

Designing a Direct-Field Acoustic Test of a Flight System: Requirements, Challenges, and Results

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ABSTRACT

A direct-field acoustic test (DFAT) was performed on a Sandia Flight System to an overall sound pressure level (OASPL) of 146.7 dB in order to verify system survival due to high-intensity acoustic environments. The DFAT technique places the test article in the direct-field of a sound source by surrounding it with a wall of speakers; the acoustic input is controlled with a closed-loop control system and multiple control microphones. This paper describes in detail the test requirements, the challenges met during test design, and the results from performing a high-OASPL, DFAT acoustic test on a contamination-sensitive Flight System in a high-bay environment.

INTRODUCTION

Before a spacecraft can be considered for launch, it must first survive environmental testing that simulates the launch environment. Typically, these simulations include vibration testing performed using an electro-dynamic shaker. For some spacecraft components however, acoustic excitation may provide a more severe loading environment than base shaker excitation. Because this was the case for a Sandia Flight System, it was necessary to perform an acoustic test in order to verify survival. Typically, acoustic tests are performed in acoustic chambers, but because of scheduling, transportation, and cleanliness concerns, this was not possible. Instead, the test was performed as a direct field acoustic test (DFAT). This type of test consists of surrounding the test article with control microphones and a wall of speakers, then controlling the acoustic input with a closed-loop control system. Obtaining the desired acoustic input environment—random noise with an overall sound pressure level (OASPL) of 146.7 dB—with this technique presented a challenge due to several factors. An acoustic profile with this high OASPL had not knowingly been obtained using the DFAT technique prior to this test. Furthermore, the test was performed in an integration facility, where floor space and existing equipment constrained the speaker circle diameter. And finally, it was required that the Flight System remain clean during testing to prevent contamination of the unit.

ACOUSTIC TEST REQUIREMENTS

The Sandia Flight System under test measured approximately 4-feet long by 4 feet wide by 4 feet tall, and weighed approximately 500-lbs. The acoustic test specification required to verify survival of this Flight System is plotted in Figure 1 and is given in 1/3-octave bands. The overall sound pressure level (OASPL) of the test spec is 146.7 dB, with a test duration requirement of one minute. Tolerances were also provided with the test specification, and are listed in Table 1. These tolerances applied not only to the final achieved OASPL, but for the individual 1/3-octave frequency bands as well; these are illustrated in Figure 1 as dashed orange lines.

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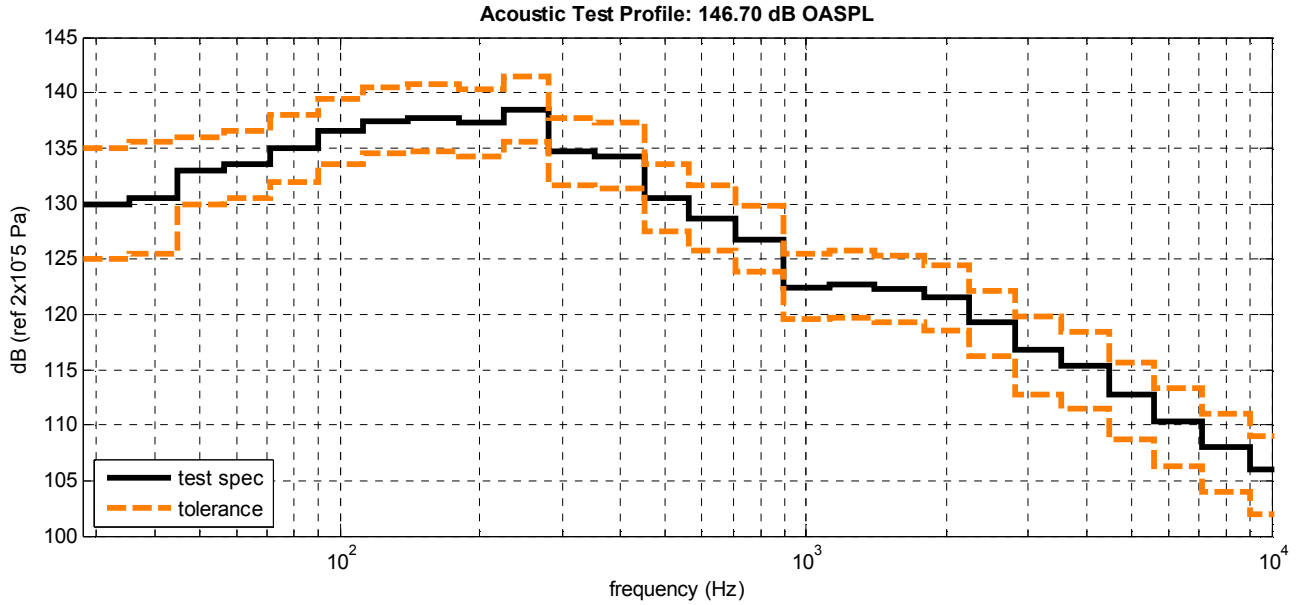


Figure 1: Acoustic Test Specification

Table 1: Acoustic Test Tolerances

Frequency Range	Test Tolerance
$f \leq 40$ Hz	± 5 dB
$40 \text{ Hz} < f \leq 2500$ Hz	± 3 dB
$2500 \text{ Hz} < f$	+3/-4 dB
Overall SPL: +1.5/-1 dB	
Test Duration: -0/+10%	

In addition to the acoustic environment specification, other test requirements were given. The first requirement given was to minimize transportation of the test article due to hardware safety concerns. When moving the Flight System from one location to another, such as from the integration facility to the acoustic test facility, it is possible that the system may be subjected to a transportation environment severe enough to consume designed fatigue-life—this life should be saved for the launch environment itself. In addition, there is always the small chance that damage could occur to the Flight System due to mishandling or accidents that may occur during transport.

The second requirement given was to minimize the impact on the Flight System delivery schedule, which provided an additional reason to minimize test article transportation. The logistics of performing a move required a lot of lead time, planning, and personnel time, which could easily add a week or more to the final delivery schedule.

The final requirement given was the acoustic test facility must provide a Class 100 clean room environment for the Flight System at all times in order to prevent contamination of the hardware. Not only would the test article need to be in this clean room environment before and after the acoustic test, but during the acoustic excitation as well.

Therefore in order to meet all test requirements, an acoustic test facility must: 1) be capable of reaching the required test specification of 146.7 dB OASPL, 2) contain a Class 100 clean room environment, and 3) need to be located in close proximity to the integration facility due to transportation and schedule concerns. If this acoustic facility did not exist, another excitation technique and test location would have had to be considered.

DIRECT-FIELD ACOUSTIC TESTING

Due to the test requirements regarding transportation, schedule, and clean room facilities, the direct-field acoustic test (DFAT) technique was considered as the ideal method for providing the acoustic input. This technique consists of exciting the test item in the direct-field of a sound source—the portion of the sound field in which sound waves have not undergone any reflection. This is in contrast to the typically-used reverberation chamber technique, where reflection of the sound waves is used to obtain the acoustic environment.

In practice, the direct-field is created by closely surrounding a test article with a wall of speakers. Multiple control microphones are then placed around the test article at varying heights, no closer than 1-foot to the test article and no closer than 3-feet to the speakers. 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. The acoustic input may be controlled open-loop, but typically (as it is presented here) it is performed closed-loop with a control system using an average control scheme in the narrow-band. Recommended practices and further information for performing DFAT tests are available [1].

The most obvious advantage of the DFAT technique is that the acoustic excitation source is portable and can be brought to the test article, as opposed to bringing the test article to the source (such as to an acoustic reverberation chamber). In addition, the equipment used to perform the test can consist of commercial sound equipment, which is much lower in cost than building and maintaining an acoustic reverberation chamber facility. A well-known disadvantage of the DFAT technique includes local hot and cold spots that exist in the direct-acoustic field due to constructive and deconstructive interference of the sound waves, respectively. This is mitigated through the use of multiple control microphones (eight to sixteen are recommended), an average control scheme, and several response microphones placed around the test item in order to better characterize the sound field if desired.

The advantages of the DFAT technique led to the decision that this method would be used to perform the acoustic test on the Flight System. With the portability of the acoustic source, transportation of the Flight System outside of the integration facility was not required. No transportation results in minimal hardware safety risks and minimal impact to the delivery schedule. Finally, the integration facility already contained the clean rooms required to keep the Flight System contamination free.

TEST DESIGN CHALLENGES

With the test method determined, certain challenges needed to be addressed in the design of the acoustic test. The requirement of most concern was actually reaching the high-intensity acoustic test environment specification of 146.7 dB OASPL (as a reference, a jet engine measured at 100-feet has an OASPL of 140 dB). Typically, environments of this intensity required acoustic reverberation chambers, such as the one at Goddard Space Flight Center, capable of reaching 150 dB [2]. As of January 2010, an OASPL above 143 dB had not knowingly been performed with the DFAT technique.

Furthermore, while Sandia National Labs does have a 12-speaker DFAT setup, the capability is limited to 133 dB OASPL. With the existing equipment, linearly extrapolating up to 146 dB would require over 200 speakers (+3dB requires double the power). Even if the money and equipment were available, the floor space in the integration facility was limited; the largest available area free of structures and equipment was 30-foot in diameter. Therefore, an acoustic supplier with many years of proven DFAT experience, Maryland Sound International (MSI), was contacted with this specific problem. Due to an upgrade that had recently been installed in their amplifiers, MSI was fairly confident that the required high-intensity test specification of 146.7 dB OASPL was obtainable with their equipment using the DFAT technique within the given available area.

After considering the available 30-foot diameter area, MSI proposed a speaker configuration that consisted of three stacks of 16 MSI-Quakes that would provide the low frequency content of the input specification, and nine stacks of 6 MSI-VT speaker cabinets that would provide the middle and high frequency content (total diameter of 29-ft 7-in). The total speaker number of speakers was 102, and the tallest stack (the MSI-Quakes) measured no taller than 16-feet. Control microphones were to be 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.

The final test design challenge was maintaining a clean Flight System during acoustic excitation. As mentioned previously, the integration facility contained the Class 100 clean rooms required by the Flight System. However, the speaker configuration and acoustic test itself would have to take place outside of the clean room due to the massive amount of time it would take to sanitize all 102 speakers to clean room specifications. Therefore, in order to allow acoustic excitation to occur on the Flight System, but maintain the clean room environment, a contamination frame was designed to encompass the Flight System while outside of the clean room. This contamination frame was double-bagged with AT film and attached to a 22,000 lbs seismic mass that supported the test article during the test, as shown in Figure 2. The film was not installed tightly, but was also not loose enough to come in contact with the Flight System. For the duration of the time outside of the clean room, nitrogen was pumped inside the bagged frame at a rate of 50 liters per minute. As a final note, the seismic mass supporting the Flight System and bagged frame 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.

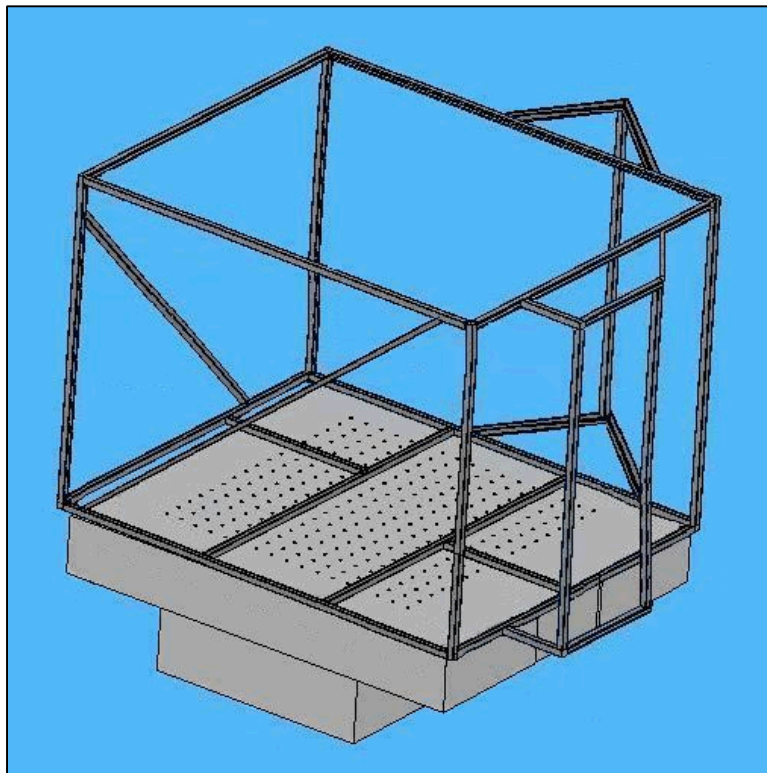


Figure 2: Flight System Contamination Frame (AT film not shown)

FLIGHT SYSTEM DIRECT-FIELD ACOUSTIC TEST

Because it was desired to remove any risk prior to testing the Flight System, and confirm that all test design challenges had been successfully addressed, a dry run was performed with MSI at the integration facility in January 2010. The speakers and control microphones were setup as shown in Figure 3; the heights of the eight control microphones are listed in the figure as well. A mass mock of the Flight System (which was fortunately available) was installed on the seismic mass, along with the double-bagged contamination frame. At the conclusion of the dry run, all test equipment was verified as working properly, and more importantly, the desired test specification level of 146.7 dB OASPL was successfully achieved with the DFAT technique using the proposed speaker and microphone configuration.

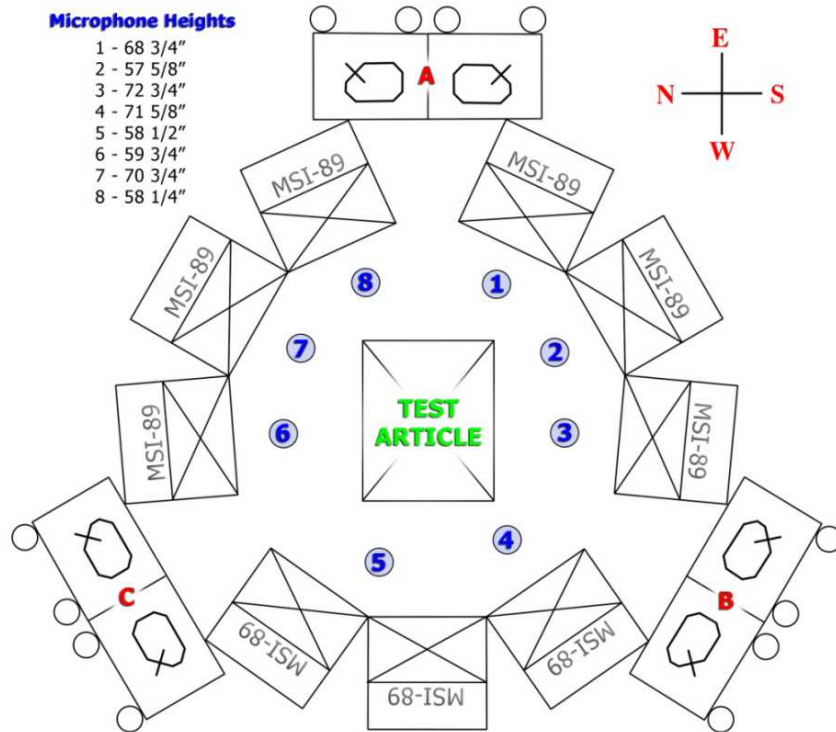


Figure 3: Speaker and Control Microphone setup for DFAT test

The actual Flight System test was performed in March 2010. Because the MSI speakers and associated test equipment was disassembled following the dry run, then reassembled two months later, a “dummy box” was tested prior to the Flight System. This dummy box consisted of two cabinets secured back-to-back, resulting in roughly the same surface area as the contamination frame and seismic mass. In addition to confirming proper acoustic equipment operation, the software and hardware abort buttons were verified as operational in case personnel or hardware safety reasons required an immediate stop during a test run. Once complete, the dummy box was removed, and the Flight System—attached to the seismic mass and encompassed by the bagged contamination frame—was moved into the circle of speakers. An overhead picture of the Flight System DFAT setup, showing all MSI speaker stacks and the contamination frame, is shown in Figure 4. The control microphones themselves cannot be seen, but the stands are somewhat visible against the floor.

Once in place, the eight control microphones were positioned and used with an average control scheme by the control system to control and measure the acoustic input. In addition, five response microphones were placed inside the contamination frame to monitor the environment inside the bag, closer to the Flight System. Microphones used for testing consisted of B&K 4944 and G.R.A.S. 46BD ¼-inch pressure-field microphones, with nominal sensitivities ranging from 0.9 mV/Pa to 1.6 mV/Pa, respectively. The Flight 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 as well as the response microphones and Flight System accelerometers. Both systems sampled at 25.6 kHz with 3200 lines, resulting in a frequency resolution of 3.125 Hz.

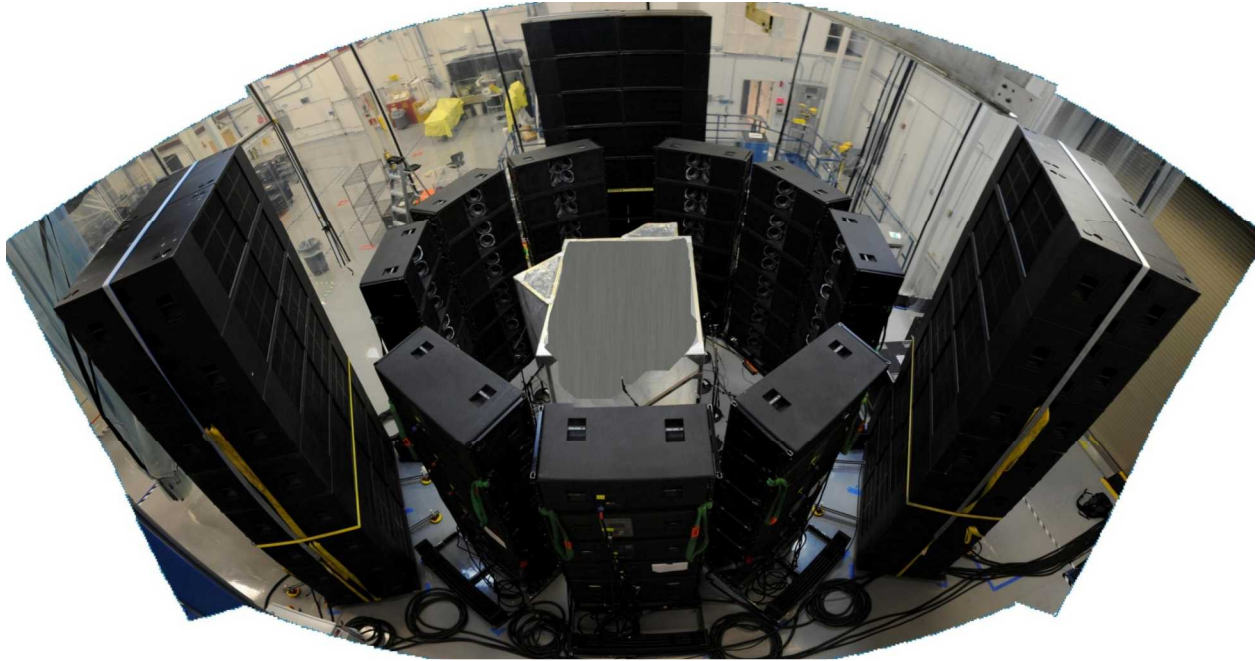


Figure 4: Flight System DFAT Setup

The Flight System test schedule consisted of performing the acoustic test specification at several levels, all for 20 seconds duration: a signature test at -12 dB, intermediate level tests at -8 dB and -4 dB, three full level (0 dB) tests, and a final signature test (all values relative to 146.7 dB). The signature level tests were performed to gather pre- and post-full level structural response data. Any large differences in the structural response could serve as an indication of damage due to the high intensity acoustic input. The intermediate levels were performed to verify that the response accelerometer measurements did not exceed the Flight System analytical models. The full level test was performed three times in order to achieve the one minute duration required by the test specification; any longer than a 20-second run time would result in overheated speakers and amplifiers. For this reason, each test level was followed by a one hour acoustic equipment cool-down period.

TEST RESULTS

Prior to testing, it was decided that the measured input control spectrum, consisting of the average of the eight control microphones, would be used to determine if the acoustic test environment successfully met the required test specification. For the first signature and intermediate level tests, the measured control spectrum were all within tolerance for all 1/3-octave frequency bands and OASPL levels. The consistency of these lower level test runs provided confidence that full level would be reached successfully. However, accelerometer response data from these lower level runs showed that damping of the structure was not increasing as much as expected with increasing test levels, and as a result, a negative margin of safety was predicted for some internal components. Therefore, the control input spectrum was adjusted at frequency bands of concern. It must be emphasized that these were not changes to the required test specification; they were changes to the control system input.

Once the intermediate level test runs were complete, the three full-level acoustic tests were performed on the Flight System, resulting in the measured 1/3-octave control spectrum plotted in Figure 5. Corresponding OASPL levels calculated from each test run are listed in the legend. To provide a reference, the required test specification is plotted as a dashed black line with the upper and lower tolerances plotted as dashed orange lines.

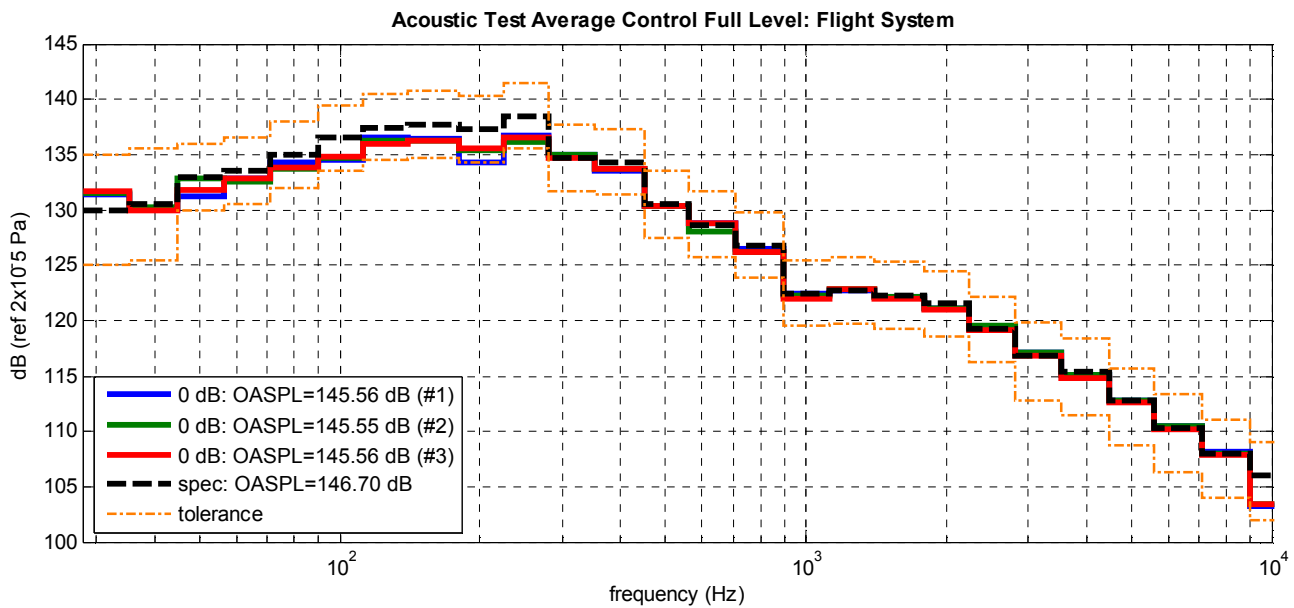


Figure 5: Control Spectrum from Full-level Acoustic Test

As seen in the results, the measured input spectra from the three full-level tests are all within the test specification tolerance, with the notable exception of the 200 Hz band for Run #1, which lies on the lower tolerance line. The input at this band had been decreased due to a concern of a negative margin of safety on a certain component seen during the intermediate level tests. Following Run #1 however, the input was increased at this band because damping increased, resulting in an increased margin of safety. The final adjustments to the control system input due to negative margins of safety resulted in a control reference (what the control system attempted to achieve) of 146.37 dB OASPL for Run #2 and Run #3. For all the test runs, the measured environment of 145.6 dB OASPL was consistent, and only missed the lower specified OASPL tolerance by 0.1 dB. Despite this discrepancy, it was agreed upon that the acoustic test environment had been successfully achieved.

Results from the five response microphones located near the Flight System inside the double-bagged contamination frame for full-level Run #3 are shown in Figure 6. The legend lists the locations of the microphones and corresponds with the cardinal directions shown in Figure 3; the corresponding OASPL values calculated from the data are listed as well. The required test specification has been plotted as a dashed black line for reference.

The microphone response data is quite interesting, as there appears to be a large spread of the acoustic environment near the Flight System, particularly from 125 Hz to 700 HZ. The largest sound pressure levels belong to the center microphone at these frequencies, which was located in the center of the seismic mass, above the Flight System. At this center location, constructive interference of the acoustic waves from the speakers more than likely occurred, resulting in these very high levels (151.63 dB OASPL), while the measured control input was 146.37 dB OASPL. Another trend shown in this data is the noticeable decrease for all response locations above 1000 Hz when compared to the input control spectrum. From previous experiments performed at Sandia and recent literature [3], this trend has been shown to be an attenuation effect on the acoustic environment as it passes through the bagging material of the contamination frame.

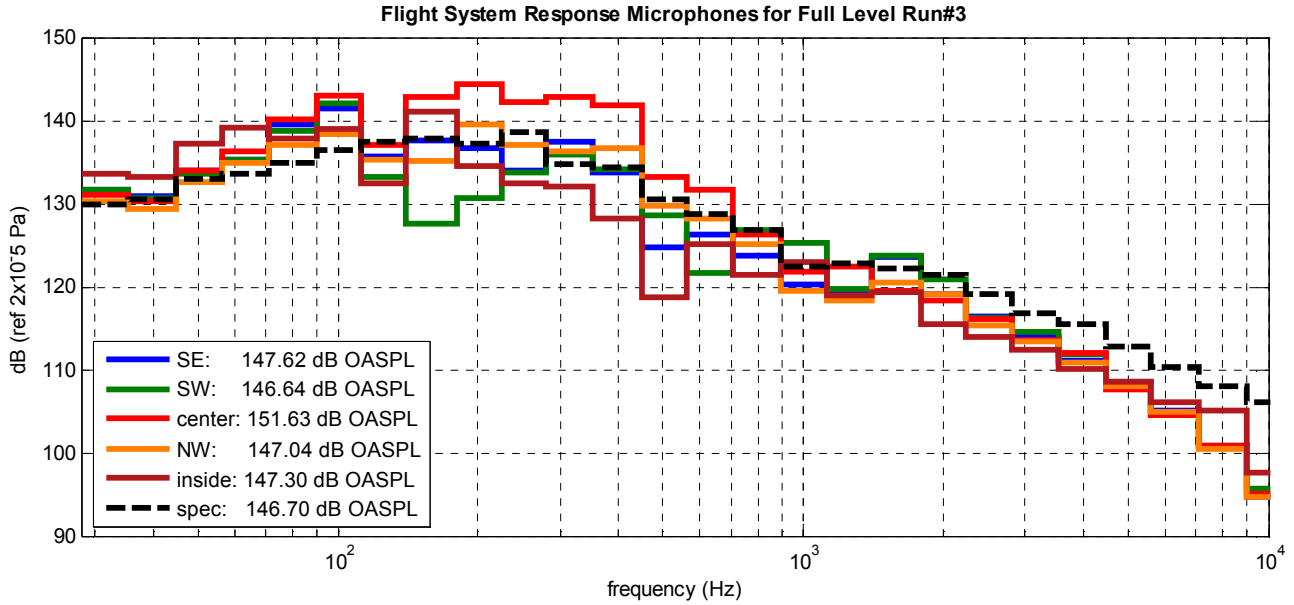


Figure 6: Response Microphones from Full-level Acoustic Test

The final data of interest from the full-level acoustic test is the structural response of the Flight System. As mentioned previously, 85 accelerometer channels were measured for each test run. For the sake of brevity, only one location will be plotted. The auto-spectrum for a tri-axial accelerometer from full-level Run #3 is shown in Figure 7, and is plotted in 1/6-octave bands. The plot legend contains the node number (T101), the direction of the channel, and the gRMS calculated from the data.

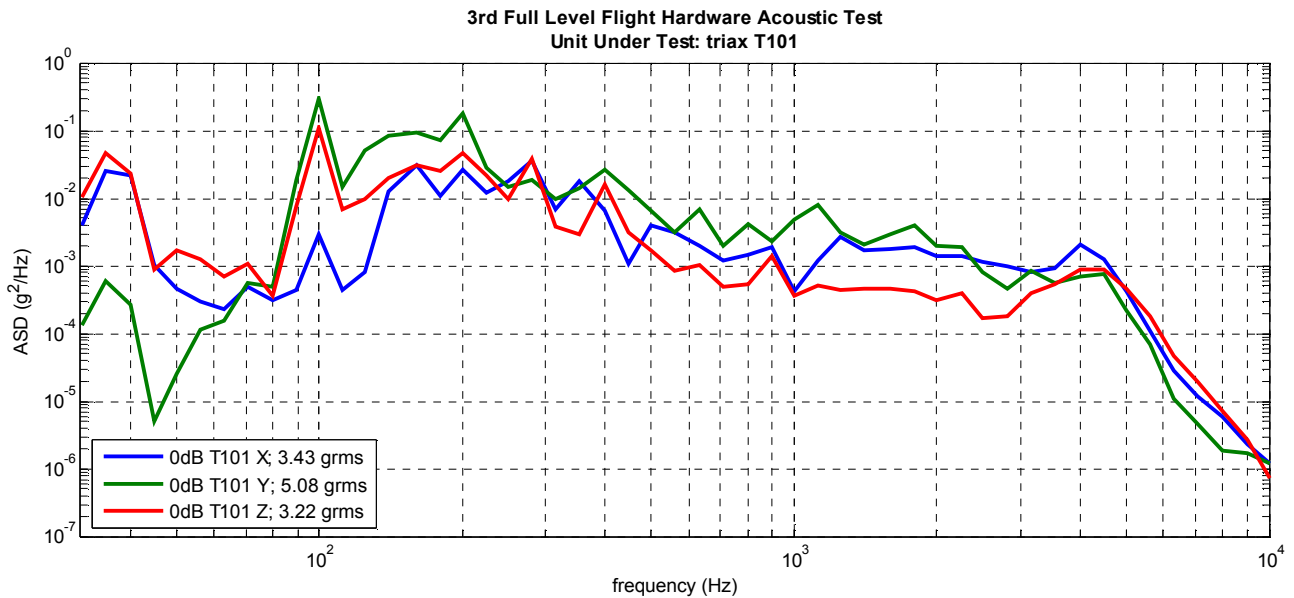


Figure 7: Response Accelerometer from Full-level Acoustic Test

The acceleration response data of the Flight System at node location T101 illustrates definite structural response due to the high-intensity acoustic test environment. There are major modes visible at 37 Hz and 100 Hz, and the gRMS values range from 3.22 to 5.08. Accelerometer response data for all measurement locations were examined following every test run, and provided data for the calculation of the margins of safety at these instrumented locations.

For the signature level (-12 dB full level) response data comparison, only one location will be plotted, again due to the large amount of locations measured on the Flight System during the test. The auto-spectra data in Figure 8 are displayed in 1/6-octave bands, with the legend designating which data are pre and post full-level signatures, in addition to the gRMS values calculated from the data. For consistency, the control inputs used for the signature tests were the same, regardless of the modifications made to the control input for the intermediate and full level environment tests.

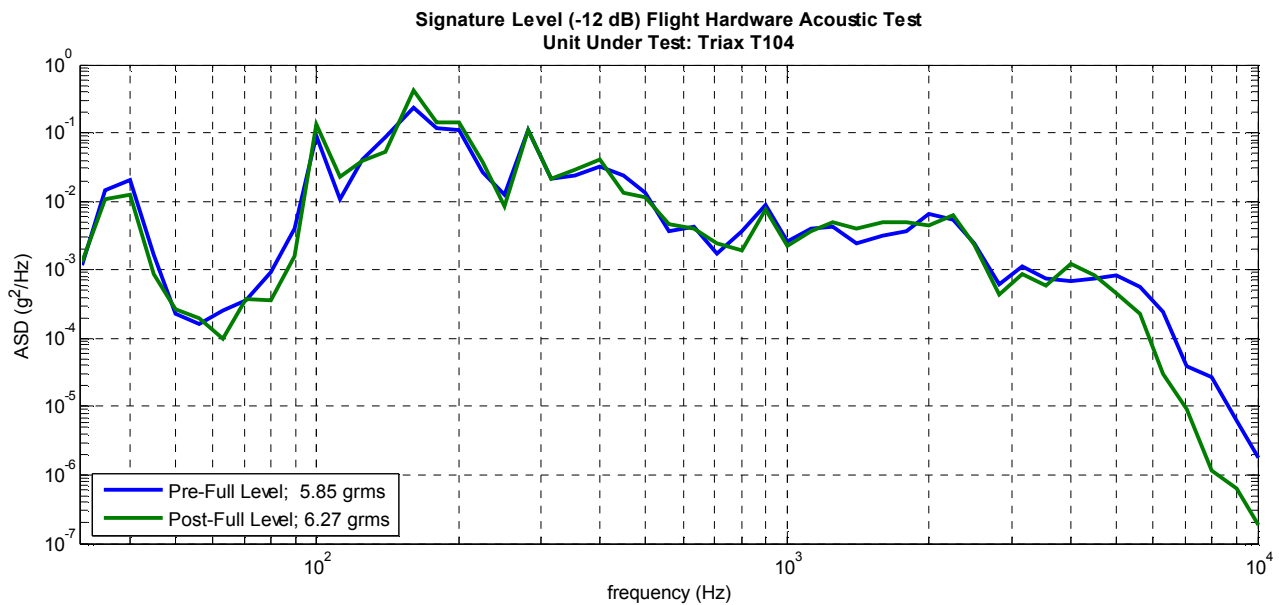


Figure 8: Response Accelerometer Comparison from Signature-level Acoustic Test

Differences in the auto-spectrum are present in the data, but these differences were not large enough to cause concern, as the general shape is similar and no major modes have disappeared or shifted in frequency. Because the allowable differences between spectra were not rigidly defined prior to testing, engineering judgment and experience were used when examining all 85 channels of accelerometer signature data. Following this examination, no large differences were discovered in the entirety of the data. From a structural response point of view, the Flight System was not damaged following exposure to the full-level acoustic test environments.

Following the acoustic test, the Flight System eventually went into a thorough visual post-test inspection. The inspection found no visible damage, which agreed with signature comparison data, and resulted in the Flight System successfully meeting the requirement of system survival due to a high-intensity acoustic environment.

CONCLUSIONS

A direct-field acoustic test (DFAT) was performed on a Sandia Flight System in order to verify system survival due to a random acoustic test environment of 146.7 dB OASPL for one minute. The DFAT technique places the test item in the direct-field of an acoustic source—performed by surrounding the test item with speakers and using multiple control microphones with a closed-loop control system. This was the ideal test method because the acoustic excitation source was brought to the test item, thereby eliminating the inherent risk to hardware safety due to moving the Flight System to an acoustic chamber, as well as minimizing the impact on the schedule.

Several challenges were identified and resolved in designing the direct-field acoustic test, such as finding acoustic equipment capable of reaching the high intensity acoustic test environment, fitting the speaker configuration within the space available at the integration facility, and keeping the Flight System clean during the test. Sandia contacted an outside acoustic supplier, Maryland Sound International (MSI), who supplied a speaker configuration and equipment setup that fit the facility and was capable of achieving the required 146.7 dB OASPL test specification, which had not knowingly been reached with the DFAT method prior to the dry run performed at Sandia in January 2010. The contamination issue was resolved by designing and building a double-bagged contamination frame around the Flight System, and filling the interior with nitrogen anytime the Flight System was outside of the clean room.

The full-level acoustic test was performed on the Sandia Flight System three times for 20-seconds (due to acoustic equipment limitations) in order to obtain the required test duration of 1 minute. The 1/3-octave bands from the measured control spectrum were all within tolerances and the corresponding OASPL for all three runs was 145.6 dB, only 0.1 dB below tolerance. This was primarily due to a lowering of the control system input due of negative margins of safety measured on certain Flight System components at the lower level tests. Signature level run data comparisons showed very little changes in response, indicating that the Flight System was not damaged due to the full-level acoustic input. This assessment agreed with a throughout visual inspection performed on the Flight System following the test. In conclusion, the required acoustic test specification environment was successfully achieved (excluding the 0.1 dB out of tolerance OASPL), all test design requirements were met, and the Flight System successfully met the requirement of system survival.

REFERENCES

- [1] Larkin, P., Goldstein, B., "Direct Field Acoustic Test (DFAT) Recommended Practice," submitted to IEST, first draft due Feb 2011.
- [2] Maahs, G., "*Direct Field vs Reverberant Field Acoustic Testing of a Spacecraft-like Structure*," Proceedings from the Spacecraft and Launch Vehicle Dynamic Environments Workshop, June 2009.
- [3] Hackel, J., Van Dyke, M., "*Acoustic Attenuation from Contamination Bagging-Fact or Fiction?*" Proceeding from the Spacecraft and Launch Vehicle Dynamic Environments Workshop, June 2010.