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Predicting Flight Environments with a Small-Scale, Direct-Field Acoustic Test Facility

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ABSTRACT

In order to predict flight environments for ground support equipment, a small-scale, direct-field acoustic test (DFAT) laboratory was recently constructed at Sandia National Laboratories. This unique laboratory setup—consisting of twenty-four commercial off-the-shelf monitor speakers driven by a multi-input multi-output control system—was capable of exciting the component with an acoustic environment of 103 dB overall sound pressure level (OASPL). The resulting measured data was used to predict the flight environment response of the component and to derive vibration test specifications for future mechanical shaker testing. This paper describes the small-scale DFAT laboratory setup, the applied acoustic test method, and the process used to predict the flight environments for the given ground support equipment.

KEYWORDS

Direct-Field Acoustic Test, DFAT, Multi-Input Multi-Output Control, MIMO, Flight Environment Prediction

INTRODUCTION

At Sandia National Laboratories, it was desired to develop a more realistic definition of the flight line environment for a particular item of ground support equipment (GSE). In order to do so, a small-scale laboratory acoustic test was performed, which would subject the GSE to a flight line acoustic environment while measuring internal location responses. The measured input and resulting responses, along with data measured from a separate vibration test, were subsequently used to derive a shaker table vibration test environment.

This paper primarily discusses the details of the small-scale acoustic laboratory setup and method used to excite the GSE, which included direct-field acoustic testing (DFAT) with multi-input multi-output acoustic (MIMO) control. This test technique, using only commercial speakers in a small-scale environment, is fairly unique and justified an in-depth discussion. The GSE response acceleration is only briefly discussed. Finally, the process used to predict the flight environments for the GSE is described and is illustrated with example data.

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TEST SPECIFICATION

The desired flight line test specification for the GSE acoustic environment was derived from MIL-STD-810G [1], which identifies a generic Sound Pressure Level (SPL) spectra for use with aircraft-induced acoustics. Since the GSE is ultimately operated by personnel on the ground, this specification was scaled to 100 dB overall sound pressure level (OASPL) based on the maximum approved levels for short duration exposure per Occupational Safety and Health Administration (OSHA) [2]. The scaled GSE acoustic test specification is shown in Figure 1 as sound pressure level (SPL) versus 1/3-octave frequency bands, with the corresponding numerical values listed in Table 1.

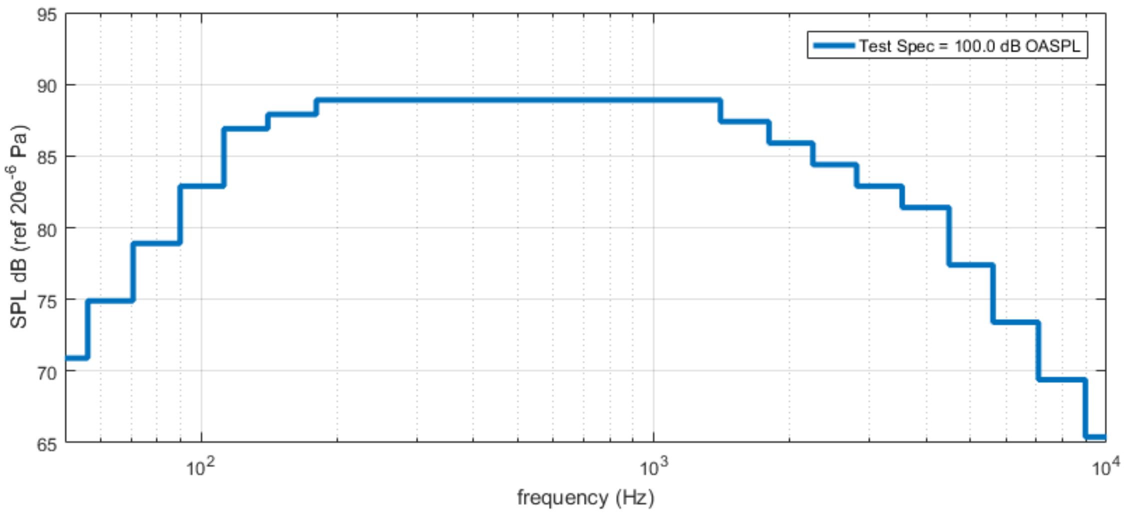

Figure 1: GSE Acoustic Test Specification SPL

Table 1: GSE Acoustic Test Specification

Frequency (Hz)	SPL (dB)	Frequency (Hz)	SPL (dB)
50	70.9	2000	85.9
63	74.9	2500	84.4
80	78.9	3150	82.9
100	82.9	4000	81.4
125	86.9	5000	77.4
160	87.9	6300	73.4
200	88.9	8000	69.4
1250	88.9	10000	65.4
1600	87.4	-	-

An exposure time for the acoustic test was not specified for the GSE. The maximum capability of the small-scale acoustic test equipment was found to be around 110 dB OASPL, which was low enough to eliminate fatigue concerns of the GSE. Based on this, it was decided that the full-level test duration by the control system would be 30 seconds, which was long enough to collect several quality data sets with a separate data acquisition system over a 10 second window.

SMALL-SCALE ACOUSTIC TEST FACILITY

The desired acoustic test environments were simulated in Sandia's small-scale acoustic test facility through the use of the direct field acoustic test (DFAT) method. This method consists of surrounding a test item with speakers and exciting the test item within the resulting direct acoustic field of the speakers. A closed-loop control system is typically used to drive the acoustic speakers based on measurements from control microphones located in the acoustic field, placed between the speakers and test item. For the GSE test, a multi-input multi-output (MIMO) control system was used to control the acoustic environment with twelve inputs and twelve drives (one microphone per speaker drive). DFAT is a useful technique when a reverberation chamber is not readily available and acoustic excitation is desired. Further information regarding DFAT can be found in [1,3].

The DFAT setup used in the small-scale acoustic test facility is contained in a 10-ft × 10-ft × 8-ft tall frame, covered with sound-attenuating blankets. Because this facility is part of a larger high-bay, the blankets were required to attenuate the resulting acoustic test noise below OSHA-allowed SPL for personnel working nearby. Additionally, the blankets provided a sufficiently quiet environment inside the test frame to allow for successful closed-loop control by the MIMO control system. Loud, ambient noise from other test equipment in the area can be picked up by the control microphones and cause failed loop-checks (performed by the control system prior to test to guarantee close-loop control), preventing the test from proceeding.

Inside the acoustic test frame, twelve pairs of commercial, off-the shelf studio monitor speakers (24 total) were placed 30-degrees apart in a 5-ft radius circle, 4-ft from the floor. The monitor designation of the speakers is used to indicate that they were designed to produce relatively flat frequency response and phase, where no emphasis is placed on any one particular frequency or frequencies. Each monitor speaker cabinet consisted of both a 5.25-in low to mid-frequency driver and a 1-in high-frequency driver. Depending on the shape of the acoustic test specification, levels as high as 110 dB OASPL have been obtained with this facility.

ACOUSTIC TEST SETUP

The Ground Support Equipment was a small box sized approximately 12-in × 8-in × 6-in, and weighed approximately 20 pounds. To measure the response of the GSE due to acoustic excitation, a number of both uni-axial and tri-axial accelerometers were internally placed at locations of interest. The GSE was placed in the center of the speaker circle and surrounded by twelve control and twelve response microphones. The control microphones were placed randomly in the field using tripod stands, near their corresponding speaker pair; previous tests performed with uniform spacing resulted in constructive interference of the acoustic waves. Four response microphones were hung from the test frame ceiling and placed to the sides (1-ft from center) of the test item, a hanging microphone was placed in the center 4-in above the test item, and a linear array of six microphones, spaced 6-in apart was placed in the field. Unless otherwise stated, all speakers and microphones were aligned along the same vertical plane in line with the test article. The GSE, speaker pairs, and the control and response microphones can be seen inside the acoustic blanket-draped test frame in Figure 2.

An overhead, graphical representation of the acoustic test setup can be seen in Figure 3. The speakers are represented by the black boxes, the control microphones are blue circles, the center microphone is orange, the response microphones placed around the GSE are red, and the microphone array is green. Each speaker number corresponds to the control system drive, and the microphone numbers represent the measurement channel (response microphone 13 and array microphone 21 were co-located). Note that each control microphone is placed near (within sight-line of) the corresponding speaker pair; if the control microphone is placed too far away, the corresponding speaker will reach the maximum control system drive voltage prior to the other speakers and result in a not-diffuse environment.

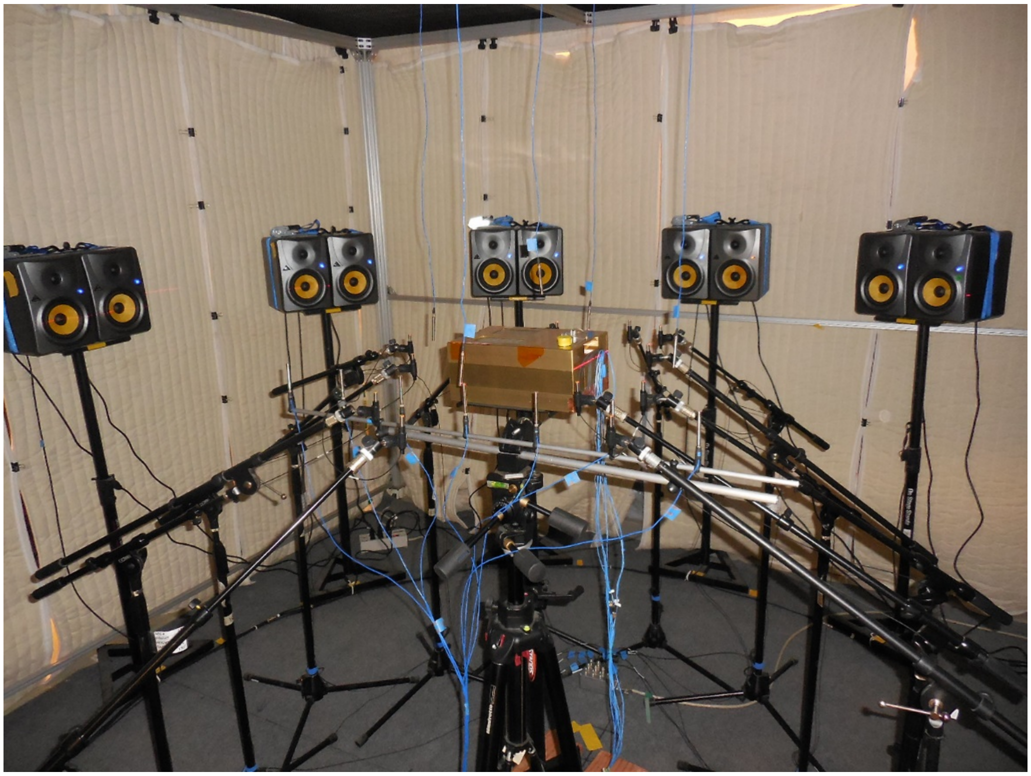

Figure 2: GSE Direct-Field Acoustic Test Setup

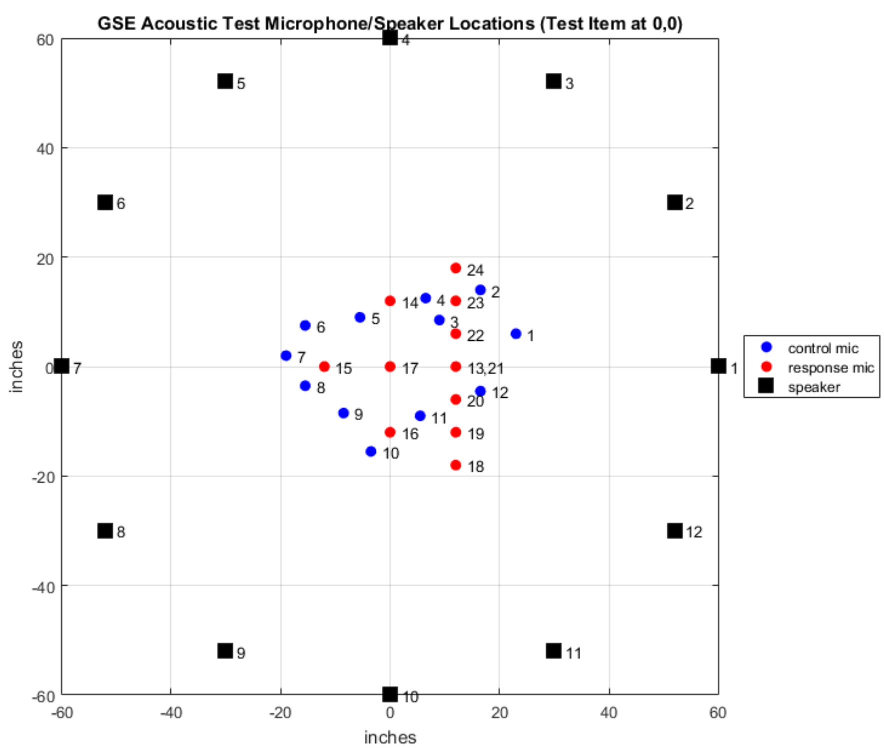

Figure 3: Speaker and Microphone Location (Top View)

The microphones used for the GSE acoustic testing were two different models of ¼-inch diameter microphones with nominal sensitivities of 12 mV/Pa and 0.9 mV/Pa; the lower sensitivity microphones were used for control and the higher sensitivity microphones were used for response monitoring. Typically used for reverberant chamber acoustic tests reaching 145 dB OASPL, the 0.9 mV/Pa microphone's sensitivity was too low (noise floor too high) for the control system to provide control (would not pass loop check) at the nominal level of 100 dB OASPL. The microphone channel table, including coordinate locations is listed in Table 2.

Table 2: GSE Microphone Table

Ch #	Description	X (in)	Y (in)	Ch #	Description	X (in)	Y (in)
1	Speaker 1 Control	23.0	6.0	**13**	0-deg, 1-ft	12.0	0.0
2	Speaker 2 Control	16.5	14.0	**14**	90-deg, 1-ft	0.0	12.0
3	Speaker 3 Control	9.0	8.5	**15**	180-deg, 1-ft	-12.0	0.0
4	Speaker 4 Control	6.5	12.5	**16**	270-deg, 1-ft	0.0	-12.0
5	Speaker 5 Control	-5.5	9.0	**17**	Center (4-in above)	0.0	0.0
6	Speaker 6 Control	-15.5	7.5	**18**	Array Mic 1	12.0	-18.0
7	Speaker 7 Control	-19.0	2.0	**19**	Array Mic 2	12.0	-12.0
8	Speaker 8 Control	-15.5	-3.5	**20**	Array Mic 3	12.0	-6.0
9	Speaker 9 Control	-8.5	-8.5	**21**	Array Mic 4	12.0	0.0
10	Speaker 10 Control	-3.5	-15.5	**22**	Array Mic 5	12.0	6.0
11	Speaker 11 Control	5.5	-9.0	**23**	Array Mic 6	12.0	12.0
12	Speaker 12 Control	16.5	-4.5	**24**	Array Mic 7	12.0	18.0

As mentioned previously, the acoustic environment was provided with a MIMO control system, capable of measuring 26 input channels and outputting 12 independent drives. For the GSE testing, the first 12 channels were used to measure the control microphones and determine the corresponding drive signal sent to each speaker pair (Microphone 1 assigned to Speaker Drive 1, etc.). The remaining channels were used to measure the 12 response microphones. ICP power to the microphones was provided with an external signal conditioner, which allowed for a larger-channel-count data acquisition system to measure the microphone data as well as the GSE accelerometer response data. Power for the accelerometers was provided by the integrated ICP power option of the data acquisition system. Time histories were also recorded by the second JAGUAR system, which would allow for future time history analysis if desired.

MIMO CONFIGURATION AND TEST PLAN

The multiple, independent drives of the MIMO control system allowed for defining phase and coherence (cross-spectrum) values between the multiple control locations. In theory, the coherence value determines how close the actual phase will be to the defined phase value. For example, with a 0-degree phase, 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).

The type of acoustic test environment desired for the GSE was a diffuse field, where at any location, the sound pressure levels are equivalent. Based on past test literature [4] and analytical theory [5], a diffuse field should be attainable with random phase using a low coherence value with a MIMO control system. Additionally, because the maximum SPL capability of the small-scale acoustic lab is not high enough to cause fatigue or damage to the test item, multiple acoustic tests were performed on the GSE with low (0.1) and high (0.9) coherence values, both with 0-degree phase. Analyzing and comparing data resulting from both coherence values may determine which method works best and aid in future tests when there are acoustic fatigue limits associated with the test item.

In addition to the varying coherence values, the linear microphone array was adjusted to three different elevations for each coherence value. The initial test plane at 4-ft above the floor was considered 0-inches. Once the initial tests were performed, the array was moved +4-in and -4-in from the origin, and the low and high coherence tests were repeated. The was done to gather information regarding the resulting acoustic field inside the speaker circle.

Based on past test experience [6], it was known that the individual control locations would follow the desired test specification very closely over the entire test bandwidth. The response microphones, however, would follow the test specification until a certain frequency, where they would then diverge to higher sound pressure levels for the remainder of the test bandwidth. Therefore, it was decided to first perform an initial low-level acoustic test with the nominal test specification as the control reference, then based on the response microphone measurements, adjust the control reference to bring the responses within the test specification. This process will be discussed in detail in a subsequent section.

Finally, it was also a challenge to find a level where the speakers would operate at steady-state. It seemed that when running at high drive voltages (above 1.4 VRMS), the speakers would require more and more voltage to maintain the test level. After some initial test runs, it was discovered that a drive voltage of 1.0 VRMS would prevent this phenomenon from occurring (or at least allow for a consistent 30 second, full-level run). The finalized acoustic test plan listing all these parameters is shown in Table 3.

Table 3: GSE Acoustic Test Plan

Test	Description	Dataset Run#
1	Run with GSE Test Specification (Figure 1) as reference at -12 dB with low coherence.	001
2	Adjust reference to bring response w/in spec and find test level for consistent speaker output/mic results	-
3	Run Adjusted Reference with low coherence (0.1), 0-deg phase, microphone array at 0-in.	006
4	Run Adjusted Reference with high coherence (0.9), 0-deg phase, array at 0-in.	007
5	Run Adjusted Reference with low coherence (0.1), 0-deg phase, array at +4-in.	008
6	Run Adjusted Reference with high coherence (0.9), 0-deg phase, array at +4-in.	009
7	Run Adjusted Reference with low coherence (0.1), 0-deg phase, array at -4-in.	010
8	Run Adjusted Reference with high coherence (0.9), 0-deg phase, array at -4-in.	011

TEST REFERENCE ADJUSTMENT

The first test performed on the GSE used the acoustic test specification of Figure 1 scaled down -12 dB as the reference for all 12 control microphones, with 0-degree phase and low coherence (0.1). The resulting sound pressure levels of all twelve control microphones are shown as 1/3-octave bands in Figure 4; the OASPL is listed in the legend as well. The control reference for this test is the original acoustic test specification, shown as the solid black line with dashed black lines representing the ±3 dB tolerance. As seen in the plot, the controls are very close to the test reference for most of the frequency bands, and all are within the tolerance bands, except at 10,000 Hz, which may be the noise floor of the microphone at that frequency band.

The SPL data for all twelve response microphones are shown as 1/3-octave bands in Figure 5; as before, the OASPL is listed in the legend. As expected from past experience, the responses follow the control pretty closely until approximately the 250 Hz band, where they begin to diverge and exceed the test reference for the remaining frequency bands. Most of the responses are grouped pretty close together, such as Microphones #13-16, located closest to the GSE. The center Microphone #17 is the highest response outlier. The other outliers, Microphones #18 and #24, are located at the ends of the array, furthest from the control microphones.

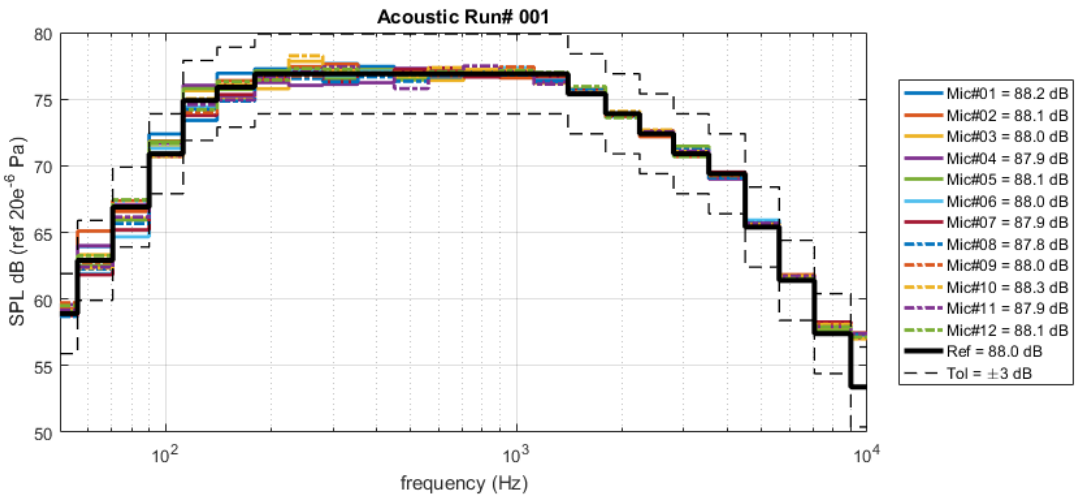

Figure 4: Control Microphone SPL for Nominal Test Reference (88 dB OASPL)

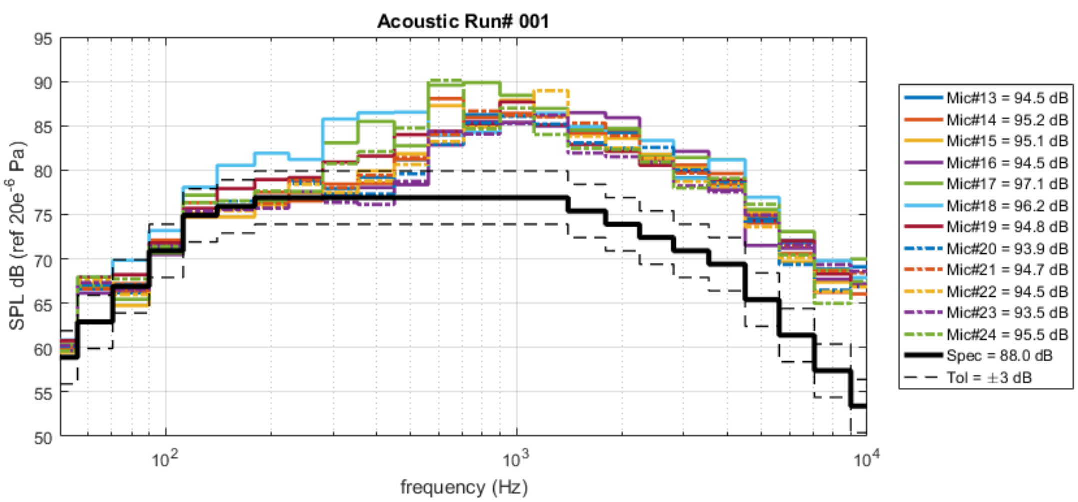

Figure 5: Response Microphone SPL for Nominal Test Reference (88 dB OASPL)

Based on this response data, it was decided to take the SPL of Microphones #13-16, closest to the GSE and 1-ft from center, and use the average to adjust the control reference. This adjustment was performed by subtracting the test specification from the average response, then subtracting this difference from the test specification, resulting in a new, adjusted control reference. This process can be seen in Figure 6; the individual Microphone #13-16 responses are shown in blue, the averaged response is shown in red, the test specification (original control reference) is shown in black, and the new adjusted control reference is shown in green. By adjusting this reference, it was expected to bring down the microphone responses and ensure closer agreement to the desired GSE test specification. What causes this response microphone divergence is not completely clear and may be due to frequency bandwidths and the distance between the control microphones and the speakers.

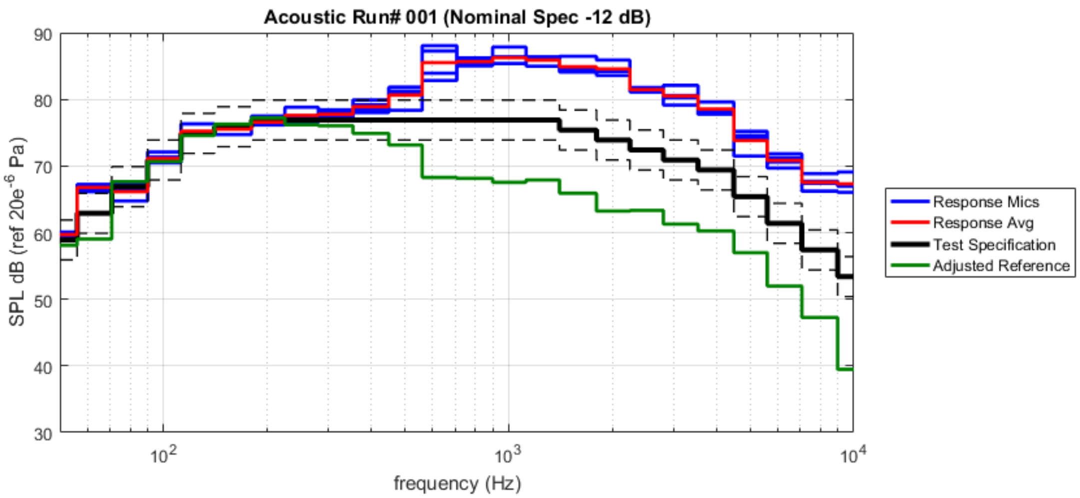

Figure 6: Response Microphone and Adjusted Reference (88 dB OASPL)

Again, this adjustment test was performed at -12 dB, so the adjusted reference values were increased to the maximum levels capable of the acoustic test system. After running the test with these adjusted reference values, it was found that the speaker drives would remain consistent at an adjusted test reference of 100 dB OASPL. The finalized control reference values used to run the remainder of the GSE acoustic tests are listed in Table 4. It must be noted that the control reference was 100 dB OASPL but the expected acoustic environment near the GSE would be approximately +3dB greater based on these exploratory tests.

Table 4: Adjusted Control Reference (100 dB OASPL)

Frequency (Hz)	SPL (dB)	Frequency (Hz)	SPL (dB)
50	73.9	800	83.1
63	77.9	1000	82.7
80	81.9	1250	82.9
100	85.9	1600	81.3
125	89.9	2000	78.4
160	90.9	2500	78.1
200	91.9	3150	76.3
250	91.2	4000	75.5
315	91.1	5000	72.0
400	90.0	6300	67.1
500	88.0	8000	62.2
630	83.5	10000	58.7

ACOUSTIC TEST RESULTS

Using the newly adjusted control reference, an acoustic test was run on the GSE with 0-degree phase and low coherence (0.1), defined as Run# 006. The GSE was excited at full-level for 30 seconds, with the DAQ recording 10 seconds worth of data. The test ran well, as the speakers drive voltages remained consistent (1.03 maximum VRMS) and did not increase for the duration of the test. The measured SPL showing all twelve control microphones is shown in Figure 7, while the SPL for the response microphones, along with the GSE acoustic test specification are shown in Figure 8.

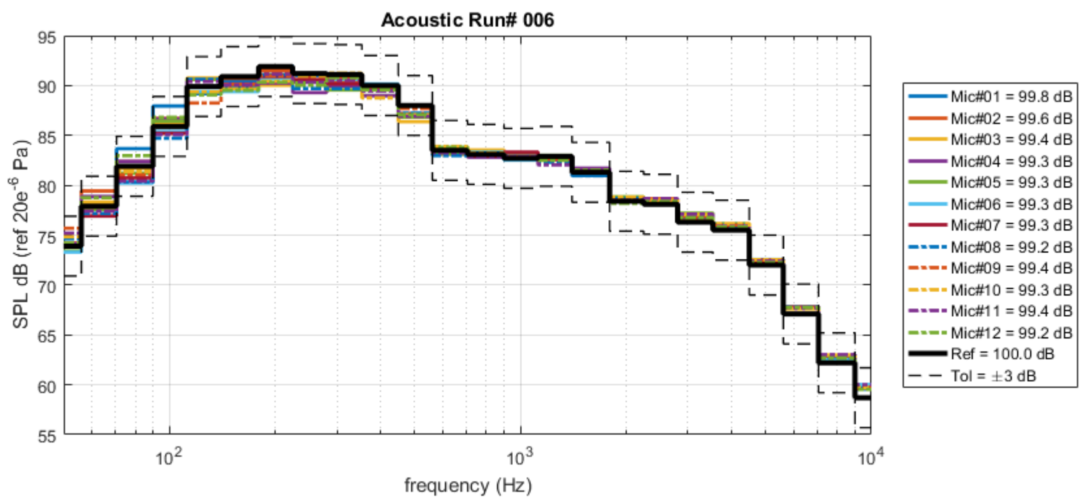

Figure 7: Adjusted Reference, Low Coherence Control Microphones

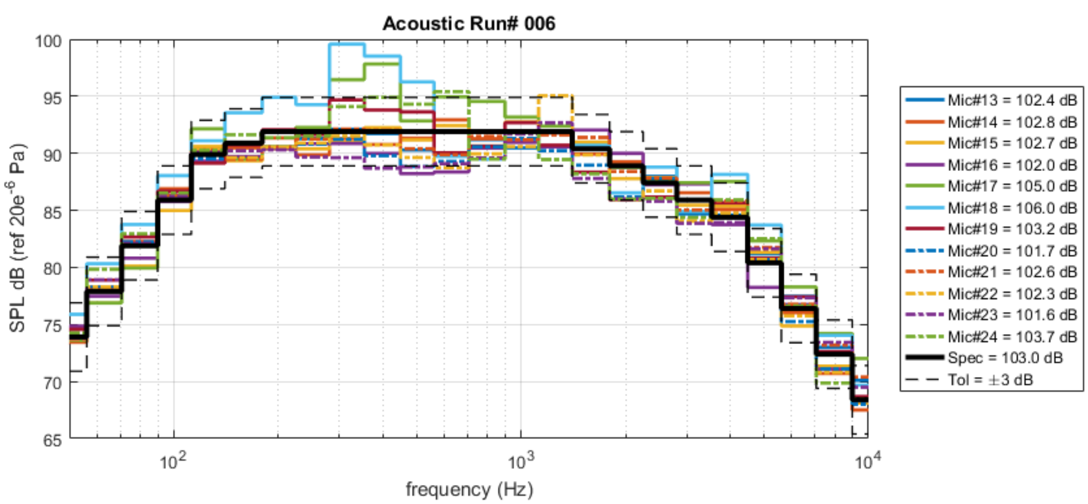

Figure 8: Adjusted Reference, Low Coherence Response Microphones

As with the previous test, the individual control microphones shown in Figure 7 are very close to the adjusted reference and within ±3 dB. The response microphones of Figure 8 show a larger spread than the controls (as expected), but they do follow the desired test specification fairly well, only deviating from the ±3 dB tolerance at a few 1/3-octave bands. As with the previous, low-level run, the largest deviation above the +3 dB tolerance were observed with the microphones located at the end of the array (Microphone #18 and #24), as well as at the center of the test setup (Microphone #17). For this test, the array was in the same plane as the speakers and GSE, and the center mic was 4-inches above the surface of the GSE.

The primary goal of this acoustic testing was to simulate a flight line acoustic input and measure the corresponding GSE response in order to derive test specification for a flight environment. After examining all microphone measurements, it was decided to use the average of the four response Microphones# 13-16 as the acoustic input for scaling purposes. This SPL average was thought to best represent the acoustic field nearest the GSE and is shown in Figure 9, plotted as a red line relative the four individual microphones in blue and the test specification in black. Although the average falls below the test specification in the mid-frequency range, the general agreement was considered sufficient. In retrospect, the adjusted test reference spectrum could have been finely-tuned to bring this average closer to the desired test specification if enough time was available to do so.

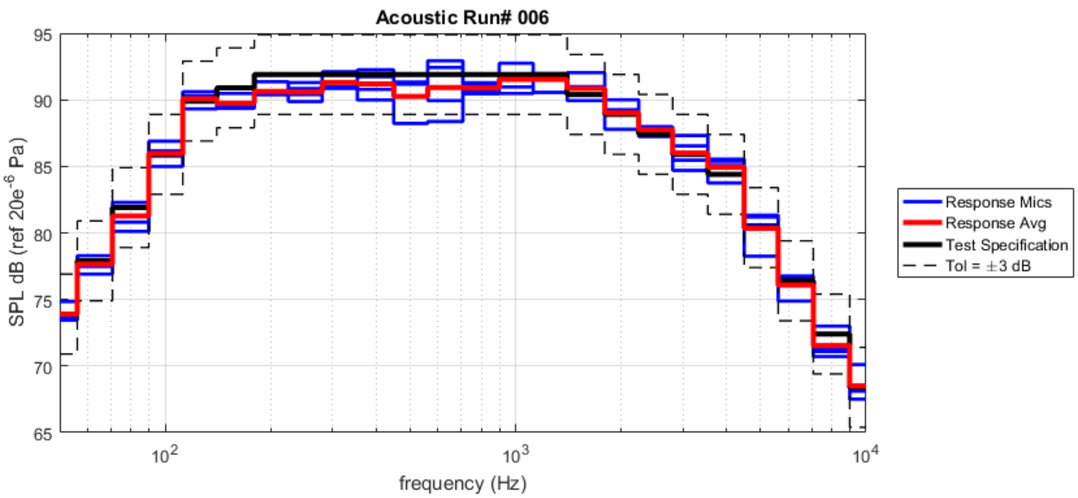

Figure 9: Adjusted Reference, Low Coherence Response and Average SPL

As previously listed in the test plan, two additional low-coherence, 0-degree phase tests were performed with the array microphones adjusted to +4-in and -4-in relative to the test plane, defined as Run #008 and #010, respectively. These additional tests were performed to better define the acoustic field above and below the primary test plane. For each test, none of the other microphones were moved, resulting in the same nominal test environment—approximately the same control and non-array response SPL for each test run.

For simplification purposes, the SPL results for all three array configurations have been plotted in Figure 10. As with the previous plot, the response average (red) is the average of Microphones #13-#16 for Run #006. The remaining SPL data consists of individual responses for Microphones #13-#16 (blue), the array microphones (green), and the center microphone (orange) for Run #006, Run #008, and Run #010. For reference, the test specification and tolerance lines are plotted as well. As seen in the figure, the response average is well within the measured acoustic field and the desired tolerance. This was further evidence for using this average to derive the vibration test specification, as shown in the subsequent section.

These tests were repeated with the MIMO controller set to 0-degree phase and high coherence (0.9) for all three microphone array elevations, defined as Run# 007 (0-in), Run# 009 (+4-in), and Run# 011 (-4-in). This was performed primarily as an experiment to see the effect of the high coherence value on the resulting acoustic field. From analytical models of these fields [5], it was expected to create a less diffuse field, with more spread between response microphone SPL. Note that the test reference for these tests were determined from the low coherence (0.1) test runs as described in the subsequent sections which may affect the results of averaging Microphone #13-16 responses (not close to the desired test specification).

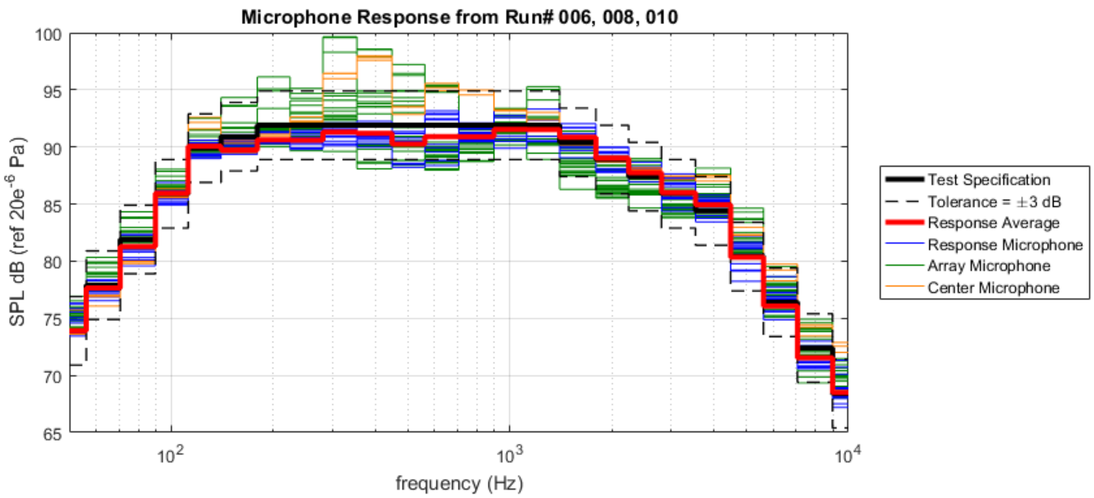

Figure 10: Adjusted Reference, Low Coherence, All Array Data

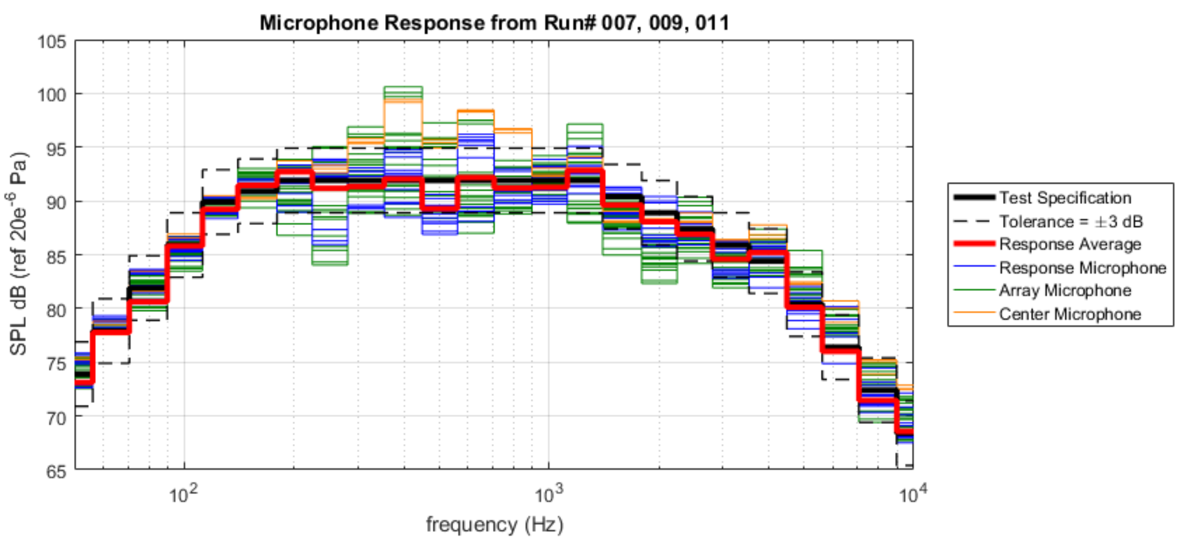

Figure 11: Adjusted Reference, High Coherence, All Array Data

Again, for simplicity, the SPL results for all three array configurations for high coherence (0.1) have been plotted in Figure 11. The response average (red) is the average of Microphones #13-#16 for Run #007. The remaining SPL data consists of individual responses for Microphones #13-#16 (blue), the array microphones (green), and the center microphone (orange) for Run #007, Run #009, and Run #011. For reference, the test specification and tolerance lines are plotted as well. As seen in the figure, the response average is closer to the test specification for the mid-frequencies, except for the 500 Hz band. However, the spread of response microphone data seems to be larger for each frequency band at 200 Hz and above, which would indicate a less diffuse environment than was observed for tests conducted with low coherence. This is simply a qualitative observation, but useful for any future MIMO acoustic tests in the small-acoustic test facility.

The interior GSE accelerometer responses due to the acoustic inputs were measured for each test. As an example of the response, the narrow-band power spectral density (PSD) of Accelerometer #13 is shown in Figure 12 due to the 0-degree phase, low-coherence (0.1) acoustic environment (Run# 006). This PSD illustrates a definite response of the GSE due to the acoustic input. Each accelerometer channel was compared with a noise-floor measurement to guarantee that the response data was valid for vibration specification derivation.

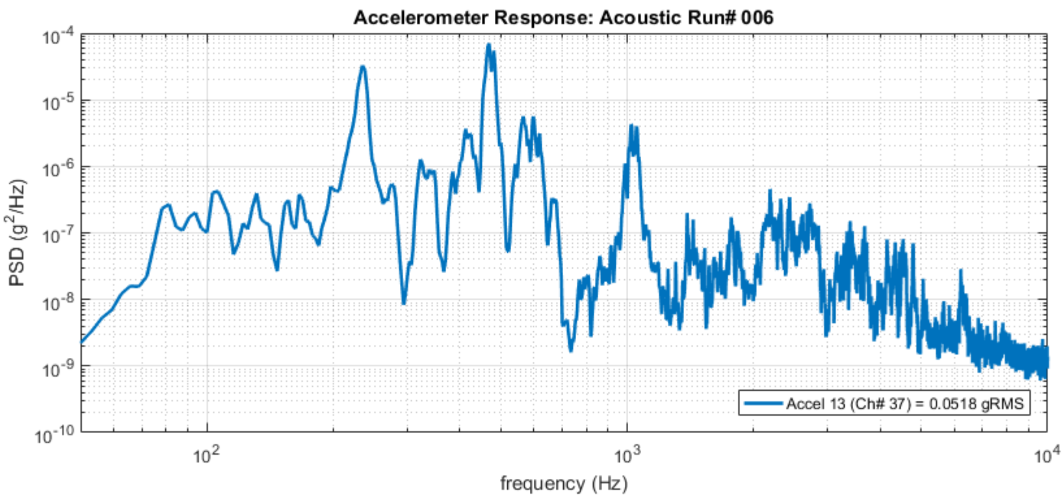

Figure 12: GSE Accelerometer Response (Ch# 37) with Low Coherence Control, Run# 006

PREDICTING FLIGHT LEVELS

The primary goal of this acoustic testing was to predict a flight environment by quantifying what vibration level is needed to envelop the acoustic flight environment that the GSE experiences in the field, replicated here in the small-scale acoustic test laboratory at scaled-down levels. Based on the acoustic test results, it was determined to use the acoustic input and internal GSE response data measured from the 0-phase, low-coherence (0.1) test run (Run# 006) for this purpose.

Two distinct acoustic levels were identified for use in this process. As stated previously, the most likely level was a 100 dB Overall Sound Pressure Level (OASPL) spectrum, since it is the highest level permitted by OSHA when test personnel are present for up to 2 hours (even with hearing protection). However, it was considered prudent to instead use this spectrum scaled to 122 dB OASPL spectrum, which represents the highest short term OSHA levels [2].

The measured acoustic environment in the small-scale acoustic facility, as determined by the average of the four microphones closest to the GSE (Microphones #13-16) for Run# 006 was 103 dB OASPL. Therefore, the GSE accelerometer response data measured at 103 dB, *P1*, was adjusted to generate both the 100 dB OASPL and 122 dB OASPL response predictions, *P2*. To scale the data accurately, the decibel formula shown in Equation (1) was used, where *dB* is the difference between overall sound pressure levels (-3 dB and +19 dB).

$$dB = 10 * log_{10}\left(\frac{P2}{P1}\right) \qquad \text{Eq.(1)}$$

A previous vibration shaker test was performed on the GSE using the MIL-STD-810G vibration environment as the test reference, with accelerometers located at the same locations as were used with the small-scale acoustic test. The vibration shaker responses at each location were scaled down together until it just enveloped the scaled-up acoustic 122 dB OASPL test responses. This process is displayed in Figure 13 for Accelerometer 13 (Ch# 37). The vibration response of the GSE at this location as measured in the acoustic test at 103 dB OASPL is shown in green. This response, scaled to acoustic levels of 100 dB OASPL and 122 dB OASPL are shown in blue and red, respectively. The response of the GSE due to the MIL-STD-810G vibration shaker test is shown scaled down -18 dB in black.

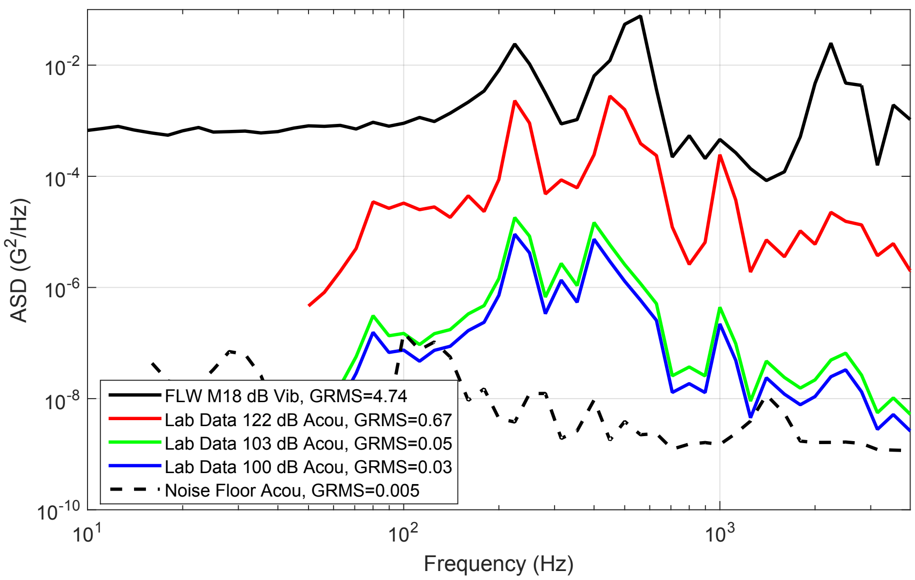

Figure 13: Flight-line Workmanship Random Vibration Response vs Laboratory Acoustic Test Response

This process was performed on all accelerometers measured from the acoustic test, until scaling down the shaker-induced response any further would cause an acoustic-induced response at another location to be larger than the vibration response. The resulting scale factor that enveloped the acoustic data with the MIL-STD-810G input was -18 dB. The scaled-down spectrum was denoted as the “Flight Line Workmanship” (FLW) test specification, and is now used as a shaker vibration test reference that represents the acoustic environment seen on the flight-line. The only other difference between this new FLW spectrum and that of the MIL-STD-810G spectrum was that the FLW spectrum was extended from 2 kHz to 3 kHz.

CONCLUSIONS

Multiple direct-field acoustic tests (DFAT) were successfully performed on the Ground Support Equipment (GSE) using a small-scale acoustic test setup implementing commercial off-the-shelf monitor speakers, microphones, and a closed-loop multi-input multi-output (MIMO) control system. Leveraging the capability of the control system to define the phase and coherence, this facility simulated a somewhat diffuse, acoustic flight environment at 103 dB overall sound pressure level with accelerometers measuring the GSE response due to this environment.

Several DFAT tests were performed on the GSE with low and high coherence values, as well as three different acoustic array locations. With a 0-degree phase defined for all tests, the coherence values were varied to see if a more diffuse field was achieved with a lower coherence value. The array was adjusted to better illustrate the resulting acoustic field near the GSE. Based on the test results, it was ultimately decided to use the low-coherence environment response data, due to the perceived diffusivity of the resulting acoustic field, to determine a vibration spectrum for the GSE.

To predict the flight environments of the GSE, the acoustic-induced accelerometer responses were scaled up from the test level of 103 dB OASPL, determined by the average of four microphones closest to the GSE in the acoustic field, to 122 dB OASPL, which is the maximum hearing allowance by OSHA. Then, response data at these same locations, measured from a MIL-STD-810G vibration shaker test, was scaled down concurrently to envelope the scaled-up 122 dB OASPL acoustic test responses. Once this envelope was satisfactory, it was determined that performing the vibration test specification at -18 dB would serve as a flight environment prediction for the GSE.

REFERENCES

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