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Experiences in Performing a High Intensity, Direct-Field Acoustic Test on a Contamination Sensitive System

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ABSTRACT

A direct-field acoustic test (DFAT) was performed on a Sandia system in order to verify survival in a 146.7 dB OASPL acoustic environment. The DFAT technique—performed by surrounding the test article with a wall of speakers and controlling the acoustic input with a closed-loop control system—was chosen as the test method in order to meet a critical schedule. In choosing this test method, other challenges became apparent, such as how to maintain a contamination-free system during the acoustic test. Additionally, the vast amounts of data measured during a single test necessitated a way for the test director to quickly visualize the acoustic environment in order to efficiently provide insight for input adjustments. Finally, the results themselves illustrated some drawbacks of the current DFAT method, leading to ideas on how to perform a better DFAT test. This paper details the DFAT setup used to obtain the test specification, the effects of the contamination frame on the acoustic environment, the quick-look data program created for visual analysis of the acoustic field, and ideas for performing more uniform DFAT tests in the future.

KEYWORDS: DFAT, direct-field acoustic test, clean room requirement, quick-look data analysis, vibro-acoutstics

INTRODUCTION

The logistics of performing an acoustic test on contamination sensitive systems can be challenging. Most systems are under a strict shipping schedule, cannot be easily moved, and most importantly, require a clean room environment at all times. This was the case for the Sandia system. To address these first two issues, the acoustic environment was brought to the integration facility in the form of the direct-field acoustic test (DFAT) method. This method consists of placing the test article in the direct field of a wall of speakers and controlling the acoustic input with control microphones and a closed-loop control system. The clean room requirement remained a concern, since the DFAT equipment would not fit inside the class 100 clean room at the integration facility. Therefore, a nitrogen-purged contamination bagged frame was built to surround the Sandia system while under test. Prior to the system test, several experiments were performed to determine what occurs to the acoustic field inside this bagged frame. During the system test, a quick-look spreadsheet was used to efficiently examine the measured data for tolerance comparison and control adjustment. Upon successful completion of the Sandia system test, it was noted that the results illustrated the known drawbacks to DFAT, which led to a discussion of control and input modifications that may optimize the method.

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SANDIA SYSTEM AND TEST SPECIFICATION

The Sandia system under test measured approximately 4-feet long by 4-feet wide by 4-feet tall, and weighed roughly 500-lbs. The acoustic test specification required to verify survival of this system was the 1/3-octave, sound pressure level (SPL) plot shown in Figure 1. The overall sound pressure level (OASPL) of the test spec was 146.7 dB, with a test duration requirement of one minute. Tolerances were also provided with the test specification, and are illustrated in the figure as well.

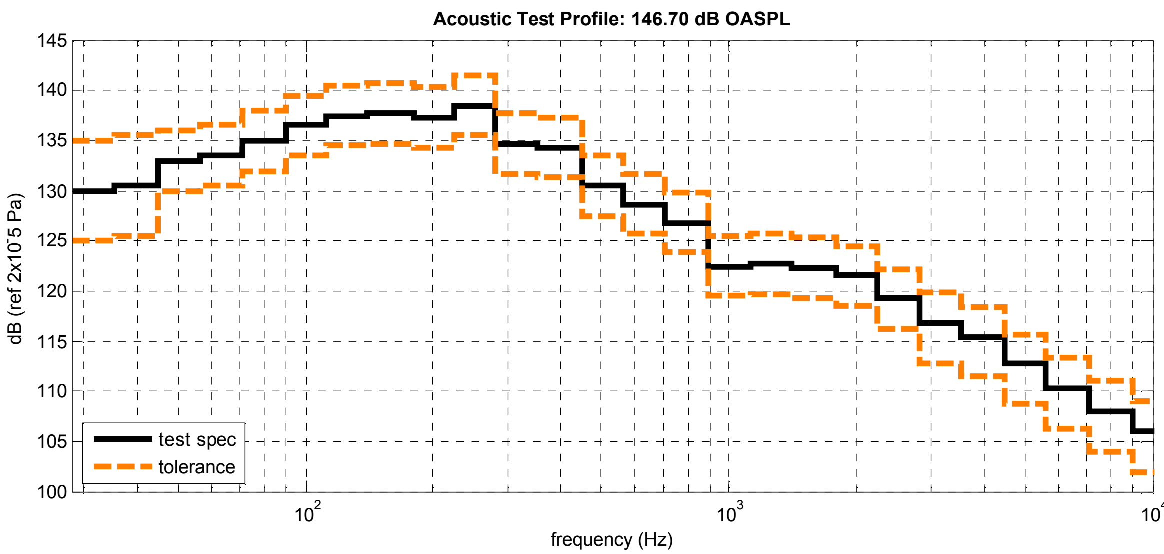


Figure 1: Sandia System Acoustic Test Specification

DIRECT-FIELD ACOUSTIC TEST SYSTEM AND SETUP

As previously mentioned, DFAT was the method used to apply the required acoustic environment to the Sandia system. This portable technique consists of exciting test items in the direct-field of a sound source—the portion of the sound field in which sound waves have not undergone any reflection. In practice, the direct-field is created by surrounding a test article with a wall of speakers and placing multiple control microphones in-between. In this case, a closed-loop control system was used with the averaged control microphone signals to reach the desired test specification. Additional response microphones are typically placed around the test item to better characterize the acoustic field. Further details regarding DFAT recommendations are available in IEST-RP-DTE400.1, which is currently under review for publication [1].

The configuration and equipment used for the Sandia system DFAT was provided by Maryland Sound International (MSI) and consisted of three stacks of 16 MSI-Quakes that provided low frequency content, and nine stacks of 6 MSI-VT speaker cabinets that provided middle and high frequency content, equaling 102 speakers. The tallest stack of speakers (the MSI-Quakes) measured no taller than 16-feet and the entire configuration fit into a 30-foot diameter area as seen in Figure 2. Control microphones were positioned at varying heights between the test article and the speakers at the recommended distances: 3-feet from the speakers and 1-foot from the test item (any closer to the test article and the microphone may measure sound waves reflecting off the article surface; any closer to the speakers and the sound field may not be fully-formed). In addition, eight response microphones were placed around the circle and five microphones were placed near the system, inside the bagged contamination frame (which will be explained subsequently).

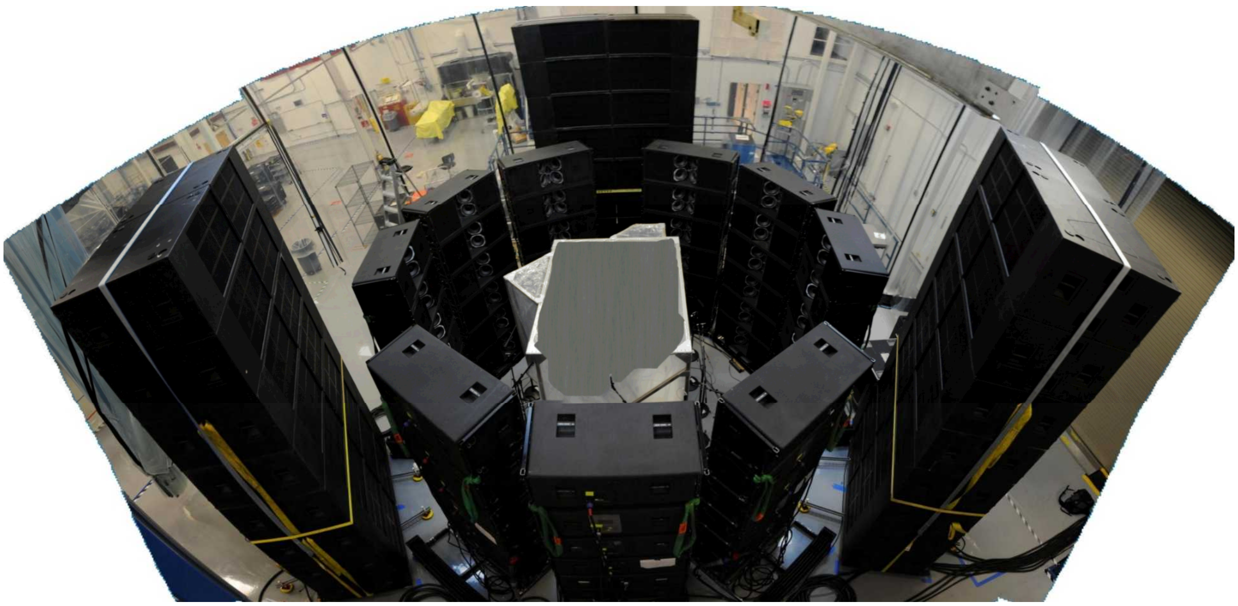


Figure 2: Sandia System DFAT Setup

The Sandia system itself was instrumented with 84 response accelerometers at locations of interest. Two Spectral Dynamics JAGUAR systems were used to perform the test; the MSI JAGUAR provided narrow-band control for the acoustic input, and the Sandia JAGUAR co-recorded the control microphones, the response microphones, and the Sandia system accelerometers. Tests were performed at -12 dB below full level and every 4dB until full level was achieved at 146.7 dB OASPL. At each level, tests were performed for only 20 seconds at a time in order to prevent overheating of the acoustic amplifiers and speakers; the required one minute duration at full level was cumulative. Full details of the test design are available in Stasiunas [2].

CONTAMINATION FRAME

As previously mentioned, the Sandia system required a class 100 clean room environment at all times to prevent contamination, even during acoustic testing. This presented a problem—the test facility clean rooms were neither big enough for the DFAT setup, nor was there enough time in the schedule to thoroughly decontaminate all 102 speakers to class 100 standards. Therefore, in order to perform DFAT on the Sandia system, but maintain a contamination-free environment, a nitrogen-purged, double-bagged frame was designed to encompass the entire system when outside the clean room. As shown in Figure 3, the frame was attached to a 6-ft × 6-ft, 22,000-lbs seismic mass that supported the test article during the test. The bagging material consisted of AT film and was not tightly installed, but neither was it loose enough to come in contact with the test unit during the test. For the duration of the time outside of the clean room, nitrogen was pumped inside the bagged frame. The seismic mass was easily moved from the clean room to the center of the speaker configuration using four air bearings placed at the corners of the mass.

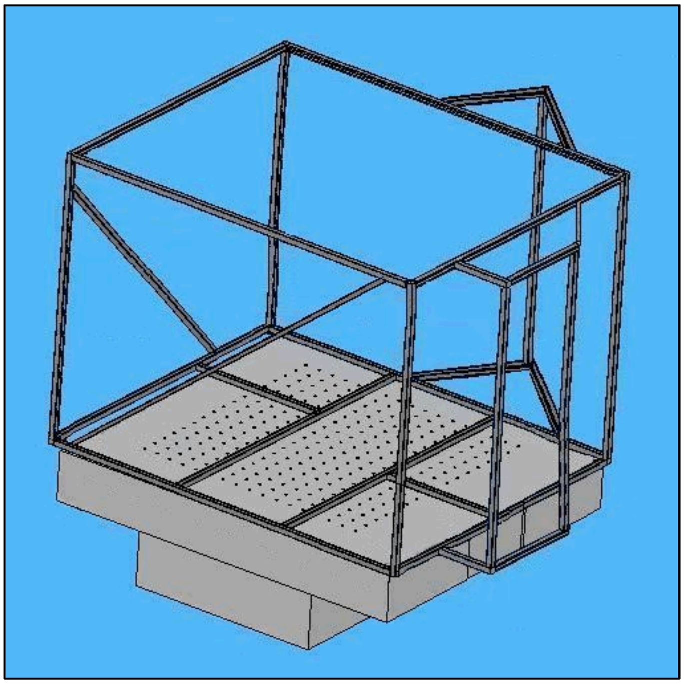


Figure 3: Contamination Frame (AT film not shown).

Now that the Sandia system clean room requirement was satisfied, several new concerns arose. What was the effect of the bagging material on the interior acoustic field, near the test unit? Conversely, what would the effect of the acoustic field be on the bagging material itself? To answer these questions and alleviate concerns, existing equipment was used to perform acoustic experiments prior to the Sandia system test.

An initial low-fidelity acoustic test was performed at the Sandia Large-Scale Vibration and Acoustic Lab. This facility contains a large reverberation chamber, 12 loud-speakers, and a closed-loop control system, capable of reaching 130 dB OASPL. For the sake of simplicity, a test item assembled from stacking a round wooden block, a cardboard box, and a round metal trash can (named TrashSat-1) was contained within a bagged contamination frame. Four stacks of speakers were placed on each side of the frame, four control microphones were placed 3-feet in front of the speakers, and four response microphones were placed 1-foot away from test item inside the frame. This DFAT configuration, as seen in Figure 4, was used to perform the test specification scaled down to 130 dB OASPL with the 1) frame and TrashSat-1, 2) frame only, and 3) TrashSat-1 only. Each of these configurations was tested three times using an averaged control scheme.

Figure 4: TrashCan-1 DFAT Setup

Resulting SPL response data for one of the four interior bag microphones (Channel 7) are shown in Figure 5 for all test configurations, along with the averaged controls. As seen in the figure, all nine averaged test controls were very similar. The response microphone SPLs for all test variations were also similar and followed the control specification fairly closely up to 1600 Hz where they began to diverge. With the bagged frame removed (blue line), the response SPL remains within 4 dB of the average control. With the bagged frame in place however, the response SPL attenuates above 1600 Hz, by as much as 11 dB at 8000 Hz. This occurs with and without the test item in place (green and red lines, respectively); therefore it was determined the bagging material causes an attenuation effect at high frequencies. The other three bagged frame interior microphones all had similar attenuation trends in the SPL measurement and OASPL values.

Months after the TrashSat-1 experiment, a dry run was performed to verify the MSI DFAT equipment configuration and test levels. The Sandia system mass mock was available for this dry run, so it was installed on the seismic mass along with the bagged frame. Following a successful full-level dry run at 146.7 dB OASPL, the test was repeated at 142.7 dB OASPL test without the bagging material since the mass mock was not contamination sensitive. A test at this level had already been performed, so comparable bagged frame data were available.

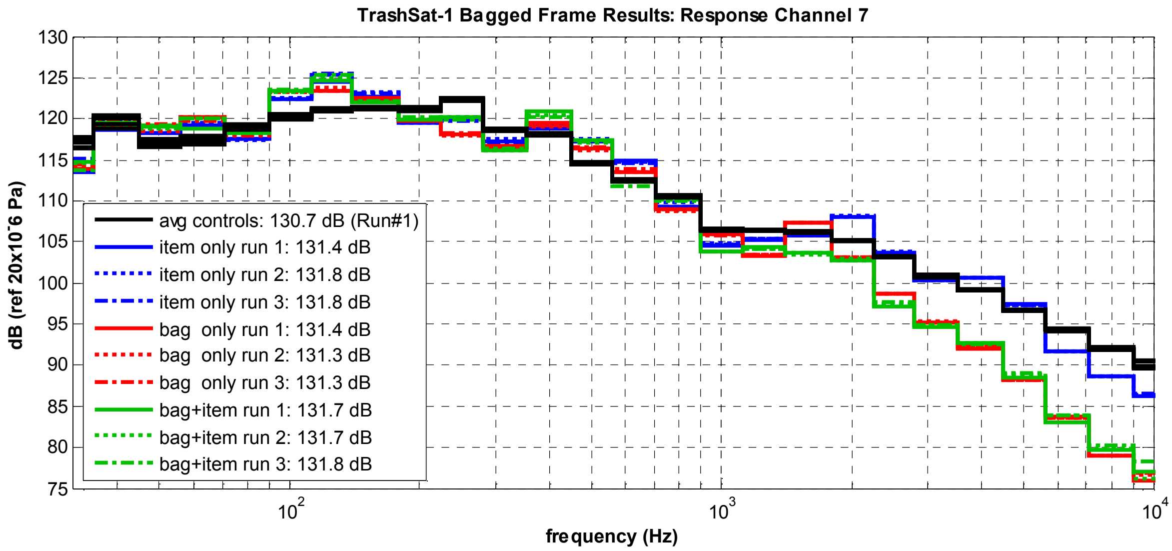


Figure 5: Trash-Sat 1 SPL Results.

Resulting SPL response data for one of the five interior bag microphones (Channel 20) are shown in Figure 6 along with the OASPL values listed in the legend. The averaged controls for both bagged and unbagged tests, plotted as dashed lines, are similar for both test configurations. As with the TrashSat-1 test, the response microphones, indicated by the solid lines, have similar responses until 1000 Hz, when the bagged configuration diverges and attenuates by as much as 8.3 dB at 6300 Hz when compared to the unbagged response. The remaining four interior microphones all exhibited similar attenuation responses.

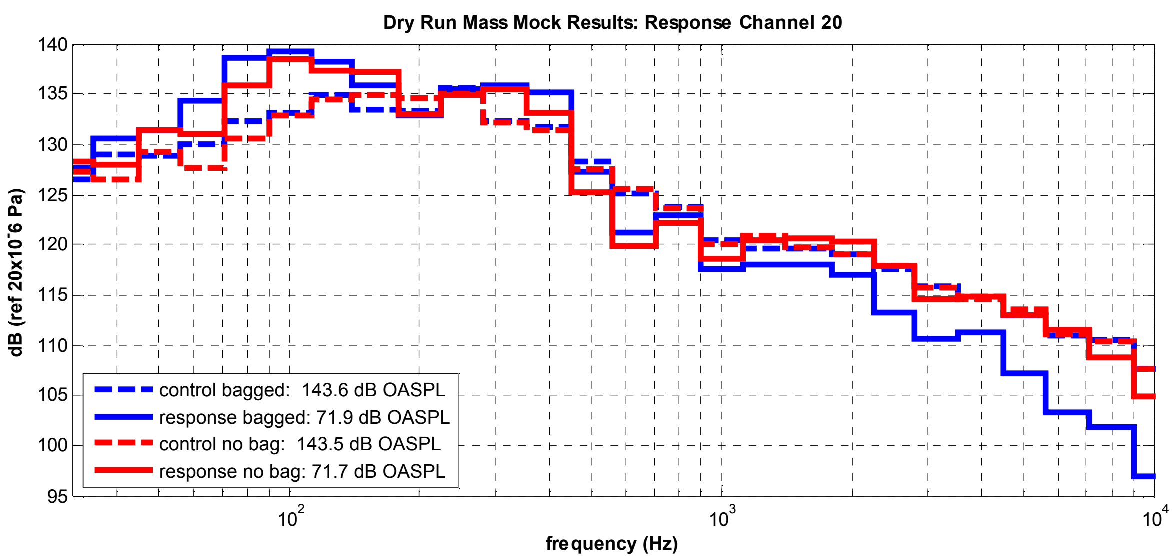


Figure 6: Mass Mock SPL Results

Results from both the TrashSat-1 and Mass Mock bagged frame experiments were very useful in predicting and alleviating some concern about what would occur during the Sandia system test—primarily that it was possible to keep the test unit uncontaminated during DFAT with the drawback of an attenuated acoustic field above 1000 Hz. The attenuation was not problematic, as the major structural modes of concern were centered within the wide peak in the environment specification (100 Hz to 300 Hz). If this were not the case, the upper frequency input reference would require an increase to make up for this attenuation. Finally, it must be mentioned that the hardware safety concern of the acoustic input effect on the bagging material itself was unfounded, as the bagged material was still in place and was seemingly unmoved following each test.

QUICK-LOOK DATA ANALYSIS

As with most system-level tests, each Sandia system DFAT resulted in a multitude of data that required examination prior to proceeding with the next test level. Even ignoring the response microphones and accelerometer data, there was plenty of data to inspect from the eight control microphones and one averaged control signal—each with SPL values for 26 frequency bands, OASPLs, and corresponding tolerances. Therefore, a quick-look spreadsheet was designed to analyze and condense the control information quickly in an easy-to-interpret format, in order facilitate effective decisions and minimize delays between tests.

Once designed, the implementation of the quick-look spreadsheet required very little effort and was mostly automated. During testing, the JAGUAR control system measured and recorded exponential-averaged, narrow-band PSDs for every control loop, which was approximately every 2 seconds. Once the test was complete, these PSDs were exported to a laptop in a MATLAB ASCII format, where a MATLAB program loaded the last twelve PSDs into the quick-look EXCEL spreadsheet. Finally, the spreadsheet calculated the 1/3-octave band SPL and OASPL values from the narrow band data and compared them to the defined test tolerances in a table and corresponding plot. Quick-look test results were available within five minutes of a completed test.

The quick-look table for the first 146.7 dB OASPL test run (Run#1) is shown in Table 1 for the control microphones; for the sake of brevity and page width, only Channels 1-4 are shown. As seen in the table, the columns list the 1/3-octave bands, test specification, tolerances, average control, and individual control microphones; the rows consist of the measured SPL values (in dB) for each. OASPL values were calculated for each microphone and are listed along the bottom row. To make the data easy to interpret, the cells are colored blue, green, and red if the SPL and OASPL values were below, within, or above tolerance, respectively. The primary column of interest was the average control column (in bold), since it was agreed that these values would define successful achievement of the test specification. Using this table, above- or below-tolerance control measurements were easily noticeable and could be quickly addressed, such as the below-tolerances seen at 200 Hz frequency band for the Average Control, Mic 1, and Mic 3.

Table 1: Quick-look Control Channel Table Run #1 (only channels 1-4 shown for brevity)

Specification		Tolerance			SPL, scaled to 0dB (dB, ref = 2e-5 Pa), dataset:				SPL_time11
Center Freq (Hz)	SPL Spec (dB)	Tolerance (dB)	Lower Bound (dB)	Upper Bound (dB)	Average Control	Mic 1 (Channel 1)	Mic 2 (Channel 2)	Mic 3 (Channel 3)	Mic 4 (Channel 4)
31.5	130.0	±5	125.0	135.0	131.38	131.57	132.51	130.90	130.97
40	130.5	±5	125.5	135.5	130.05	130.21	131.57	129.65	129.58
50	133.0	±3	130.0	136.0	131.26	129.79	132.50	130.44	130.24
63	133.5	±3	130.5	136.5	132.84	129.14	133.97	131.80	132.85
80	135.0	±3	132.0	138.0	134.20	132.11	137.99	134.38	132.43
100	136.5	±3	133.5	139.5	134.52	126.01	135.84	136.60	130.67
125	137.5	±3	134.5	140.5	136.54	134.51	133.95	135.70	132.55
160	137.7	±3	134.7	140.7	136.45	136.84	133.86	138.15	136.66
200	137.3	±3	134.3	140.3	134.27	131.16	138.53	130.59	134.54
250	138.5	±3	135.5	141.5	136.73	133.06	140.42	134.62	135.17
315	134.7	±3	131.7	137.7	134.94	135.26	134.82	132.93	136.44
400	134.3	±3	131.3	137.3	133.59	135.46	135.96	130.44	131.67
500	130.5	±3	127.5	133.5	130.34	131.20	132.19	130.98	128.78
630	128.7	±3	125.7	131.7	128.71	129.53	124.87	130.57	128.48
800	126.8	±3	123.8	129.8	126.41	128.02	124.41	127.38	121.98
1000	122.5	±3	119.5	125.5	122.42	121.44	124.52	119.60	121.42
1250	122.7	±3	119.7	125.7	122.66	122.68	126.92	122.72	118.95
1600	122.3	±3	119.3	125.3	122.12	122.11	124.30	120.94	120.16
2000	121.5	±3	118.5	124.5	121.15	123.16	119.92	119.79	123.07
2500	119.2	±3	116.2	122.2	119.38	118.61	118.54	119.31	116.20
3150	116.8	+3 / - 4	112.8	119.8	117.06	119.44	116.75	116.36	116.21
4000	115.4	+3 / - 4	111.4	118.4	115.07	114.28	113.50	114.56	115.26
5000	112.7	+3 / - 4	108.7	115.7	112.83	113.62	112.66	111.67	112.93
6300	110.3	+3 / - 4	106.3	113.3	110.40	109.70	112.12	108.92	110.66
8000	108.0	+3 / - 4	104.0	111.0	108.10	106.35	111.69	107.83	108.05
10000	106.0	+3 / - 4	102.0	109.0	103.28	102.52	104.31	104.03	102.37
OASPL	146.7	+1.5/-1	145.7	148.2	145.56	144.46	147.10	145.20	144.59

A plot also was created from the data in Table 1 and consisted of the average control, eight control microphones, and respective tolerances for every 1/3-octave band. These quick-look tables and plots were created for the response microphones as well. While not integral in controlling the acoustic input, these response results aided in characterizing the acoustic field.

Another useful feature of the quick-look spreadsheet was the ability to view the PSDs as a function of time. As previously mentioned, the last twelve exponentially averaged PSD measurements (labeled SPL_time1 through SPL_time12) were loaded into the quick-look spreadsheet. As seen in the yellow, highlighted cell in the upper-right of Table 1, a pull-down menu allowed the user to flip through each PSD dataset and see the individual SPL measurement results in the table. A better way to view these control PSDs was to combine them all in a 1/3-octave plot such as the one shown for the first full-level test (Run#1) in Figure 7.

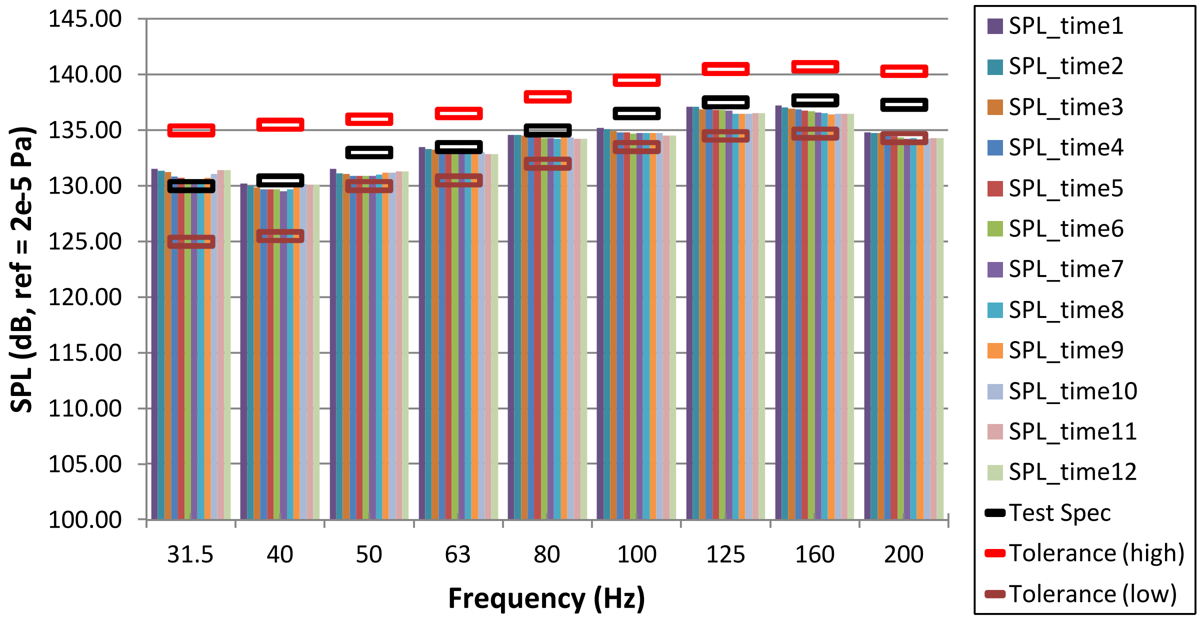


Figure 7: Average Control SPL (Cumulative) versus Time Run #1

Again for the sake of brevity and page width, the data in Figure 7 consist of only the first nine 1/3-octave frequency bands with the averaged control SPL as a function of time from left to right (SPL_time1 measurement occurred toward beginning of test, SPL_time12 measured at the end of the test). Visually, this plot illustrates how the DFAT system (control system, speakers, and amplifiers) perform during a test. For example, in data shown, the control at 200 Hz was initially within tolerance, then drops below as time increases. Therefore, it was decided to increase the input at 200 Hz on the control system, which was then within tolerance for the remaining two full-level runs. The time to decide upon this modification would have taken much longer (or may not have occurred at all) if the SPL time histories were not captured and plotted effectively.

In addition to efficiently presenting tables and plots, another benefit of the quick-look spreadsheet was the rapid availability of the results to the customer following a test. As mentioned previously, the time between testing and providing quick-look printed results was about five minutes. This allowed the customers to analyze the results without disturbing the Sandia test engineers, allowing them to concentrate on the important work of preparing for the next test level (data analysis, adjusting input, troubleshooting, restroom breaks, etc.).

SANDIA SYSTEM DFAT RESULTS

Following all the test preparation, including the bagged contamination frame experiments and quick-look spreadsheet design, three full-level 146.7 dB OASPL acoustic tests were performed on the Sandia system, resulting in the 1/3-octave averaged control spectrum plotted in Figure 8. Corresponding OASPL levels calculated from each test run are listed in the legend. As a reference, the required test specification is plotted as a dashed black line with the upper and lower tolerances plotted as dashed orange lines.

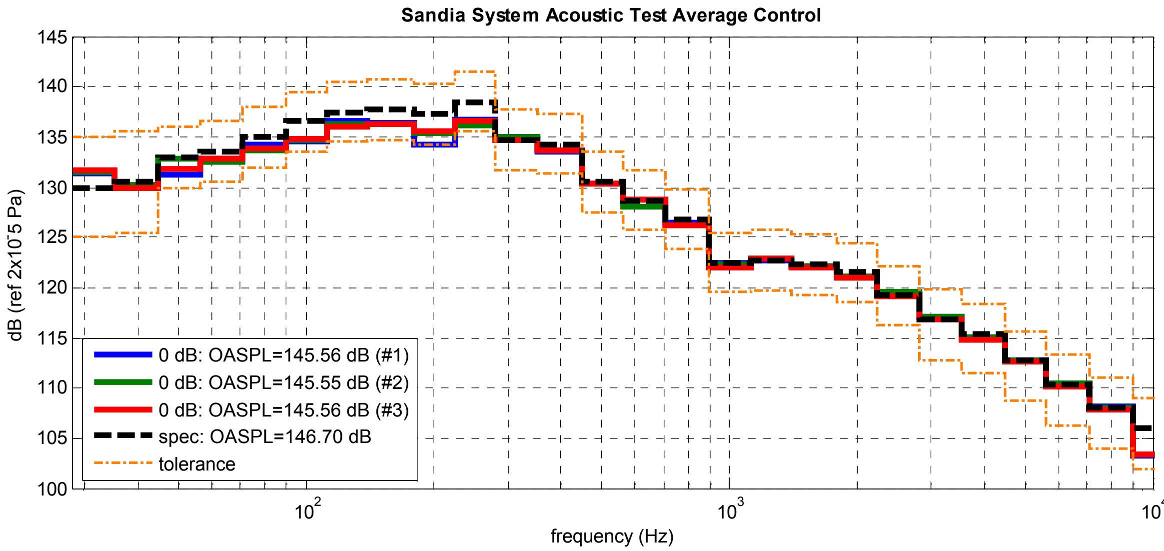


Figure 8: Sandia System Average Control SPL Results

Results from the five response microphones located inside the double-bagged contamination frame near the Sandia system for full-level Run #3 are shown in Figure 9. The corresponding OASPL values calculated from the data are listed in the legend. The required test specification has been plotted as a dashed black line for reference. As expected from the contamination fame experiments, the acoustic response at all locations attenuates above 1000 Hz when compared to the test specification and the average control spectra in Figure 8.

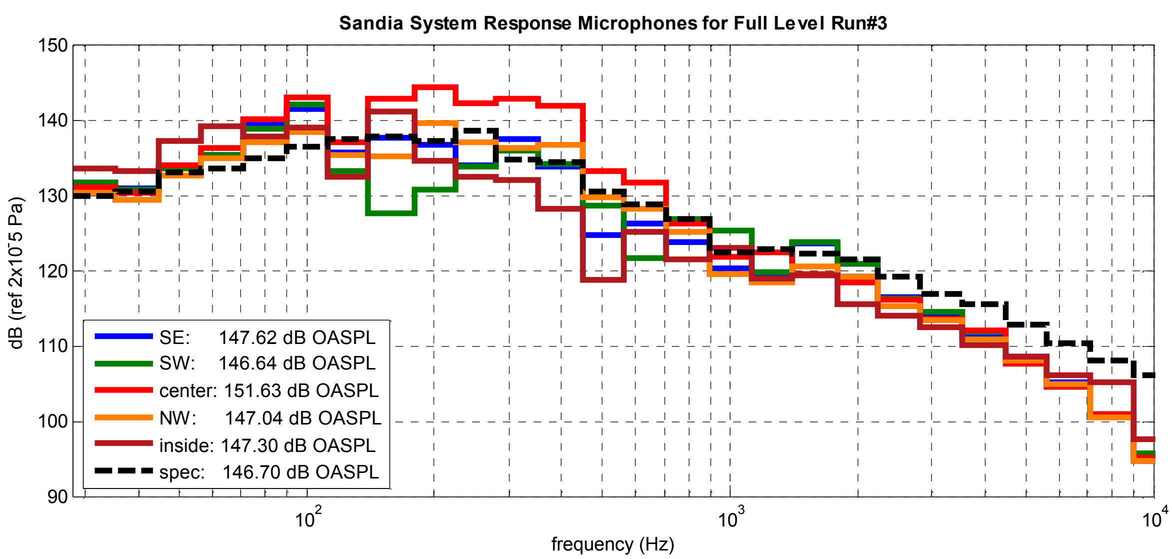


Figure 9: Sandia System Interior Bagged Frame SPL Results Run#3

Another noticeable aspect of the interior microphone response data is the large spread of the acoustic environment, particularly from 100 Hz to 700 Hz. The largest sound pressure levels belong to the center microphone at these frequencies, which was located at the center of the seismic mass, above the Sandia system. At this center location, constructive interference of the acoustic waves from the speakers more than likely occurred, resulting in these very high sound pressure levels. The OASPL for the center microphone was much larger as well; 151.63 dB compared with the average control 146.37 dB. This was not discussed, but the same large magnitude SPL can be seen at 100 Hz and 125 Hz in the TrashSat-1 and Mass Mock test data shown in Figure 5 and Figure 6. These results lead to some interesting ideas on how to perform a better DFAT.

IMPROVED DFAT METHOD DISCUSSION

The DFAT performed for the Sandia system implemented a single drive signal to all speakers based on multiple microphone inputs; this is also known as multi-input, single output (MISO) control. While being the simplest closed-loop control test method, it also presents a major disadvantage in that the speaker signals are correlated, resulting in a coherent (fixed phase), acoustic field where constructive and deconstructive interference occurs throughout. This is most evident in the sound pressure levels measured in the center of the field near the test items, regardless of the presence of a contamination frame, as seen in Figure 5, Figure 6, and Figure 9. For example, the center microphone in Figure 9 measured 144.3 dB at 200 Hz, while the input specification was 137.3 dB (an increase of 7 dB); conversely, at 160 Hz, the response for the SW microphone is 127.6 dB while the input is at 137.7 dB (a decrease of 10 dB). These results may indicate that over- or under-testing of the test unit occurred at certain frequency bands and locations in the acoustic field.

The disadvantage of a single correlated speaker drive resulting interference can also be seen in the spread that occurs in the control microphones SPL measurements. The eight control microphones, as well as the average control, are plotted in Figure 10 for the Sandia system full-level Run #3. As seen in the plot, while the average control is within the tolerance, the spread in the SPL of the control microphones is substantial, ranging from 1.8 dB to 11.1 dB. This indicates an acoustic field that is not very uniform. Some advanced MISO control strategies are available to address these concerns immediately, while other control methods are being developed to improve the acoustic field itself.

If a MISO system is the only closed-loop control scheme available, one way to addresses the over- or under-test concern of the test item is through the application of response limits. This limiting is a feature available on most commercial control systems and can be applied to microphones near the test item (inside the contamination frame in this case). Or if the design load limits of individual system components are known, limiting can also be applied to acceleration measurements at the components of concern.

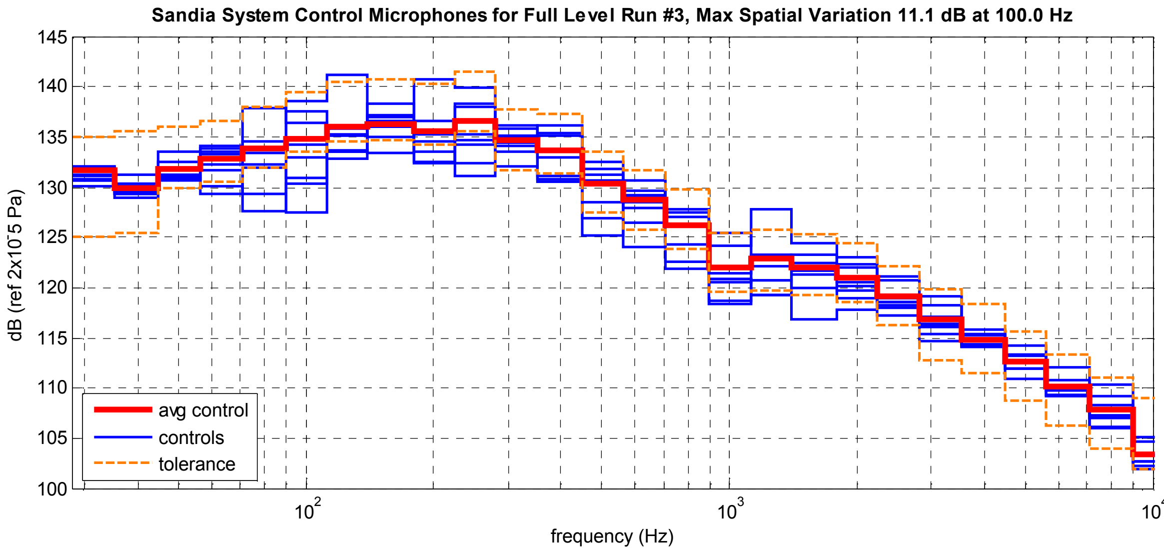
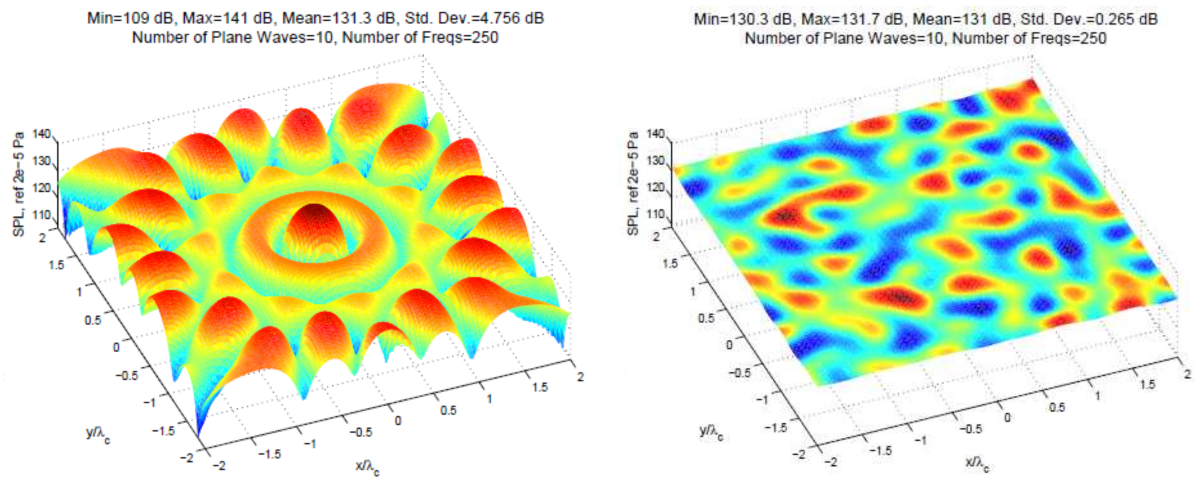


Figure 10: Sandia System Control Microphone SPL Results (Run #3)

In addition to MISO control, there is another control scheme that implements multiple, independent drive signals determined by multiple inputs; also known as multi-input, multi-output (MIMO) control. In the case of the Sandia system DFAT setup, each speaker stack would have an independent drive signal based on the multiple control microphone measurements. The primary advantage of MIMO control is the ability to define the phase and coherence between the drive signals, resulting in uncorrelated outputs and a more uniform acoustic field. Current research applying MIMO control to DFAT testing is being performed by Larkin and indicates a decrease in the spatial variation from ±12 dB to ±3 dB [3].

One other method that may improve the uniformity of the DFAT field is the random phase technique proposed by Rouse [4]. Based on the definition of a diffuse field—a field consisting of an infinite number or plane waves with random phase relations—the idea is to take a single drive signal from a MISO controller, split it into multiple signals, add a random relative phase to each, then output the signal as multiple drives into the speakers. This method has been proved with analytical models of the DFAT field, as shown in Figure 11.

The model in Figure 11 represents ten sources outputting 250 Hz plane waves with (a) equal phase and (b) random phase. The large peaks and valleys present in the equal phase plot, due to the previously discussed constructive and deconstructive interference, are minimized in the random phase plot; note that the SPL scale is the same in both plots. The spatial standard deviation decreases from 4.75 dB to 0.27 dB. Validating this work experimentally is currently underway at Sandia National Labs.



(a) **(b)**

Figure 11: DFAT Acoustic Field Model With (a) Equal Phase and (b) Random Phase

CONCLUSION

An acoustic environment of 146.7 dB OASPL was applied to a Sandia system using the direct-field acoustic test technique. The portability of this technique allowed Sandia to meet a critical shipping schedule, minimize transportation of the system, and utilize clean room infrastructure in the integration facility. To keep the system contamination free during testing, a nitrogen-purged, bagged frame was constructed around the system. Acoustic experiments, as well as the actual test, indicated that the acoustic field attenuated inside the bag above frequencies of 1000 Hz. Additionally, the bagged material did not appear to visibly deform following a test, easing hardware safety concerns. During Sandia system testing, quick-look spreadsheets were implemented to present the test engineers (and customers) with relevant control and response data that allowed for efficient acoustic system adjustments prior to the next test run. While the DFAT was considered successful, results from the Sandia system acoustic test illustrated the major disadvantage of standard DFAT testing—the non-uniformity of the acoustic field due to a single, correlated drive signal. Response channel limiting can be used to address over-test concerns due to this non uniform field. Multi-input multi-output control systems have been experimentally shown to decrease the spatial variation of a DFAT field; the proposed random phase technique has shown a decrease as well, but has currently only been analytically proven.

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BIOGRAPHIES

Eric C. Stasiunas is a Senior Member of the Technical Staff at Sandia National Laboratories in Albuquerque, NM, where he has worked in the field of experimental structural dynamics since 2002, performing experimental modal analysis, vibration, and acoustic testing. Eric holds a BS in Mechanical Engineering from Tennessee Tech and an MS in Mechanical Engineering from Virginia Tech.

Vit Babuska is a Principal Member of the Technical Staff at Sandia National Laboratories in Albuquerque NM, where he has worked since 2005. He earned his Ph.D. in Aerospace Engineering in 1993 from The University of Texas at Austin. He has worked on various spaceflight programs and spacecraft R&D projects during his career and was the test director of the acoustic test described in this paper.

David J. Gurule is an Electro-mechanical Technician at Sandia National Laboratories in Albuquerque, NM. Mr. Gurule has over seven years of experience conducting vibration, acoustic, and mass properties testing and is the lead technologist of the Vibro-Acoustic Lab. He holds a BS in Electrical Engineering Technology from New Mexico State University.

Troy J. Skousen earned his BS in Mechanical Engineering from BYU in 1999 and MS in Mechanical Engineering from BYU in 2002. He has been a Member of the Technical Staff at Sandia National Laboratories since 2002. Since 2006 he has been working in the environments engineering field mainly supporting satellite program testing that include random vibration, pyro-shock, quasi-static, and acoustic testing.

Jerry W. Rouse has been a Senior Member of the Technical Staff in the Analytical Structural Dynamics Department at Sandia National Laboratories since 2007. Prior to conversion to full staff member, Dr. Rouse was a postdoctoral appointee at Sandia National Laboratories beginning in 2004 at the completion of his Ph.D. He has B.S. and M.S. degrees in Mechanical Engineering from North Carolina State University, and a Ph.D. in Mechanical Engineering from Duke University.