are almost equal to the Truth Test #1 values, and ranged from 131.7 dB to 136.4 dB, about +4 dB to +9 dB higher than the test reference.

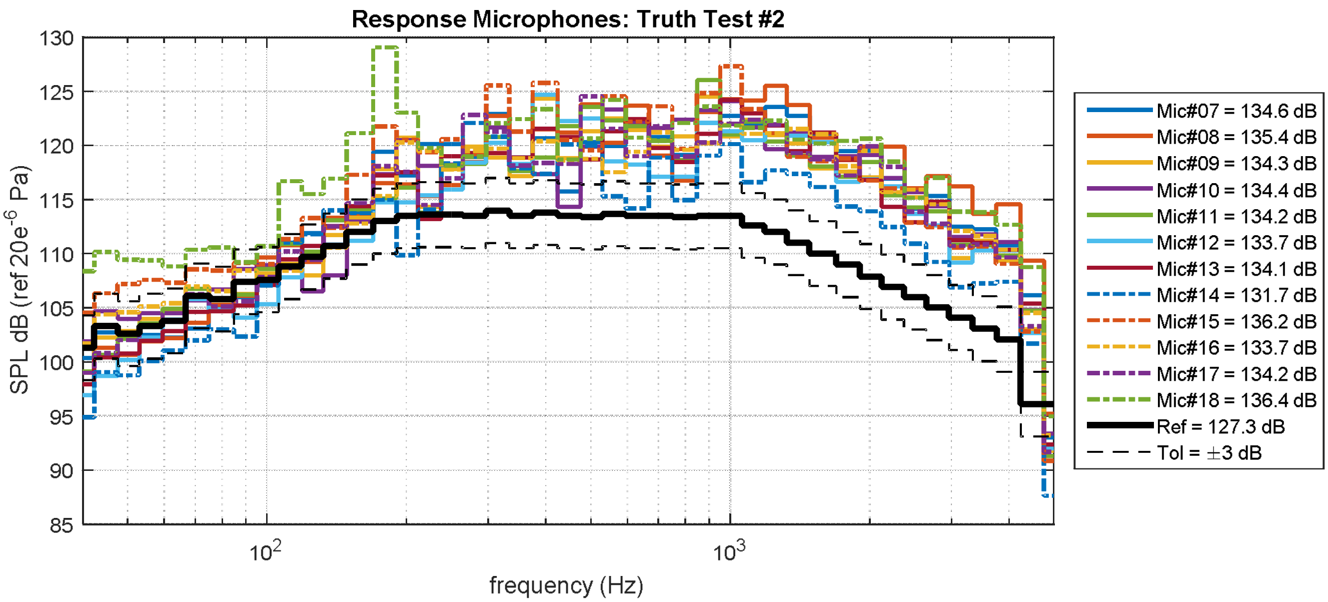


Figure 7: Truth Test #2 Response Microphone Sound Pressure Level

The mean, maximum, and minimum of the SPL for the control and response microphones were calculated for each 1/6th octave band and plotted in
Figure **8**. The plot clearly shows the accuracy of the control microphones, as well as the amplification and spread of the response microphones that occurs at 180 Hz and above. Comparing the spatial variabilities of Truth Test #1 and Truth Test #2, the low coherence MIMO parameter reduced the variability at some frequency bands, but not others.

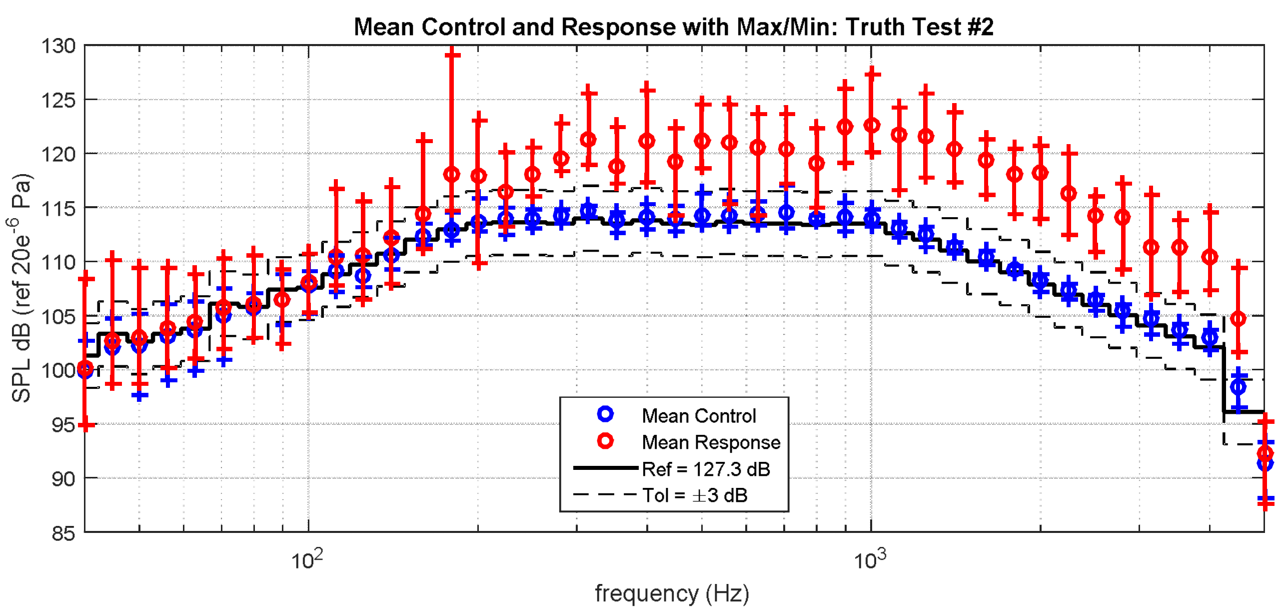


Figure 8: Truth Test #2 Mean, Maximum, and Minimum SPL (Control and Response)

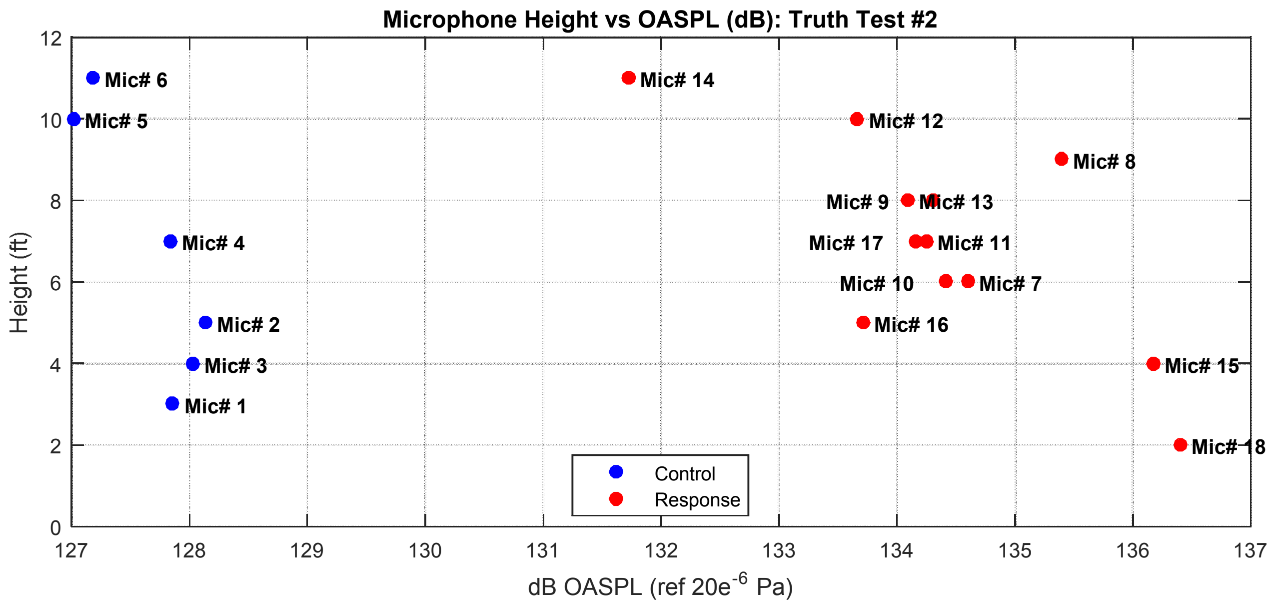


Figure 9: Truth Test #2 OASPL versus Microphone Height

In order to better visualize the overall shape of the resulting acoustic field, the calculated OASPLs for each microphone are plotted versus microphone height in
Figure **9**. It must be mentioned that the OASPL is one number that describes the total energy contained in the SPL spectrum; therefore this plot should only be used for a general, simplified view of the acoustic field. The shape of the control microphones is somewhat uniform as expected, while the response microphone levels seem to decrease from the bottom of the setup to the top.

TEST RESULTS – TRUTH TEST #4

The Truth Test #4 consisted of a shaped, gradient acoustic field by applying the test specification to the lower control microphones located near the aft end of the Flight System (Microphones #1-4), and applying the test specification scaled - 6 dB to the upper control microphones located near the forward end of the Flight system (Microphones #5-6). A low coherence value (0.1), and a phase value of 0-deg was used between all control microphone locations.

Since there were two test specifications used for this testing depending on control microphone location, two separate 1/6th-octave SPL control microphone plots are shown. The results for the lower control microphones located near the aft end of test unit are shown in Figure 10; the results for the upper control microphones located near the forward end of the test unit are shown in
Figure **11**. The test specifications, the recommended ±3 dB tolerance lines, and OASPL are shown as well.

The aft end control microphone data shown in Figure 10 indicates the control SPL was within tolerance over the entire test spectrum. The forward-end control microphones data shown in
Figure **11** indicate that the SPL was consistently higher than the reference and exceeded tolerances at a few frequency bands. When comparing this data to the Truth Test #3 data (high coherence), the spread in control microphone data was much less, which may be due to the low coherence value used for Truth Test #4 control.

The higher-than-desired levels of the forward-end microphones indicate that controlling a shaped field with a 6dB gradient may have been too ambitious for this particular test setup; the reflective panels, control microphone locations, and speaker stack configuration may have contributed to the inability to reduce acoustic levels on the forward end. If the OASPL levels are examined, they indicate a 4 dB gradient present in the acoustic field. Therefore, for this test setup, if the control system specification gradient had been 4 dB or lower, then the control microphones at the forward end may have been closer to the desired values.

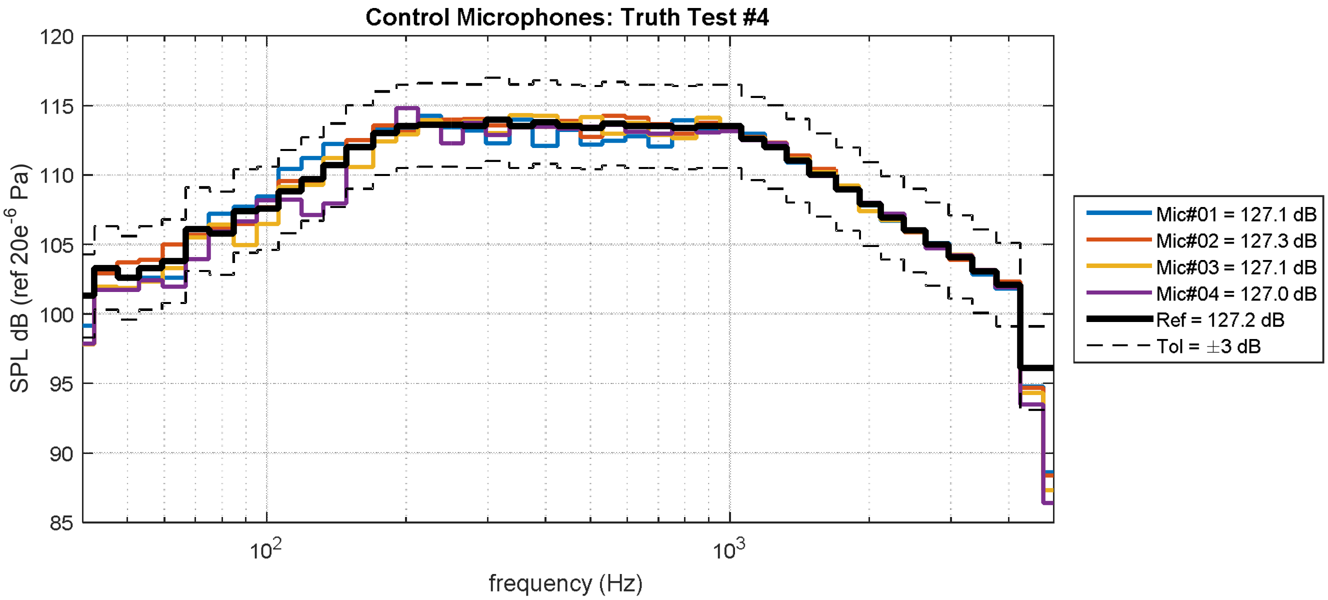


Figure 10: Truth Test #4 Control Microphone Aft End (mic #1-4) SPL

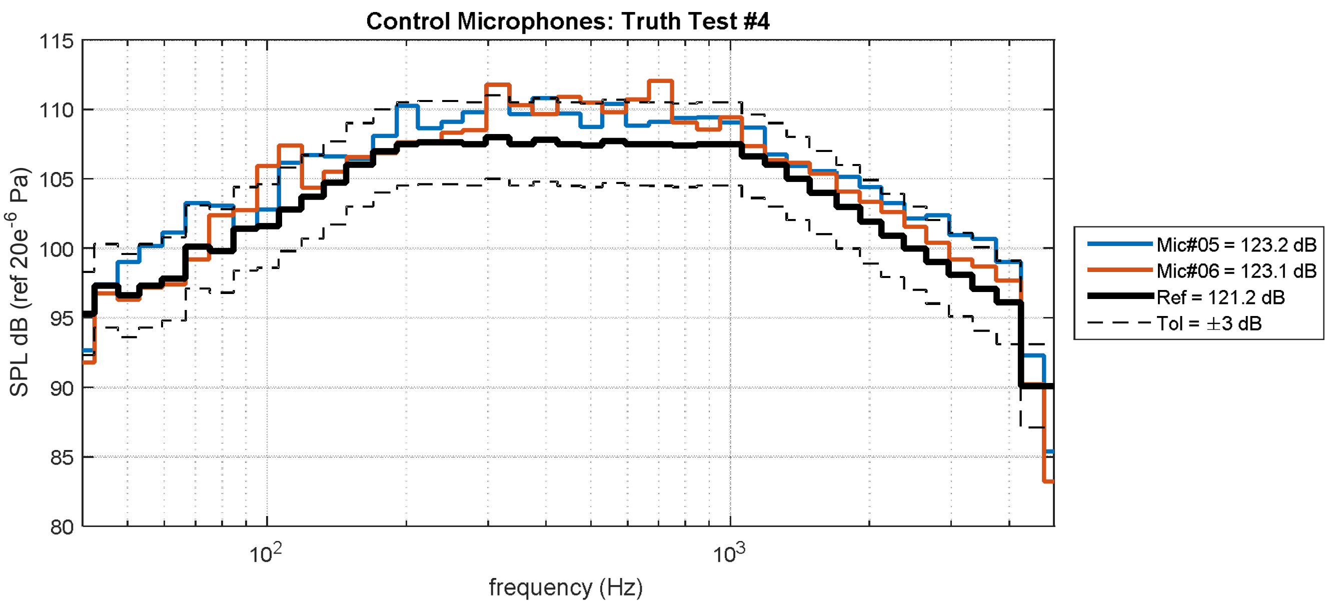


Figure 11: Truth Test #4 Control Microphone Forward End (mic# 5-6) SPL

The 1/6th-octave SPL for the 12 response microphones are shown in
Figure **12**, along with the test specification, the ±3 dB tolerance lines, and the OASPL values. Because of the gradient control specification used for this test, this response data should be expected to have more spatial variability than the Truth Test #1 and #2 results. While not directly comparable to the Truth #2 response data due to the gradient control, it should be noted that the Truth Test #4 response data illustrates a similar offset of +5 dB to +7 dB relative to the control.

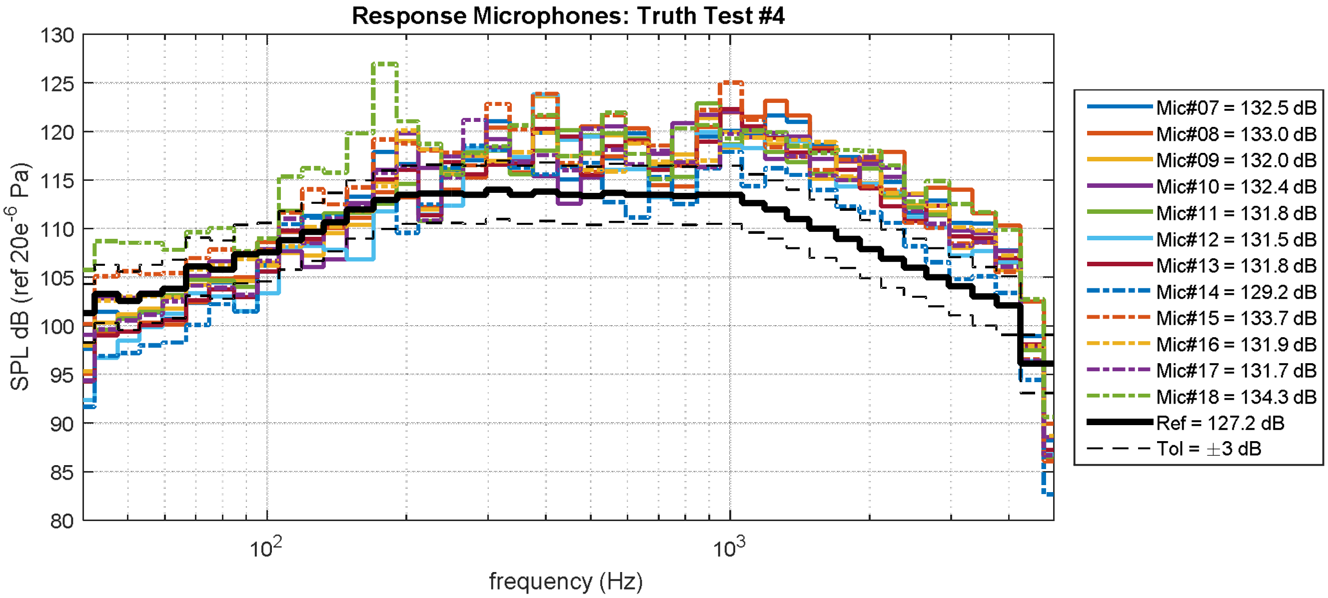


Figure 12: Truth Test #4 Response Microphone Sound Pressure Level

The shape of the acoustic field due to the gradient test specifications can clearly be seen in the OASPL versus microphone height data shown in
Figure **13**. The control microphones are well-grouped by location (maximum difference of 0.4 dB), better than the Truth Test #1 and #2 (maximum difference of 1.5 dB), although that may be primarily due to control microphone location relative to the speakers. The response microphones have a larger range as expected, but only by approximately 1 dB, resulting in a gradual shaped acoustic field.

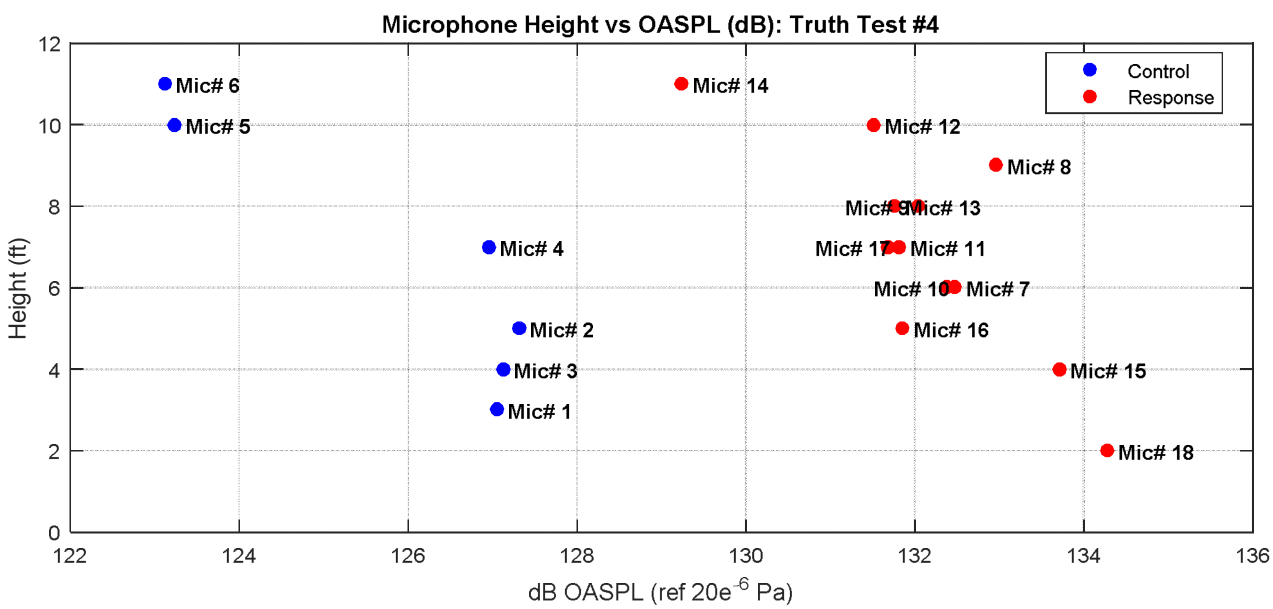


Figure 13: Truth Test #4 OASPL versus Microphone Height

TEST DATA APPLIED TO ACOUSTIC FINITE ELEMENT SIMULATION

A motivation for performing the laboratory acoustic tests was to provide data for the Sandia structural dynamics finite element model for acoustic loading. The loads on the structural dynamics model in this case are pressures on the external surface. As measuring on-surface pressures during the DFAT test was not possible, an acoustic source inversion methodology was employed wherein experimentally measured pressures (microphone pressures) are used to determine the loads on an acoustic finite element model—an ellipsoidal subdomain of the acoustic test environment from the test, as seen in Figure 14. A benefit of this subdomain approach is a large savings in computational cost; the volume of the subdomain is about 2.5 times smaller than the as-tested acoustic volume (10-foot diameter speaker stack octagon). However, this method eliminates the true sources and boundary conditions from the experiment and instead relies on a large number of representative sources on the outer surface of the subdomain, indicated as multi-colored patches in the figure. Ultimately, the acoustic source inversion simulation determines acoustic acceleration loads for each of these patches, which generate a field at microphone locations that match the target data, in this case the as-tested microphone pressures [5,6].

Results of the source inversion simulations provided excellent agreement with the test pressures at the test microphone locations. As the acoustic finite element model includes a void for the Flight System, wetted surface pressures on the Flight System can be extracted from the acoustic simulation. These wetted surface pressures are then applied to the structural dynamics model of the flight system to obtain predictions for system and component acceleration response to this acoustic field. Simulated accelerations were then compared with the accelerations measured in the DFAT test to assess the model in this acoustic environment.

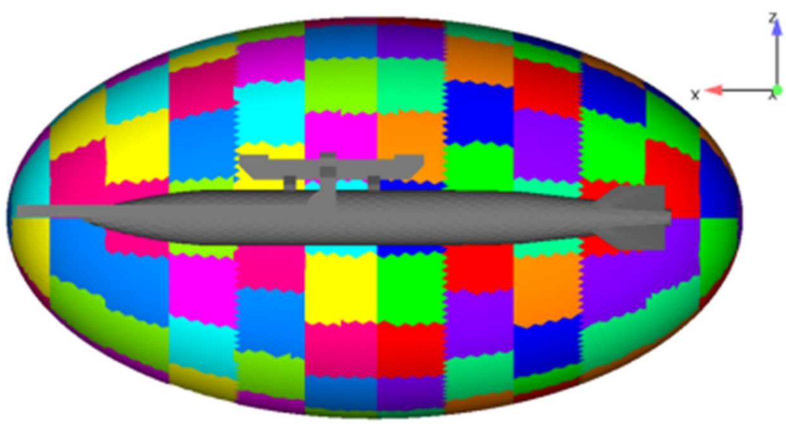


Figure 14: Acoustic Finite Element Subdomain

RESPONSE MICROPHONE EXAMINATION

As noted in the test results, the response microphone for all Truth Tests measured anywhere from 4 dB to 9 dB larger in magnitude than the control microphones. Analysis of noise floor measurements verified that there was no bias error due to erroneous test setup; the noise floors were nominally the same for the control and response channels. Therefore, it was hypothesized that the amplification of the acoustic field at the response locations must have been a real occurrence in the experimental acoustic field. To validate this statement, the acoustic source inversion simulation method, (as described in the previous section) was performed to predict the pressures at the six control microphone locations (Microphone #1-6) using *only* the measured pressures from the twelve response microphones (Microphone #7-18) as input.

Overall, the resulting predictions agreed well with the test data up to 1 kHz; the simulation data dropped off at frequencies greater than 1 kHz due to the coarse mesh used in the model, which is not useful at predicting higher frequencies. A comparison of the predicted (red) versus the test data (blue) can be seen in
Figure **15** for response microphone #7 and control microphone #6 on the left and right, respectively. Based on the results of the noise floor and simulation analysis, it can be stated that the response microphone data was correct and the magnification

of the acoustic environment at these locations did occur in the acoustic field. Further study into the control algorithm, influence of coherence and mixing parameters, and acoustic modes of the speaker stack may provide useful insight into this phenomenon.

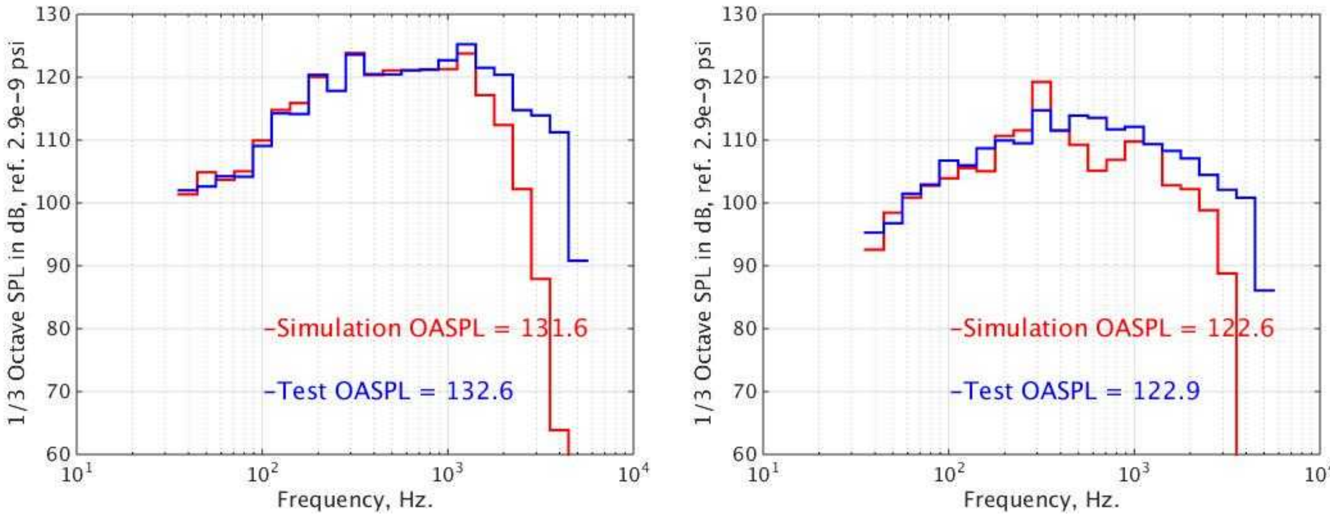


Figure 15: Response Microphone #7 (left) and Control Microphone #6 (right)

CONCLUSIONS

Direct-field acoustic tests were performed on a heavily instrumented Sandia Flight System in order to obtain test data for yet-to-be-flown acoustic loading environments. A realistic test specification was applied to the Flight System using a closed-loop multi-input multi-output control system; the six independent controls allowed for testing with both uniform and shaped acoustic fields with varying (high and low) coherence values. Maximum overall sound pressure levels of approximately 127 dB were successfully obtained with this setup.

The resulting control microphone pressures were within the ±3 dB test specification tolerances for the uniform acoustic field test. For the shaped acoustic field test, which consisted of a -6 dB gradient from aft to nose, the resulting control microphones pressures were within the ±3 dB tolerance for the aft end of the Flight System. However, the control microphone pressures at the nose of the Flight System were above the desired -6dB test specification, but grouped closely together. It was surmised that the 6 dB gradient was too large for the system to achieve, and a smaller gradient of 4dB would have more than likely controlled better.

While the controls were within tolerance, the response microphones for all acoustic fields consistently measured acoustic pressures ranging +4 dB to +9 dB above the various test specifications. This was unexpected, but not unreasonable, as these microphones had no effect on the acoustic control and were only measuring the resulting field. Analysis of measured instrumentation noise floor data, as well as analytical predictions of the pressures at the control microphone locations based off of response microphone data, proved that the larger magnitude data was valid and this response did occur in the acoustic field during the various tests.

There was no discernable difference in the spatial variation of the response microphones with the different MIMO coherence values (0.1 and 0.9) used to perform the acoustic tests. Based on theory and various references, it was expected that the lower coherence would result in a less variable acoustic field. The reduction of spatial variation may have not been realizable with this test configuration due to the boundary conditions and the physical test configuration used (placement of the speaker stacks and plywood panels).

An acoustic source inversion methodology was used with the measured acoustic pressures (microphones) to determine multiple acoustic sources of an acoustic finite element subdomain, used to model the acoustic test. The acoustic sources were then used to predict the acoustic pressures at the microphone locations as well as predict the wetted surface acoustic pressures of a high fidelity structural dynamics model of the Flight System to provide structural response predictions. The microphone predictions and simulated accelerations were compared to the measured test data to assess the model in the acoustic environment.

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