Impact of Acoustic Standing Waves on Structural Responses

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ABSTRACT

For several decades large reverberant chambers and most recently direct field acoustic testing have been used in the aerospace industry to test larger structures with low surface densities such as solar arrays and reflectors to qualify them and to detect faults in the design and fabrication. It has been reported that in reverberant chamber and direct acoustic testing, standing acoustic modes may strongly couple with the fundamental structural modes of the test hardware (Reference 1). In this paper results from a recent reverberant chamber acoustic test of a composite reflector are discussed. These results provide further convincing evidence of the acoustic standing wave and structural modes coupling phenomenon. The purpose of this paper is to alert test organizations to this phenomenon so that they can account for the potential increase in structural responses and ensure that flight hardware undergoes safe testing. An understanding of the coupling phenomenon may also help minimize the over and/or under testing that could pose un-anticipated structural and flight qualification issues.

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

INTRODUCTION

The phenomenon of structural modal coupling with acoustic standing waves has been discussed by this author in the past[1-3]. The data from a series of acoustic tests have clearly indicated that whenever the acoustic standing waves coincide with the structural modes, whether the hardware is exposed to acoustic environments in the chamber or direct field acoustic testing (DFAT), result in significant increase in the structural responses. Such an increase in structural responses due to the coupling is often not considered in acoustic testing. It is a paramount importance that the impact of such a coupling be assessed when sensitive flight hardware undergoes qualification testing. The impact of such couplings has been discussed in NASA handbooks[4-5]and guidelines provided for reverberant acoustic and direct field acoustic testing of flight hardware to deal with this issue. This paper provides further evidence of flight hardware structural coupling with acoustic standing waves that can result in an increase in structural response.

Impact of Acoustic Standing Waves on Structural Responses

It has been demonstrated that the structure and acoustic modes coupling can result in an un-anticipated overtest for some low mass to area structures like antennas, solar arrays, etc.[1-3]. Recently, the reverberant chamber acoustic/structural coupling phenomenon was demonstrated by tailoring the dimensions of a 1/4-inch aluminum panel to couple with chamber standing modes. The panel was suspended at three locations perpendicular to one of the chamber dimensions. A series of diffuse acoustic tests were performed on the aluminum panel in the reverberant chamber. The panel structural responses, measured by one of the accelerometers positioned close to the monitor microphones have shown to vary by more than 20 dB when such coupling occurs, as depicted in Figure 1. These results, discussed in some detail in reference 1, convey an important finding related to the coupling phenomenon. These observations are remarkable in that a significant increase in the structural responses occurs only when the acoustic standing waves couple with the structure modes. The increase in the structural responses occurs at chamber pressure nodes where the particle velocity of the standing waves is maximum. The simple aluminum panel acoustic test and similar observations made from a few flight hardware acoustic qualification tests[1] demonstrate that the coupling phenomenon can significantly impact structural responses.

The existence of the acoustic standing waves has also been observed in DFAT tests[2, 6-8]. In addition to using control microphones in the DFAT test, discussed in great detail in these references, a linear array was positioned across the speakers and in the vertical direction to measure possible standing waves within the volume between the speakers. Figure 2 shows the schematic of the DFAT acoustic cavity formed by the speakers and the locations of the microphones comprising the linear array. Several dominant modes were observed; the first one closer to 93 Hz is shown in Figure 3. This mode, which provided high pressure fields in both SISO and MIMO control schemes, was identified and classified as an acoustic standing wave. To understand the acoustic standing waves of the cavity made up of the speakers in the DFAT test setup, a simple model with speakers forming a cylindrical cavity was provided in Reference 2. The acoustic field in the cavity was modeled using wave equation in cylindrical coordinates. The predicted standing waves are also correlated with the measured data as shown in Figure 3. The existence of these standing waves should not be confused with interference patterns discussed in Reference 6. The differences between interference patterns and acoustic standing waves are twofold: 1) the interference patterns could be removed from the acousti
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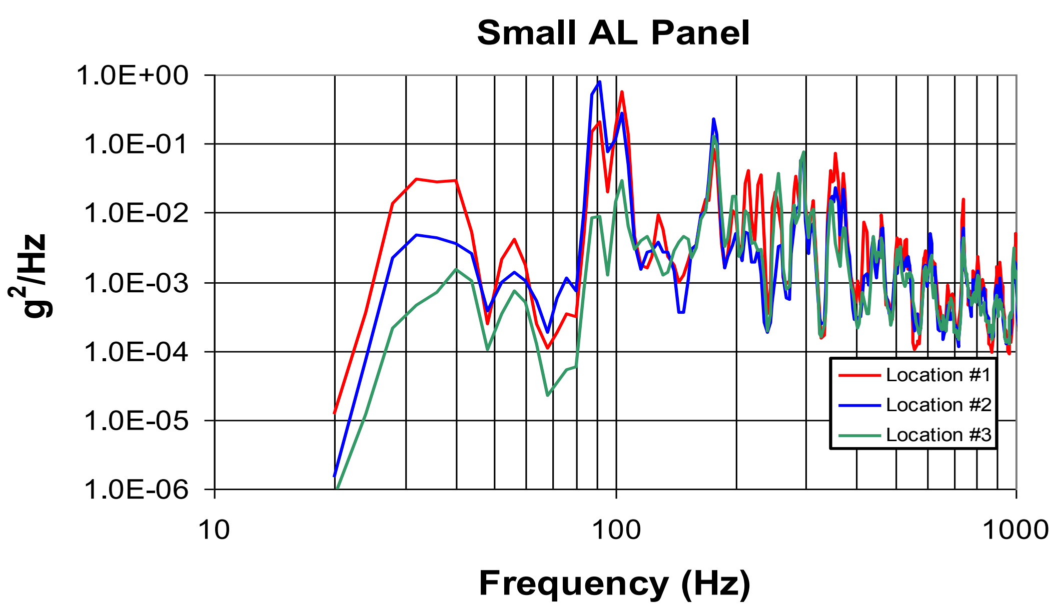

Figure 1: Panel structural responses measured at panel locations 1, 2 and 3 in the chamber by one of the accelerometers mounted on the panel. Close to 20 dB differences in the structural responses were observed near 90 Hz, where strong coupling occurred[1].

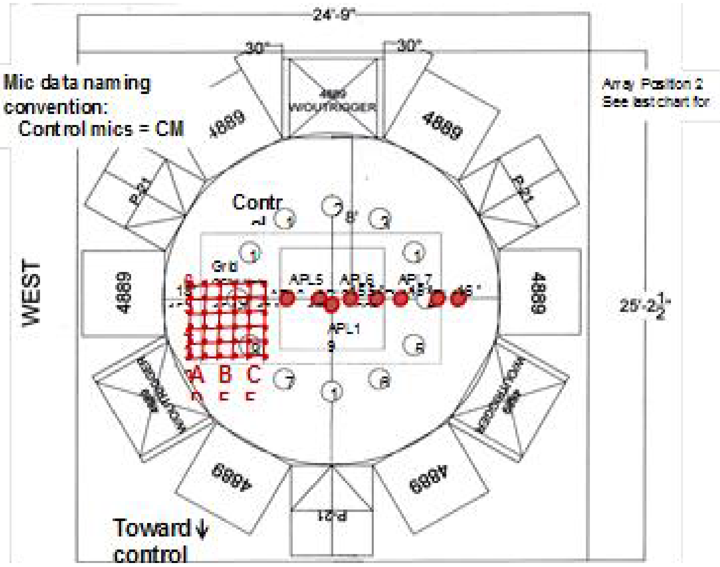

Figure 2: The APL speakers and woofers arrangement with control microphones, the microphone array, and linear microphone array[2] (the array, illustrated in red, is orientated vertically for the test).

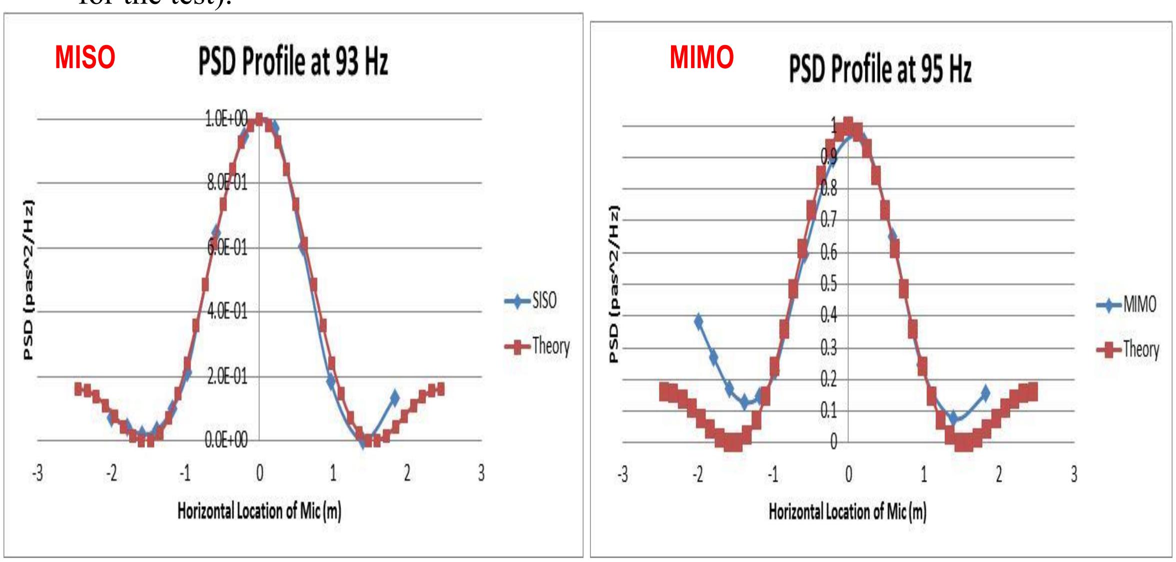

Figure 3: The predicted radial acoustic mode shape with frequency of ~93 Hz correlated with measured data obtained from DFAT tests using both SISO and MIMO controller schemes[2].

To further evaluate the impact of acoustic standing waves on the structural responses, a series of acoustic tests were performed using a space flight reflector borrowed from the Aquarius project. Aquarius reflector's resonance modes were computed using Nastran Finite Element model. To demonstrate the chamber acoustic field and Aquarius reflector modal coupling phenomenon, the reflector was exposed to a diffuse acoustic field while positioned in several different locations in the reverberant chamber (See Figure 4). The reflector was acoustic tested in the chamber to the OASPL of 140 dB. The reflector was instrumented with seventeen tri-axial and uni-axial accelerometers mounted on the reflector's back. It was positioned at seven locations parallel to one of the chamber walls, then clocked 90 degrees and placed in six locations parallel to other wall. The acoustic testing of the reflector started with it positioned at the center of the chamber parallel and moved closer to the north and east walls in 2-ft increments. At each reflector position five response microphones were placed in front of the reflector six inches off its surface. These microphones were used to record the sound pressures experienced by the reflector and to correlate the pressures with the structural responses measured by the accelerometers mounted on the reflector.

In addition to the five response microphones, eight microphones were used to control the sound pressure levels (SPLs) in the chamber. The 1/3rd octave band SPLs from the individual control microphones and the average of the control and the response microphones, were analyzed for each panel location. (A test run is plotted in Figure 5.) The departure from the mean SPLs is pronounced below ~150 Hz, where the Schroeder cut-off frequency is computed for this chamber. The differences in the SPLs below 150 Hz are very clear. These differences are attributed to the acoustic waves scattering and radiating by the reflector and standing waves with varying amplitudes within the chamber.

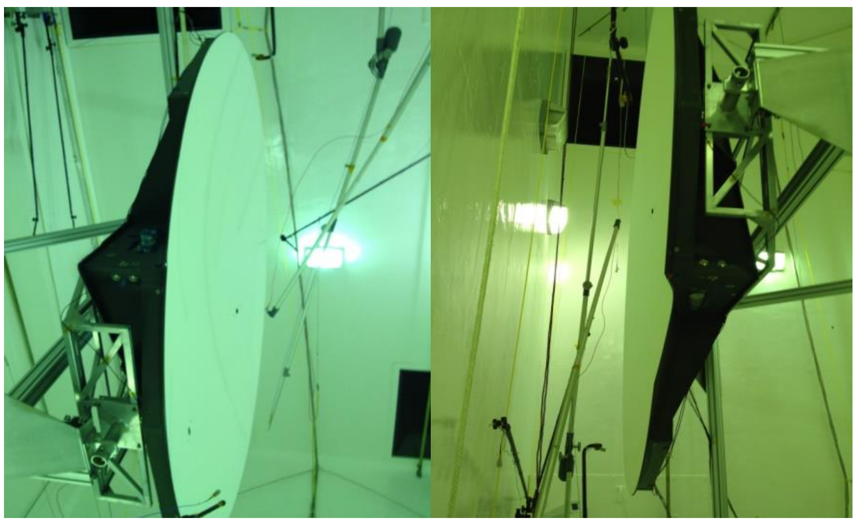

Figure 4: JPL's acoustic chamber: 21.75'(L)×18.5'(W)×26.5'(H) with Aquarius reflector facing one of the chamber's walls. The image on the left is showing the reflector facing east and the

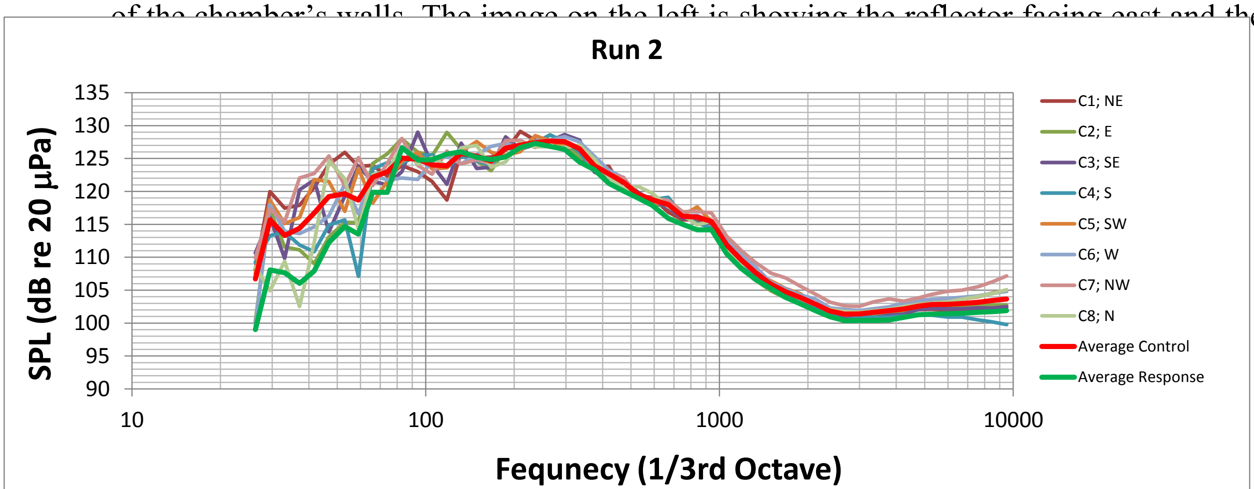

Figure 5: The individual SPLs from the 8 control microphones, the averaged SPL of the 8 controls, and the averaged SPL of the 5 monitor microphones near the reflector are shown in 1/3 octave bands for a typical test run.

AQUARIUS REFLECTOR MODES

The normal modes of the reflector fixed to a frame were computed using fixed-fixed boundary conditions. The predicted first two mode shapes and frequencies are shown in Figure 6. These modes are just a few examples that were near the acoustic standing waves and most likely coupled with them. The first reflector mode of about 59 Hz was close to the acoustic standing wave mode #6 (61 Hz in one of the lateral directions). The predicted structural mode of approximately 75 in the other lateral direction is close to the chamber acoustic modes 78 Hz.

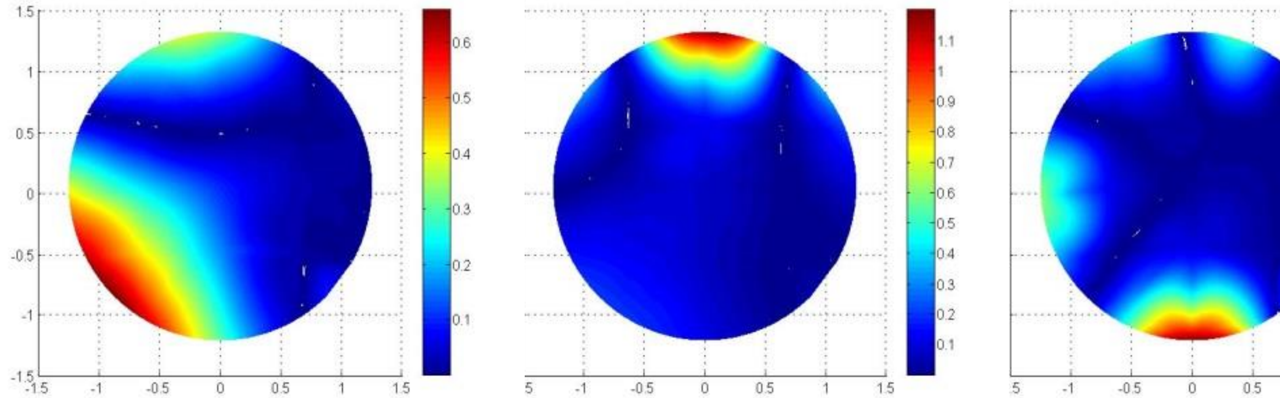

Figure 6: The first two mode shapes (displacement) of the Aquarius reflector obtained from FEM analysis.

COMPARISON OF EXPERIMENTAL AND FEM RESULTS

The structural responses of the Aquarius reflector at different locations were measured and compared with the FEM predicted modes. The reflector's structural responses, measured by one of the accelerometers positioned at the edge of the reflector, are shown in Figures 7 and 8 for locations facing two chamber walls. These figures indicate a few important findings related to the coupling phenomenon under discussion, where similar observations were made using a flat panel exposed to reverberant sound pressure field[1-2]. First, the reflector measured modes closer to 64 Hz and 84 Hz facing east of the chamber wall were very close to the predicted reflector's first mode of 59 Hz and 75 Hz. The discrepancy between the predicted and measured modes is due to the uncorrelated testing configuration FE model. These figures show significant changes in the structural responses. For example, the structural response of the first mode changed by ~ 13 dB, depending on the location of the reflector, whereas the sound pressure level differences between the five microphones measured near the reflector were almost the same near this frequency. The second significant structural/acoustic modal coupling occurred at approximately 84 Hz. The difference in sound pressure levels at this frequency for the reflector's locations was less than a few dBs, whereas the structural responses differed by more than 12 dB. Similar behavior is noted in Figure 8, where structural modes close to 70 Hz and 92 Hz show significant changes in the structural responses of the reflector at various locations facing the chamber's wall to its north side. The responses shown in Figures 7 and 8 are further confirmation of the structural/acoustic coupling phenomenon. These observations show significant increase in the structural responses occurred when the acoustic standing waves coupled with the structure modes. The increased in structural responses occurred at pressure nodes where the particle velocity of the standing pressure waves was maximum. The acoust

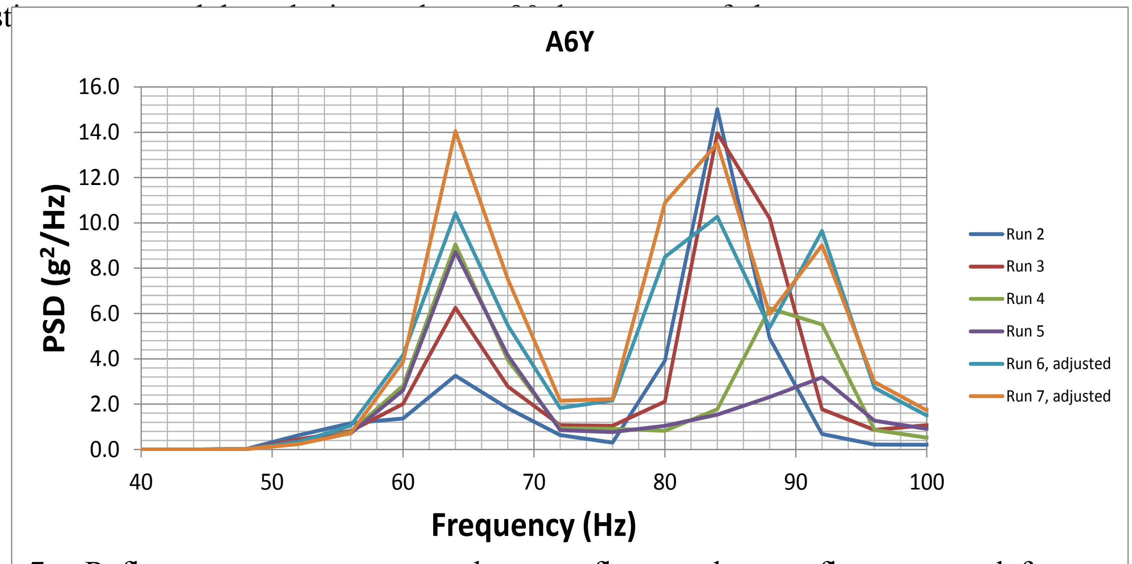

Figure 7: Reflector responses measured near reflector edge - reflector moved from center of acoustic chamber toward east chamber wall in 2-ft increments.

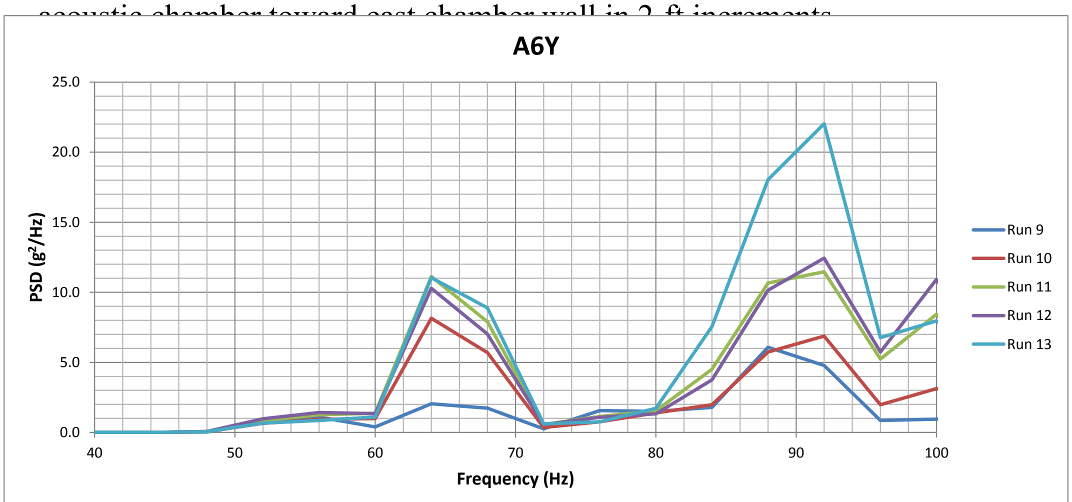

Figure 8: Reflector responses measured near reflector edge – reflector moved from center of the acoustic chamber toward north chamber wall in 2-ft increments.

SUMMARY

Acoustic standing waves in reverberant acoustic chamber testing have been shown to induce significant structural responses when they couple with test article structural modes. This phenomenon is evident below a couple of hundred Hz in most chambers. It has been shown that the standing waves also exist in DFAT and, due to much smaller volumes than most reverberant chambers, the standing waves tend to extend to higher frequencies. A series of acoustic tests were performed by positioning the Aquarius reflector at several locations inside the JPL reverberant chamber, which further demonstrated the impact of the acoustic standing waves on structural responses. These tests provided additional insight into the phenomenon of acoustic standing waves coupling with structural modes discussed in this paper. This structural coupling produces an over test which, if not addressed, increases the chance of flight hardware failure during acoustic qualification tests.

By positioning the Aquarius reflector in several locations parallel to two of the chamber walls, the acoustic standing waves and its structural couplings were examined. The structural responses were observed to increase between 8 to 15 dB when they coupled with acoustic standing waves. The observed structural modes were near the acoustic wave frequencies and not exactly coinciding with them. The structural responses would have been higher than these observations if any modes exactly coincided with the acoustic standing waves.

ACKNOWLEDGMENT

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REFERENCES

1. Ali R. Kolaini, Michael R. O’Connell, and Wan B. Tsoi, “Acoustically Induced Vibration of Structures: Reverberant vs. Direct Acoustic Testing,’ ATS 2009.
2. Ali R. Kolaini, Benjamin Doty, and Zensheu Chang, “Reverberant Acoustic Testing and Direct Field Acoustic Testing Acoustic Standing Waves and Their Impact on Structural Responses,” SCLV Workshop 2012.
3. O’Connell, M. (June 2007). *Direct Field and Reverberant Chamber Acoustic Test Comparisons.* Paper presented at the Spacecraft and Launch Vehicle Dynamic Environments Workshop, El Segundo, CA.
4. “Payload Vibroacoustic Test Criteria,” NASA-HDBK-7001A, 2011.
5. “Direct Field Acoustic Testing (DFAT),” NASA-HDBK-7010, in preparation.
6. Van Dyke, M. B., Portia R. Peters, “*Spatial Variability Caused by Acoustic Wave Interference in Single-Drive Direct Field Acoustic Testing*,” Paper presented at the 26th Aerospace Testing Seminar, Los Angeles, CA, March 2010.
7. Paul Larkin and Dann Hayes, “*Status of Direct Field Acoustic Testing*,” 27th ATS, October 2012.
8. Gordon Maah, *“Direct Field vs Reverberant Field Acoustic Testing*,” 2009 SC&LV Dynamics Environments Workshop.

BIOGRAPHIES

Dr. Ali R. Kolaini has been a Member of the Technical Staff at JPL since 2005. He currently has a position as a Principal Engineer and group supervisor of the Dynamics Environments group of the Mechanical Systems Division. Prior to joining JPL, Dr. Kolaini was an Engineering Specialist at The Aerospace Corporation, and an associate professor at the University of Mississippi. He has a B.S. degree in Mechanical Engineering from the Lawrence Tech University, and a M.S. and a Ph.D. in Mechanical Engineering from the University of California, Santa Barbara. He has more than 25 years of experience in the fields of vibration, shock, and acoustics.

