ACOUSTICALLY INDUCED VIBRATION OF STRUCUTRES: REVERBERANT vs. DIRECT ACOUSTIC TESTING

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ABSTRACT

Large reverberant chambers have been used for several decades in the aerospace industry to test larger structures such as solar arrays and reflectors to qualify and to detect faults in the design and fabrication of spacecraft and satellites. In the past decade some companies have begun using direct near field acoustic testing, employing speakers, for qualifying larger structures. A limited test data set obtained from recent acoustic tests of the same hardware exposed to both direct and reverberant acoustic field testing has indicated some differences in the resulting structural responses. In reverberant acoustic testing, higher vibration responses were observed at lower frequencies when compared with the direct acoustic testing. In the case of direct near field acoustic testing higher vibration responses appeared to occur at higher frequencies as well. In reverberant chamber testing and direct acoustic testing, standing acoustic modes of the reverberant chamber or the speakers and spacecraft parallel surfaces can strongly couple with the fundamental structural modes of the test hardware. In this paper data from recent acoustic testing of flight hardware, that yielded evidence of acoustic standing wave coupling with structural responses, are discussed in some detail. Convincing evidence of the acoustic standing wave/structural coupling phenomenon will be discussed, citing observations from acoustic testing of a simple aluminum plate. The implications of such acoustic coupling to testing of sensitive flight hardware will be discussed. The results discussed in this paper reveal issues with over or under testing of flight hardware that could pose un-anticipated structural and flight qualification issues. Therefore, it is of paramount importance to understand the structural modal coupling with standing acoustic waves that has been observed in both methods of acoustic testing. This study will assist the community to choose an appropriate testing method and test setup in the planning stages.

KEYWORDS: Reverberant acoustic field, direct acoustic field, speakers, vibro-acoustic, acoustic/structural modal coupling

INTRODUCTION

For most spacecraft and many of their components, acoustic testing is required to attain their flight qualification. Acoustic chambers provide a reverberant diffuse field, except at low frequencies, and have been used to qualify flight hardware to the launch acoustic environments for the past several decades. It has only been relatively recently that the direct acoustic field testing method has been used in flight hardware testing[1-4]. The first such testing was reported by Scharton et al. on the QuikSCAT spacecraft[1-2]. This method of testing has some advantages over diffuse field testing, which are outlined in Larkin & Walen, 1999[3]. However, the direct acoustic field characteristics can be strongly affected by test setup factors, especially variations in speaker layout[5], and the acoustic field produced by this test method has not yet been fully characterized. Unlike diffuse acoustic testing, testing guidelines do not exist for direct acoustic testing. Testing is performed based on a limited knowledge of the acoustic field generated by the speakers and ad hoc approaches are implemented in order to obtain the desired sound field.

The structural responses induced by direct field testing often differ significantly from those induced by diffuse field testing, usually at specific frequencies or a range of frequencies[6-7]. In this paper we attempt to address the differences in these methods of acoustic testing and provide physical parameters attributing to them. One of the parameters that strongly influences structural responses is the acoustic standing wave coupling with the structural modes. To explore this phenomenon, we considered a simple aluminum flat panel and forced a few of its modes to be coupled with acoustic chamber modes. To further explore the acoustic/structural modal coupling phenomenon, results from flight hardware acoustic tests, using both the direct and reverberant chamber acoustic fields, are discussed in this paper.

The results discussed in this paper and the conclusions provided herein may be helpful in the preparation of the direct acoustic field testing guidelines, a subject that will be discussed at the Aerospace Testing Seminar special session.

SPACECRAFT/INSTRUMENT ACOUSTIC TESTS

To demonstrate the acoustic chamber and structure modal coupling phenomenon, a simple aluminum flat panel was exposed to a diffuse acoustic field in a reverberant chamber. Several flight hardware acoustic qualification test results that provide further evidence of this phenomenon are discussed in this report. Results discussed include Aquarius instrument reflector, which was acoustic tested in two different size chambers, the CloudSat spacecraft and Antenna subjected to protoflight reverberant assembly testing and direct acoustic testing at the spacecraft level, and the entire DAWN spacecraft that was subjected to a protoflight direct field acoustic test and workmanship reverberant chamber testing. Plausible explanations are provided discussing the differences in direct and reverberant acoustic testing. Results for these cases are discussed in the following sections.

a) Aluminum Panel Reverberant Acoustic Test

A simple ¼ inch thick aluminum panel, 37.5 x 42 inches, was selected as a test article to explore the chamber/structure coupling, as shown in Figure 1. The dimensions of the panel were tailored to ensure that a few of its structural modes would couple with the chamber acoustic modes. Several fundamental modes of the acoustic chamber, calculated under the normal conditions (filled with nitrogen gas at 15°C), are ~ 22 Hz, ~26 Hz, ~31 Hz, ~42 Hz, ~53 Hz, ~61 Hz, 64 Hz, 78 Hz, 86 Hz, 92 Hz, and 104 Hz (Figure 2). The selection of a simple structure allowed us to control the acoustic field/structure interaction and to better interpret the results. The finite element model of the panel in free-free boundary conditions (to represent a panel suspended from the chamber ceiling) was analyzed to obtain mode shapes and frequencies. Some of the panel structural modes that strongly coupled to the acoustic standing waves are plotted in Figure 3. The drum mode at 29.1 Hz was forced to couple with the fundamental acoustic standing wave of 31 Hz. This acoustic mode shape had a pressure minimum or velocity maximum at the center of the chamber in the direction perpendicular to the panel as shown in Figure 2. The second mode shape shown in Figure 3 is 52.8 Hz and was close to the second acoustic mode parallel to the panel. The third mode of the panel was computed to be 88.1 and was very close to the third chamber mode in the direction perpendicular to the plate (See Figure 2). Finally, the mode at 105.4 Hz was coupled with the fourth acoustic mode in the direction parallel to the panel.

The panel was acoustic tested in the JPL chamber to the OASPL of 142.7 dB. The panel was instrumented with five triaxial accelerometers mounted at four corners and at the center as shown in Figure 1. The panel was suspended from the ceiling and was positioned at three locations in the chamber: the chamber center 114 inches, 50 inches, and 14 inches from the chamber wall (Figure 1b). Eight microphones were used to control the SPL in the chamber with an additional five response microphones positioned in front of the panel very close to the accelerometers, six inches off the surface (See Figure 1a). A series of diffuse acoustic tests were performed on the aluminum panel in the reverberant chamber and data from all 13 microphones and five accelerometers was recorded and post-processed. The sound pressure levels (SPLs) in the chamber in 1/3rd octave band were obtained by averaging overall control microphones. The SPL of the five response microphones averaged in 1-Hz bands were used to correlate to the nearby accelerometers on the panel. Figure 4 shows the SPLs obtained from the averaged response microphones measured at the three aforementioned panel locations. Also shown in this figure is the average control SPL measured by eight microphones distributed within the chamber volume.

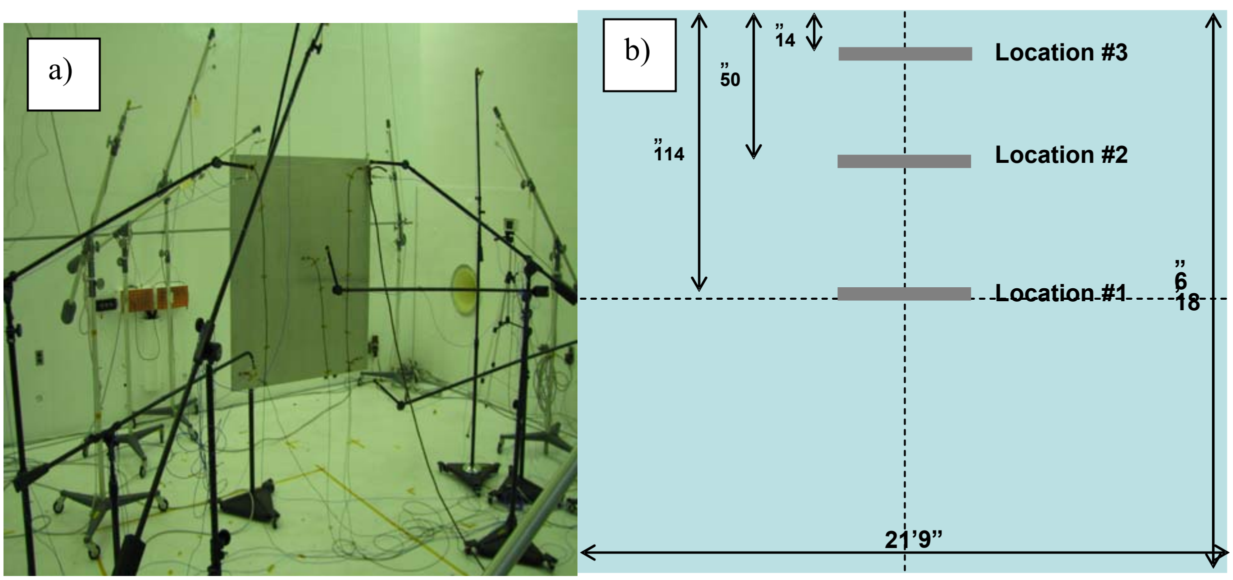

Figure 1: The ¼-inch aluminum panel suspended from three locations in the acoustic chamber.

Mode	Theoretical Freq. (Hz)	Freq. at peak in mic-to-mic SPL variation (Hz)
Z-1	21.4	21
Y-1	26.1	26
X-1	30.7	31
Z-2	42.9	44
Y-2	52.3	53
X-2	61.4	60
Z-3	64.3	65
Y-3	78.4	79
Z-4	85.8	84
X-3	92.2	90
Y-4	104.5	103

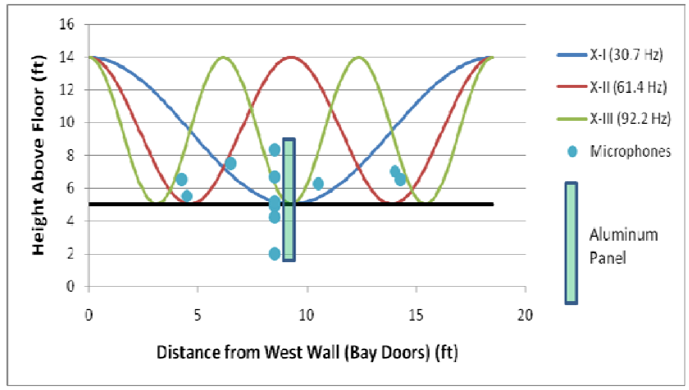

Figure 2: Several measured and computed chamber fundamental acoustic modes and pressure mode shapes in the direction perpendicular to the panel.

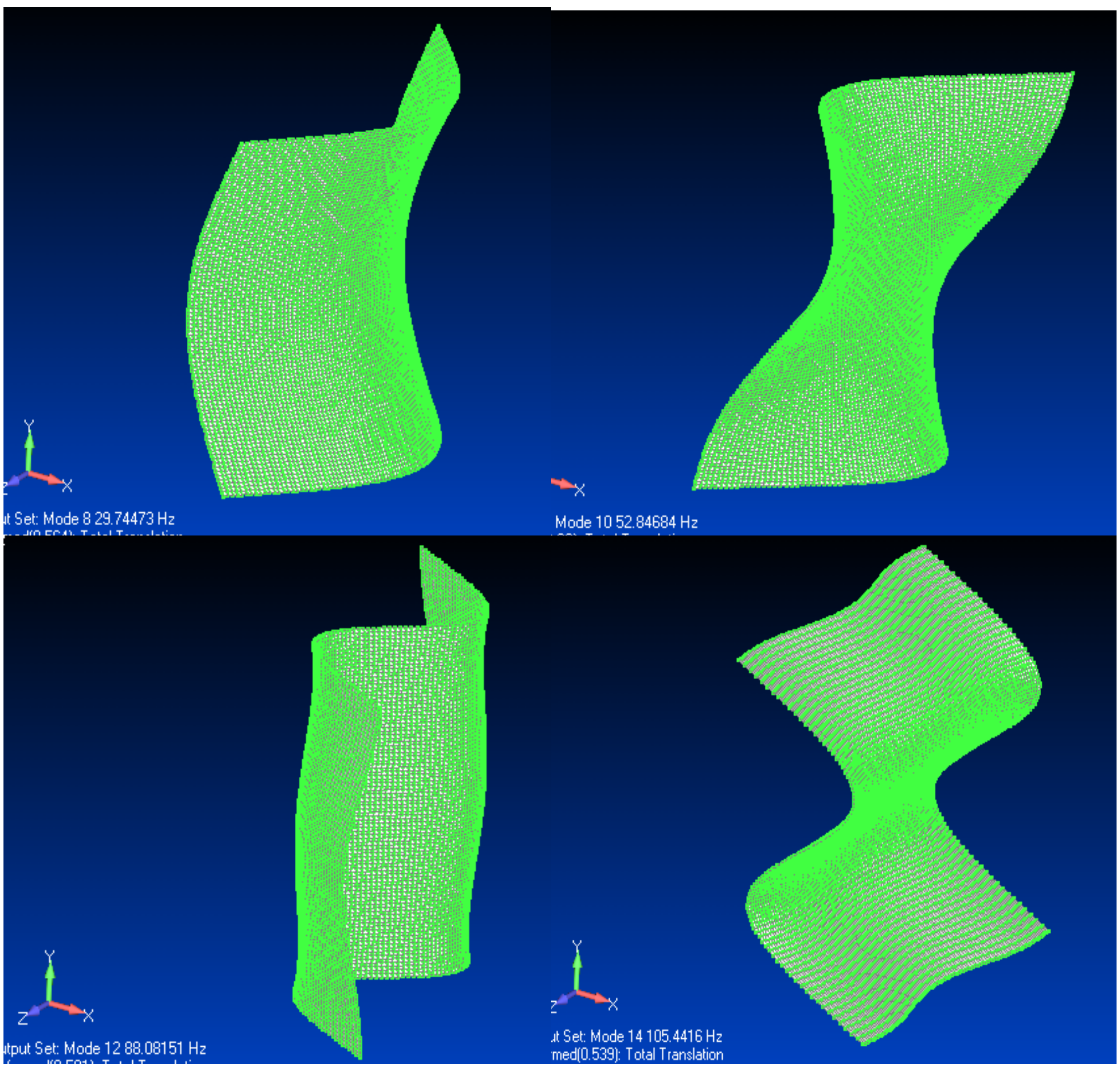

Figure 3: Aluminum panel mode shapes that were observed to couple with the acoustic chamber modes.

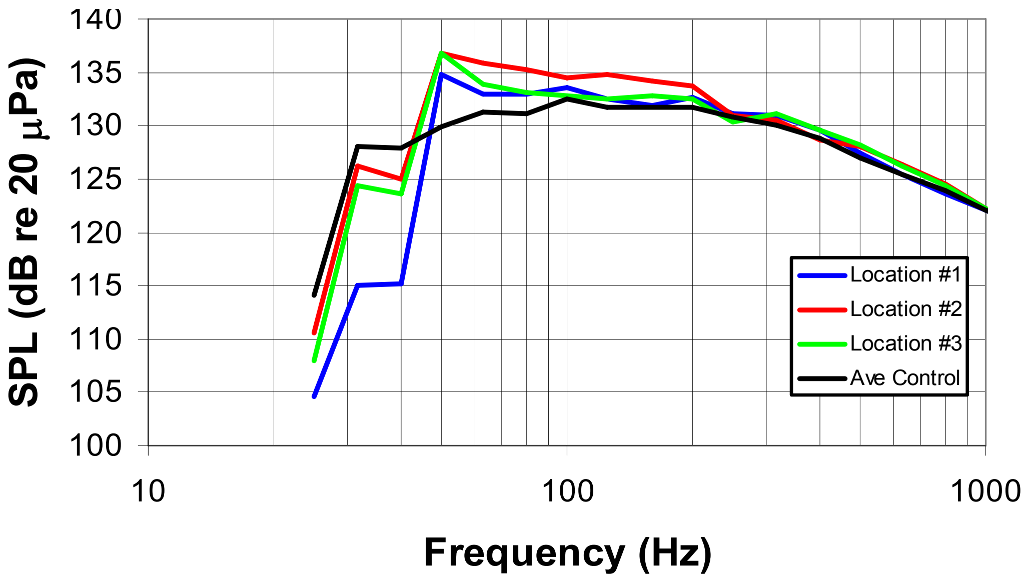

Figure 4: Average response microphones SPLs measured at three panel locations in the chamber and the average control microphones SPLs with OASPL of 142.5 dB.

The panel structural responses, measured by one of the accelerometers positioned close to the monitor microphones, are shown in Figure 5 for each of the three panel locations. This figure conveys a few important findings related to the coupling phenomenon under discussion. First, the drum mode of the structure at approximately 31 Hz coupled with the first acoustic standing wave in the direction perpendicular to the panel. The sound pressure level differences between the three panel locations were measured to be more than 10 dB, whereas the structural responses at this coupled frequency differed by more than 15 dB, with the largest response measured at location #1 (i.e. chamber center where the acoustic pressure is minimum, see Figure 2). The second significant structural/acoustic modal coupling occurred at approximately 92 Hz (computed panel mode of ~89 Hz). The difference in sound pressure levels at this frequency for the panel's three locations was less than 3 dB. However, the structural responses differed by more than 20 dB, again highest measured at the location #2 close to the pressure minima of this acoustic mode. If this panel had been placed at the exact pressure minimum of this mode the structural responses would have been much higher than the measured 20 dB (see acoustic mode shape of this frequency shown in Figure 2.) Structural/acoustic coupling also occurred at frequencies of 56 Hz and 104 Hz, indicating these modes were coupled with the acoustic waves in the other two directions in the chamber. Finally, the structural responses of the mode at ~176 Hz were identical at three panel locations (Figure 5); a condition that one would expect in a diffuse acoustic field without acoustic standing waves. These observations are remarkable in that a significant increase in the structural responses only occurred when the acoustic standing waves coupled with the structure modes. The increased structural responses occurred at pressure nodes where the particle velocity of the standing pressure waves was maximum. The acoustic pressure and the velocity modes are 90 degrees out of phase.

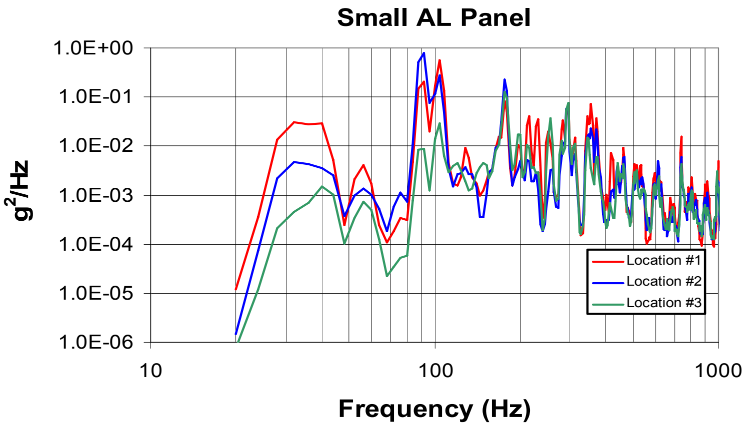

Figure 5: Panel structural responses measured at panel locations 1, 2 and 3 by one of the accelerometers at its corner.

Figures 4 and 5 show direct evidence of the impact of acoustic standing waves on hardware responses. The measured structural responses shown in Figure 5 clearly demonstrate the acoustic/structural coupling phenomenon. This phenomenon is inherently nonlinear and if it occurs during testing or flight it may have un-anticipated consequences on the health of flight hardware.

To further examine this phenomenon results from a few acoustic tests of flight hardware recently performed using both the acoustic chambers and speakers are discussed in the following sections.

b) Aquarius Instrument Reflector Acoustic Tests

The Aquarius Instrument reflector depicted in Figure 6 was first acoustic tested in the Jet Propulsion Laboratory's acoustic chamber and an identical reflector design was tested in a Wyle Laboratory's chamber. The reflectors were suspended in both chambers at an angle to the chambers' walls to minimize the impact of acoustic standing waves. The acoustic fields in these chambers were each measured by 4 control microphones. An additional five microphones were used in each test; four of which were placed very close to the control microphones for monitoring the SPLs in the chamber and a fifth one was suspended in the middle of the chambers above the reflectors. The two acoustic tests were performed with similar settings and a similar acoustic profile with a fundamental difference being the Wyle laboratory's chamber was much smaller than the JPL chamber (Figure 6). Figure 7 shows the pressure spectral densities (Pa^2/Hz) measured using all four control microphones in both chambers with the hardware present. The chamber controller systems were able to control the acoustic spectrum up to approximately 1000 Hz. Above this frequency, even at lower acoustic level runs (-9 and -6 dB from the full level), background noise from the compressor that delivered nitrogen gas to the chamber dominated the spectrum, therefore, the controller system was not able to control levels above 1000 Hz. With the test hardware in the JPL chamber the microphone-to-microphone variations shown in Figure 7 were more than 12 dB at approximately 60 Hz and more than 20 dB in the Wyle chamber at certain frequencies below 100 Hz. Some of the primary reflector modes coincided with the fundamental acoustic modes of the chambers below 100 Hz.

Several fundamental modes of the Wyle chamber were computed to be 28 Hz, 36 Hz, 36 Hz, 51 Hz, 57 Hz, 73 Hz, 85 Hz, and 102 Hz. As was the case with the JPL acoustic testing some of these modes were coupled with the reflector modes resulting in increased structural responses. For example, the microphone-to-microphone variations are 18 dB, 9.5 dB, 19 dB, 17 dB, and 21 dB at approximately 44 Hz, 68 Hz, 52 Hz, 80 Hz, and 104 Hz, respectively. Figure 8a indicates the reflector's mode close to 61 Hz coupled with the acoustic wave close to this frequency when acoustic tested at JPL, whereas the same hardware tested at Wyle indicates no chamber coupling at this frequency. The location of the hardware in the chamber that may couple with a given acoustic standing wave is important. Figure 8b shows structural mode at ~ 67 Hz coupled with the Wyle chamber mode. The same figure shows that the Wyle test had structure responses, close to 80 Hz, 20 dB higher than the JPL test. Figures 8c and d also show some of the structural modes coupled with the acoustic standing waves. The reflectors' responses shown in Figure 8, obtained from both acoustic reverberation chambers tests, clearly indicate a strong correlation between the variations in the SPLs of chambers and the increase in the reflector responses at the coupled modes. The data from these acoustic tests confirms the coupling phenomenon discussed in the previous section.

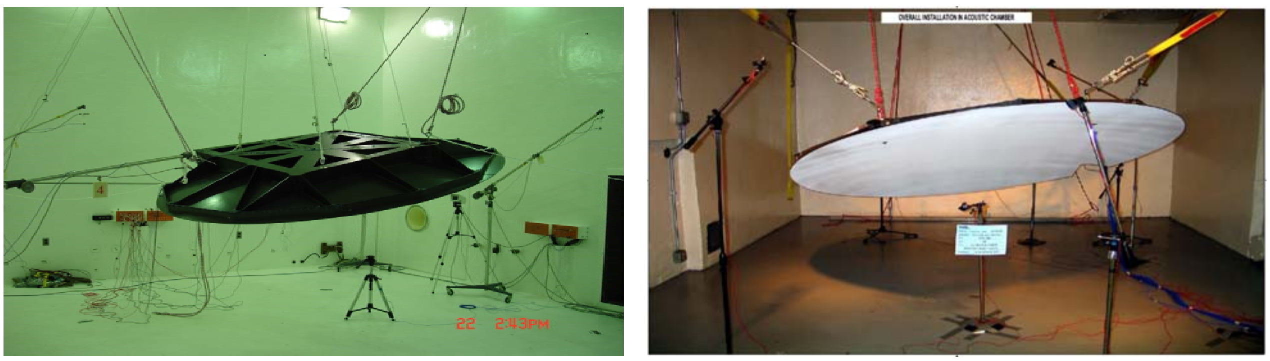

Figure 6: Aquarius reflector suspended in the JPL (10,000 cubic feet) and Wyle acoustic chamber (1,500 cubic feet).

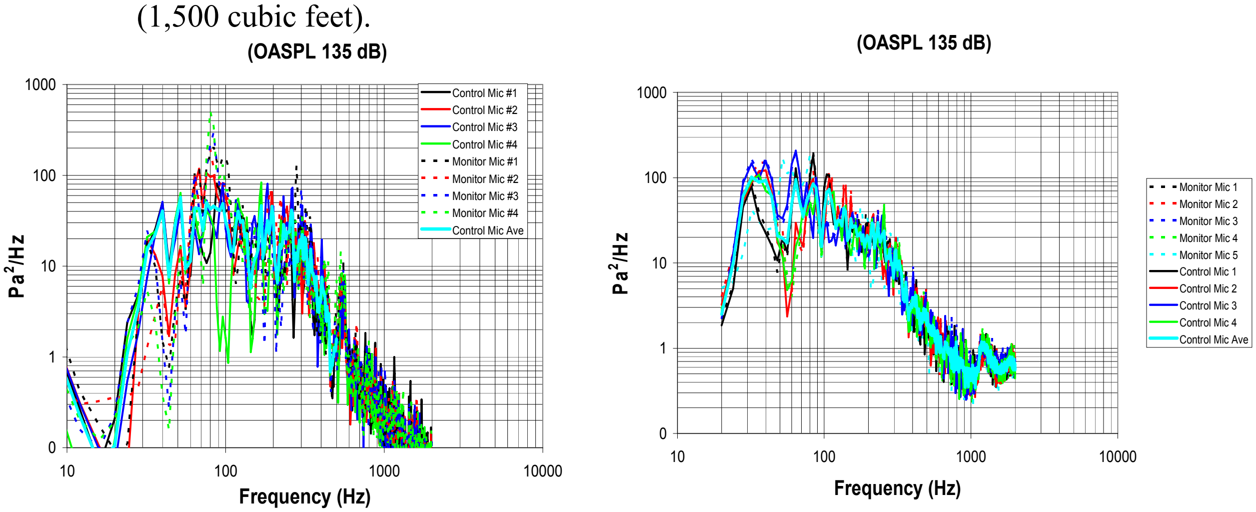

Figure 7: The sound pressure spectra (Pa^2/Hz) with the hardware measured in two different size acoustic chambers.

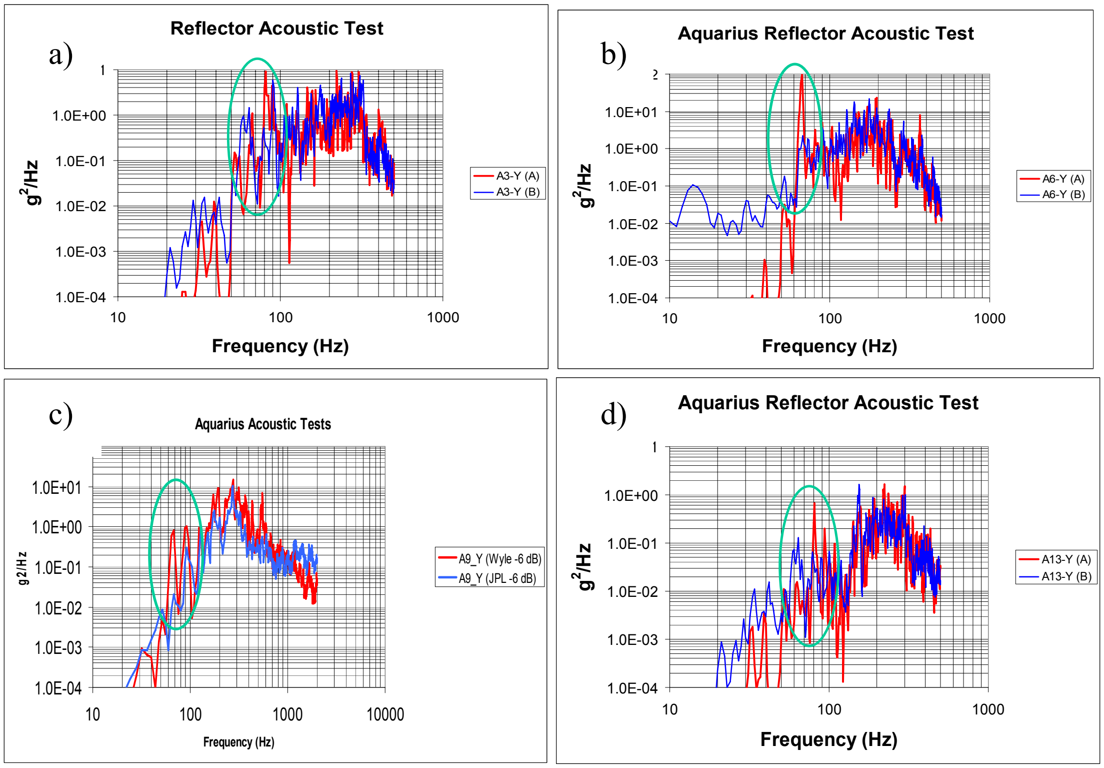

Figure 8: Responses measured on various locations of the Aquarius reflectors obtained from both JPL (blue lines) and Wyle acoustic (red lines) tests. The coupled frequency regions are circled.

c) CloudSat Main Reflector and Spacecraft Acoustic Tests

The Cloud Profiling Radar (CPR) Antenna Subsystem PF acoustic testing was performed at NGST's large acoustic chamber in Manhattan Beach. The CPR acoustic test was controlled to the average of four microphones with the CPR positioned in the middle of the chamber on its handling cart. Control microphones were located 24 inches from the CPR antenna and arranged around its perimeter. Reflector full level acoustic test inputs, shown in Figure 9a, was performed to the OASPL of 143.0 dB.

The same CPR assembly, integrated with the spacecraft, was later exposed to direct speaker acoustic testing at Ball Aerospace at 138 dB overall. Figure 9b shows the CloudSat spacecraft, in its launch configuration and mounted on a handling cart, positioned within the speaker bank for direct acoustic testing. Acoustic levels were controlled by an m+p control system with feedback from four control microphones. Testing was performed in the Ball Aerospace environmental test facility high bay in an area approximately 40 feet by 40 feet with the speakers arranged in a 19 foot (5.75 meter) diameter circle centered around the spacecraft. Control microphones were located 24 inches from the spacecraft and arranged around the spacecraft perimeter. Four control microphones, located at mid bus vertically, were used for control with an additional 10 response microphones situated around the spacecraft. Spacecraft responses were scaled up by the difference between the spacecraft and antenna subsystem 1/3 octave band acoustic test input levels depicted in Figure 9a.

The CPR responses during the direct speaker spacecraft acoustic test and during the main reflector assembly reverberant chamber acoustic test were compared for the secondary reflector, radiator and TT&C antenna and are plotted in Figures 10a-c. The spacecraft/CPR direct speaker acoustic test response peaks were about 10 dB higher than the CPR reverberant chamber test, between 70 Hz and 150 Hz. Calculation of standing wave modes indicate these strong structural responses were the result of standing waves within the speakers/hardware space. Several fundamental acoustic modes of the NGST acoustic chamber were computed to be below 60 Hz. As shown in Figures 10a-c, no structural modes were excited by the acoustic standing waves below 60 Hz because CPR frequencies were at 85 Hz and above.

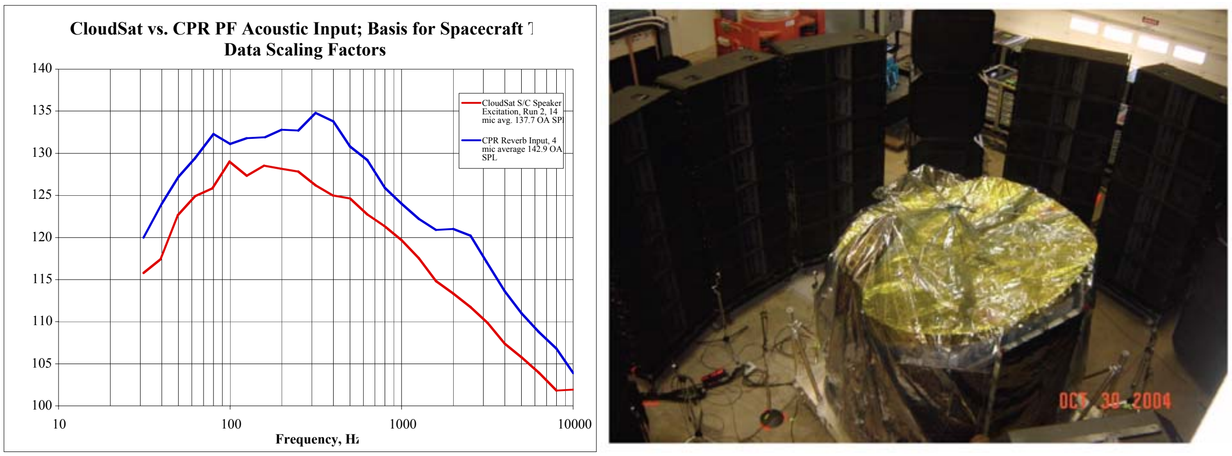

Figure 9: a) CloudSat and CPR antenna acoustic input spectra and b) reflector within speaker bank at Ball Aerospace.

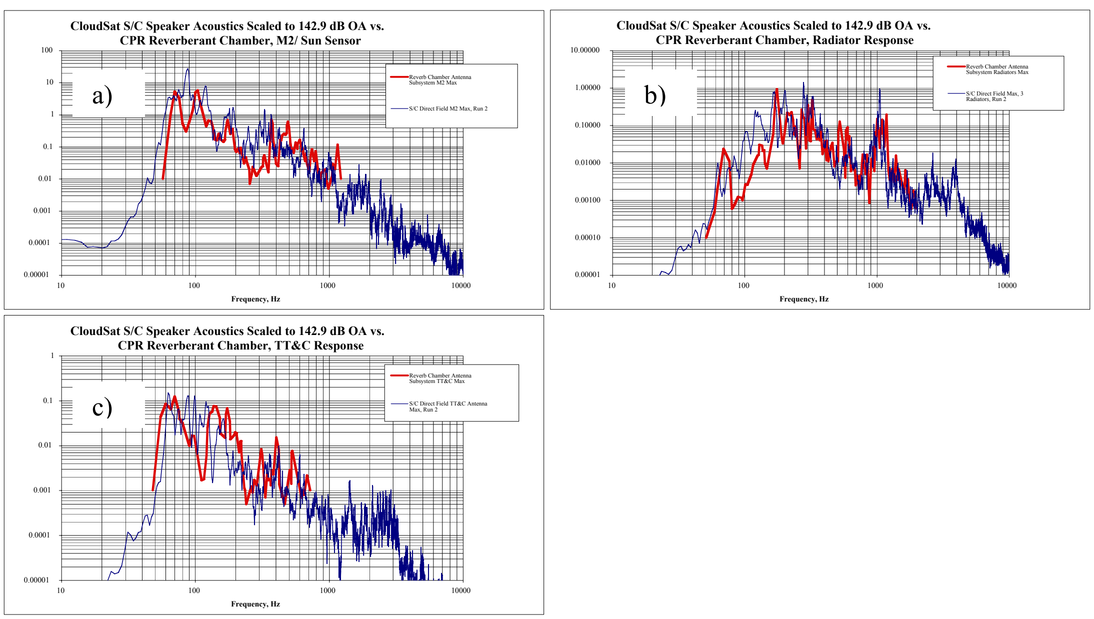

Figure 10: a) Secondary CPR reflector response, speaker vs. reverberant chamber input, b) Radiator response, speaker vs. reverberant chamber input, and c) TT&C antenna response, speaker vs. reverberant chamber input.

d) DAWN Spacecraft Acoustic Tests

The DAWN spacecraft in the speaker test configuration is shown in Figure 11a. The flight DAWN acoustic testing was performed at Orbital Scince Corporation's environmental test laboratory to the levels shown in Figure 11b with an overall SPL of 141.3 dB. The PF acoustic testing was conducted utilizing speakers and was completed in two separate full level test runs to keep speaker temperatures within safe limits. Speakers were arranged in a 300 inch diameter circle (7.6 meter) centered around the spacecraft. Acoustic levels were controlled using 8 microphones that were located approximately 24 inches from the spacecraft and arranged around the spacecraft perimeter. An additional 8 response microphones situated around the spacecraft were used to verify the SPLs within the volume. The DAWN spacecraft was instrumented with an extensive number of accelerometers to capture acceleration responses in critical locations.

A separate workmanship acoustic test was performed on the DAWN spacecraft to workmanship levels with an overall SPL of 136.8 dB (Figure 11b). The workmanship acoustic testing was conducted at the Naval Research Laboratory's reverberant chamber, which is powered with nitrogen horns. The target acoustic input spectra was 138 dB OASPL based on the spectral shape of the DAWN PF acoustic requirement and the NASA minimum workmanship acoustic requirement of 138 dB. In an effort to keep the assembly responses to the levels obtained from the direct acoustic test, response limiting was implemented that resulted in notches measured at 80 Hz (2.8 dB), 100 Hz (5.0 dB), 125 Hz (2.9 dB) and 200 Hz (2.6 dB).

In addition to the two DAWN spacecraft tests mentioned above the spacecraft's High Gain Antenna (HGA) was acoustically tested to a higher PF level using the Wyle reverberant acoustic chamber. Spacecraft responses from the PF test and the workmanship test were scaled up by the differences in the spacecraft and antenna assembly 1/3 octave band acoustic test input levels shown in Figure 11b. Figure 12a shows the DAWN Y panel response (facing speakers). The instrumentation locations on the HGA were the same for all three tests. Figures 12b and c show the HGA responses measured from the three HGA with spacecraft test setups. DAWN HGA component responses were significantly higher below 125 Hz for both HGA alone and for the spacecraft reverberant tests as compared to the DAWN DAF test. Two HGA modes at 65 Hz and 100 Hz showed strong responses, more than 15 dB higher than the direct acoustic testing of the spacecraft with the HGA Antenna. The grms from these three accelerometers measurements taken from Figure 12b were 43.5 grms, 15.7 grms and 33.1 grms in the reverberant tests, which were significantly higher than the 28.8 grms, 12.7 grms, and 19.4 grms measured during the direct acoustic spacecraft tests (See Figure 12c). The increased responses during reverberant chamber testing were attributed to standing waves that coupled with the HGA that were absent in the DAWN speaker setup. The differences in higher frequencies are probably attributed to the acoustic grazing effect and will be discussed in a future publication.

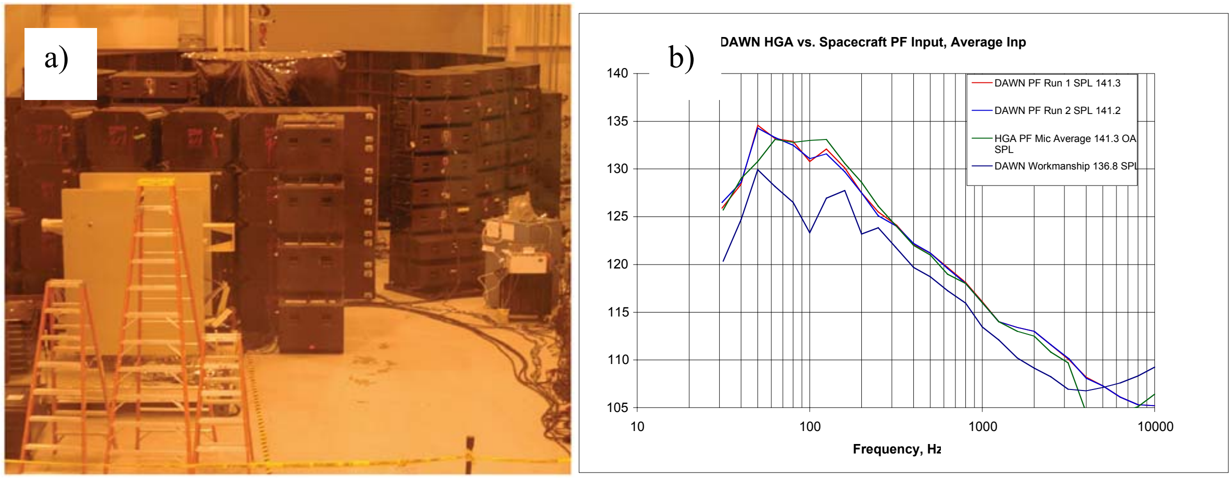

Figure 11: a) DAWN spacecraft in acoustic test speaker bank and b) speaker and reverberant spacecraft acoustic inputs.

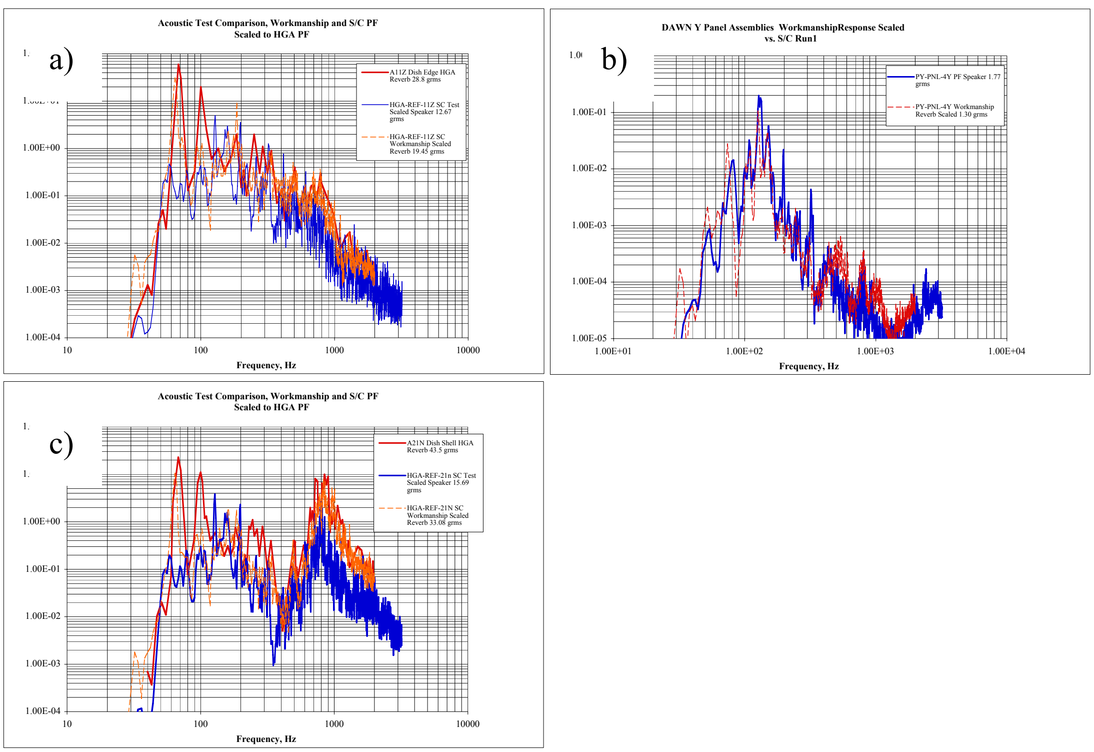

Figure 12: a) DAWN Y bus panel response, speaker vs. reverberant input, b) HGA dish edge, three test responses, speaker vs. reverberant input, and c) HGA dish edge, three test responses, speaker vs. reverberant input.

CONCLUSIONS

Comparisons of vibration responses during acoustic testing using reverberant chambers and direct speaker testing indicate there are differences between the two test methods. It is clear that flight structure and acoustic mode coupling can result in an un-anticipated over test for some low mass to area structures like antennas, solar arrays, etc. Therefore, it is of paramount importance to characterize acoustic chamber and speaker test article locations and identify major structural modes that may couple with the acoustic standing waves before subjecting light weight large structures to an intense acoustic field. The reverberant chamber acoustic/structural coupling phenomenon was demonstrated by tailoring the dimensions of a 1/4-inch aluminum panel to couple with two chamber modes. The panel was suspended at three locations perpendicular to one of the chamber dimensions. The structural modes coupled with the acoustic modes located closer to the pressure minimum of the standing waves indicated significant structural excitations in excess of 20 dB.

To further gain confidence on occurrence of this phenomenon, data from a few flight hardware acoustic tests in acoustic chambers and speaker testing were examined. The data from these tests have clearly indicated that whenever the acoustic standing waves coincide with the structural modes, albeit in the chamber or speaker setting, the result is significant increases in the structural responses. The combined results from the simple aluminum acoustic test and the tests from flight hardware acoustic qualification prove that the coupling phenomenon can significantly impact acoustic test outcomes. Such an increase in structural responses due to this coupling must be considered in sensitive flight hardware testing and should be discussed in the context of guidelines development for direct acoustic testing since speaker layout/arrangement and speaker phasing has a large impact on structural/ acoustic coupling. The aerospace industry also needs better guidelines for reverberant testing that considers the coupling phenomenon discussed in this paper.

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