Impact of Acoustic Standing Waves on Structural Responses: Reverberant Acoustic Testing (RAT) vs. Direct Field Acoustic Testing (DFAT)

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ABSTRACT

Loudspeakers have been used for acoustic qualification of spacecraft, reflectors, solar panels, and other acoustically responsive structures for more than a decade. Limited measurements from some of the recent speaker tests used to qualify flight hardware have indicated significant spatial variation of the acoustic field within the test volume. Also structural responses have been reported to differ when similar tests were performed using reverberant chambers. To address the impact of non-uniform acoustic field on structural responses, a series of acoustic tests were performed using a flat panel and a 3-ft cylinder exposed to the field controlled by speakers and repeated in a reverberant chamber. The speaker testing was performed using multi-input-single-output (MISO) and multi-input-multi-output (MIMO) control schemes with and without the test articles. In this paper the spatial variation of the acoustic field due to acoustic standing waves and their impacts on the structural responses in RAT and DFAT (both using MISO and MIMO controls for DFAT) are discussed in some detail.

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

INTRODUCTION

A few years ago for the first time we reported about the reverberant chamber acoustic standing waves/structural modal coupling phenomenon by demonstrating the coupling of 1/4-inch aluminum panel structural modes with chamber acoustic modes[1-2]. The panel was suspended at three locations perpendicular to one of the chamber dimensions. The panel structural modes coupled with the chamber acoustic modes when the panel was located closer to the pressure minimum of the standing waves and showed structural excitations in excess of 20 dB[1]. To gain further confidence on the 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, whether the hardware is exposed to acoustic environments in the reverberant chamber or in direct field acoustic testing (DFAT), the result is a significant increase in the structural responses. Such an increase in structural responses due to this coupling is often not considered in acoustic testing. It is of paramount importance that the impact of such a coupling be assessed before sensitive flight hardware undergoes acoustic qualification testing. This is a subject that is being discussed in the context of guidelines for the DFAT method in a NASA handbook under development[3] since the speaker layout/arrangement may have a large impact on structural/acoustic modal coupling. The aerospace industry also needs better guidelines for reverberant testing that considers the coupling phenomenon discussed in this paper.

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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[1-2]. One of the parameters that strongly influence structural responses is the acoustic standing wave coupling with the structural modes. To gain confidence with the speaker acoustic testing using the multi-input-single-output (MISO) and multi-input-multi-output (MIMO) control systems a series of tests were performed at the Applied Physics Laboratory (APL) with involvement from several institutions[4-5]. A simple aluminum panel with an electronic box attached to it and an aluminum cylinder were used as test articles. These articles were previously acoustic tested at JPL, first using the DFAT method, then in the acoustic chamber. The DFAT JPL acoustic field was controlled using MISO control system and these same acoustic environments then employed in reverberant tests of the panel and cylinder test articles. The differences in the acoustic fields generated by the speaker and reverberant acoustic fields were discussed in some detail in prior publications[1-2].

The emphasize in this paper is on demonstrating the existence of acoustic standing waves in DFAT testing that may couple with test article structural modes. The conclusions provided herein may be helpful in the preparation of the DFAT testing.

EXPERIMENTAL SETUP

The first extensive DFAT test was performed at the JPL environmental test facility during March 23-25th, 2010. The second, more elaborate DFAT test was performed at Applied Physics Laboratory (APL) during July 23-25, 2011. The Speakers, woofers, and control system for both tests were provided by Maryland Sound Incorporation (MSI). They were responsible for setting up the testing configurations. A series of control microphones (up to 16) were used in different configurations to generate the sound field within the speakers to the overall sound pressure level (OASPL) of 140 dB. In addition to using control microphones another 8 monitor microphones were spread within the volume to obtain the sound pressure spatial variations. Finally an array of 36 microphones was also used and positioned in several locations to obtain the detail sound pressure variation within the volume in these two test setups. In the case of the APL test a linear array were positioned across the speakers and in the vertical direction to measure the possible standing waves within the speakers' setup. The major difference between the JPL and APL tests was the control system, where in the APL test improvement was made in the control system to generate sound field using both MISO and MIMO control schemes. Figure 1a shows the schematic of the DFAT acoustic cavity formed by the speakers, a 36-microphone array, and the linear array. The 36-microphone array was used to examine the difference in the sound field between the MISO and MIMO and assess the spatial variation within the cavity, whereas the linear array was used to measure the sound pressure levels across the speakers and along the height. Figure 1b depicts the speakers set up used for acoustic field characterization using MISO and MIMO at APL's testing facility.

The linear array discussed above was used to measure acoustics standing waves in the radial and vertical directions. Figure 2 depicts the pressure spectral density identifying most acoustics modes measured using the 36-microphone array. In this figure both the interference wave patterns and acoustic standing waves are identified. The interference wave patterns are critically dependent on the control system and the MIMO control scheme has shown to minimize the hot-cold acoustic field measured in DFAT testing[6]. The interference wave patterns are not the

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subject of the discussion in this paper, whereas the acoustic standing waves due to the potential increase in structural responses are the main topic of discussion in this paper. Figure 3a and 3b are the pressure spectral densities identifying the acoustic standing waves using the APL DFAT test for both the MIMO and MISO control schemes, respectively. Two dominant modes close to 93 Hz and 225 Hz that provided hot pressure fields in both control schemes were identified and classified as acoustic standing waves. These waves will be discussed in some detail in the following sections. A simple model is also provided in the next section to predict the acoustic standing waves of the cylindrical cavity formed by the speakers and will be correlated with the measured data.

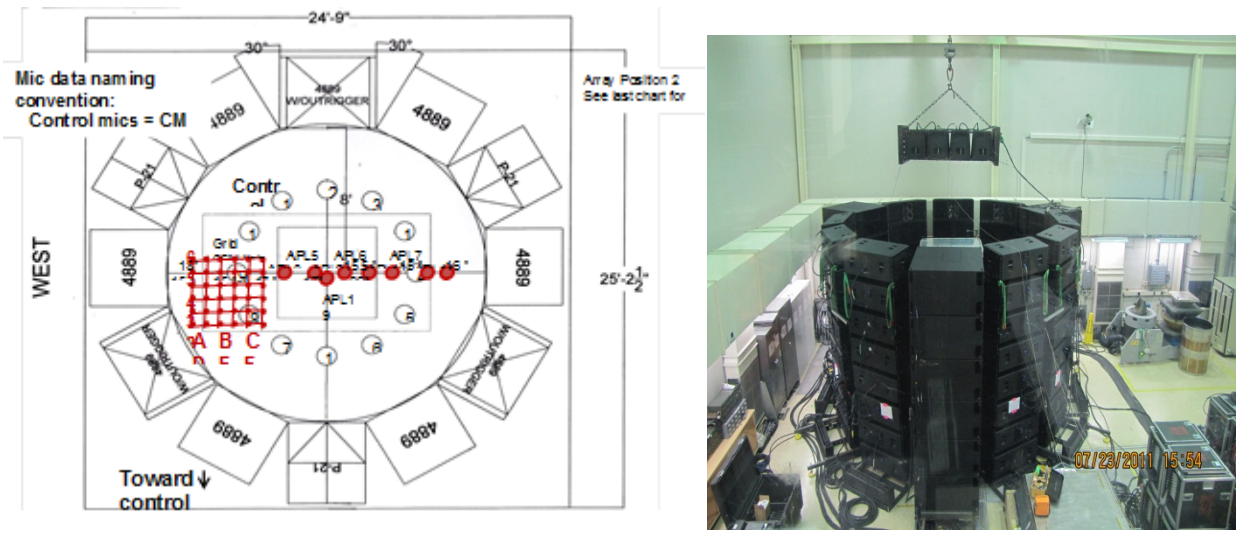

Figure 1: a. The APL speakers and woofers arrangement with control microphones, the microphone array, and linear microphone array. **b.** A photo of the APL DFAT setup is shown in this figure.

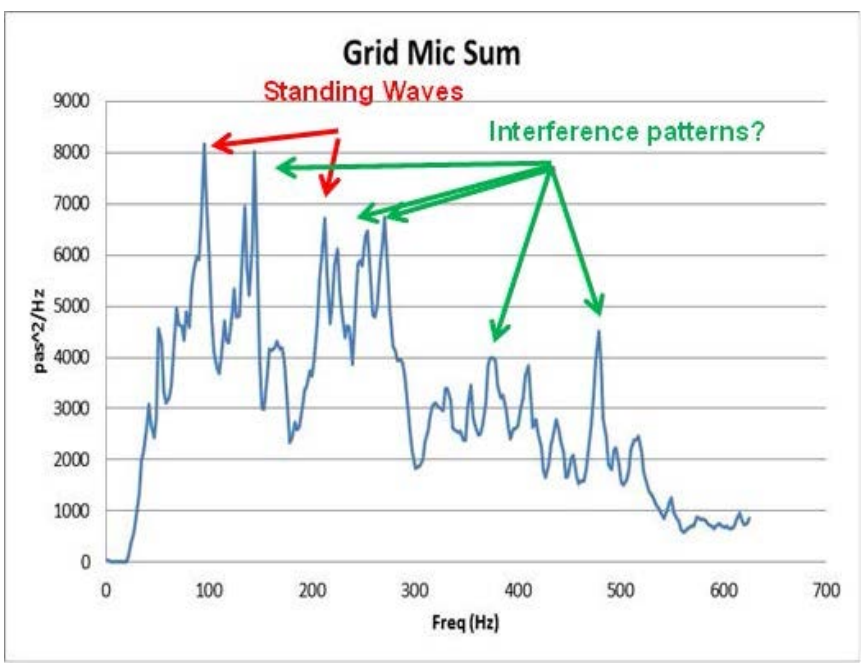

Figure 2: Sound pressure spectral density obtained from APL DFAT test. The acoustic modes identified in this plot are due to the acoustic standing waves and interference wave patterns.

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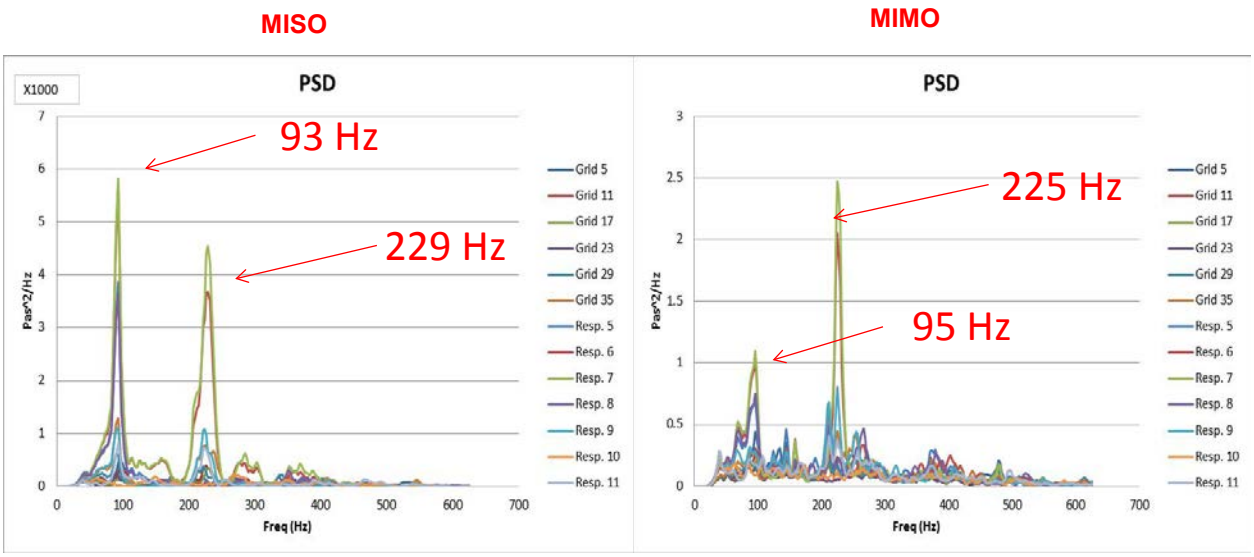

Figure 3: Sound pressure spectral densities obtained from APL DFAT tests using MISO and MIMO control schemes. The acoustic modes identified in these plots are acoustic standing waves.

SIMPLE MATHEMATICAL MODEL

The power spectral densities of the sound pressures measured by the linear microphone array within the speakers shown in Figures 3a and 3b for MISO and MIMO control schemes indicate that the MIMO control system did not eliminate the modes at 93 Hz and 225 Hz, whereas some of the interference patterns shown in Figure 2 were significantly reduced in magnitude using the MIMO control system. The pressure PSDs in Figures 3a and 3b are plotted in 1-Hz constant bandwidth. The pressure peaks within the speakers shown in Figure 2 are results of two wave patterns as discussed earlier. Some of the wave patterns are the result of wave interferences generated by the speakers and propagated in various directions and phases. The MIMO control scheme tends to minimize the existence of the interface patterns[6]. The other wave patterns measured within the speakers are acoustic standing waves. The existence of acoustic standing wave patterns and their impact on the flight hardware structural excitations are the thrust of this paper.

To understand the acoustic standing waves of the cavity made up of the speakers in the DFAT test setup we consider a simple model with speakers forming a cylindrical cavity. The acoustic field in the cavity may be modeled using wave equation in cylindrical coordinates, which is given by:

$$\frac{\partial^2}{\partial r^2} + \left(\frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial Z^2} + k_{n'}^2\right) P(r,\theta,z) = 0, \qquad (1)$$

where $P(r,\theta,z)$ is the pressure, and $k_{n'}$ is the wavenumber. For the speakers setup cylindrical cavity, we assume the speaker surfaces and ground are rigid (assumptions used for first order estimate of the standing waves in the cavity), therefore, the normal velocity at speaker surfaces and ground are zero, i.e.

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$$\frac{\partial P(D/2,,\theta,Z)}{\partial r} = 0, and$$

$$\frac{\partial P(r,,\theta,0)}{\partial Z} = 0. \tag{2}$$

The pressure release assumption is made for the top of the cavity (i.e. $P(r,\theta,H)$=0). The D and H in equations (2) are the cavity diameter and height, respectively. The radius of the cavity for APL DFAT test was 8-ft and the height was 150-inch. In the radial direction, the acoustic pressure in the middle of the cavity is assumed to be finite. By decomposing the pressure field into $P(r,\theta,z) = R(r)\varphi(\theta)Z(z)$, Equ. (1) becomes,

$$(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + k_m^2 - \frac{k_n^2}{r^2})R(r) = 0,$$

$$(\frac{\partial^2}{\partial \theta^2} + k_n^2)\varphi(\theta) = 0, \tag{3}$$

$$(\frac{\partial^2}{\partial \theta^2} + k_l^2)Z(z) = 0.$$

By replacing $k_m^2 = k_{n'}^2 - k_l^2$ the general solution of Equ. (1) leads to 1st and 2nd order Bessel solutions. The wave numbers that satisfy Equ. (3) lead to Eigen frequencies[7] with the cavity's wall and ground being rigid and with the top of the cavity having a pressure release condition.

Figures 4 and 5 show predicted modes using the simple model described above. Figure 4 depicts the first radial mode with a frequency of 88 Hz (m=0, and n = 1) and the first vertical mode with the same frequency (l =1) in the z-direction. Figure 5 indices the second radial mode with frequency of 203 Hz (m = 1 and n = 3) and the vertical mode for l = 2 with frequency of 237 Hz. These modes are very close to the acoustic standing modes identified using the linear microphone array shown in Figures 2 and 3. The predicted acoustic standing modes are correlated with the measured modes obtained from DFAT test results. Figures 6a and 6b show the predicted radial mode of about 93 Hz compared with the measured modes obtained both from acoustic fields generated using MISO and MIMO control schemes. The differences in the mode shape closer to the speakers for this mode in the case of the MIMO results are probably due to the acoustic field distortion due to the pressures measured near field of the acoustic sources (i.e. speakers). Figures 7a and 7b show the correlation between the predicted and measured acoustic standing mode with frequency of 225 Hz in the radial directions for MISO and MIMO, respectively. Finally, Figures 8a, 8b, 9a, and 9b are the predicted acoustic standing vertical modes of approximately 95 Hz and 225 Hz correlated with the measured modes for acoustic field controlled using MISO and MIMO, respectively. The predicted acoustic standing waves shown in Figures 6 to 9 provide reasonable correlation with the measured modes, except the vertical mode of about 225 Hz. We believe the pressure waves at the open end of the speakers setting are very complex and the pressure release boundary condition assumed in the prediction may not accurately provide the complex acoustic field in this region. The numerical analysis efforts currently are underway to use boundary element method (BEM) to predict the acoustic field generated by speakers that models the test article and the speakers[8]. The effect of the near field on the acoustic standing waves and the cavity opening will be explored using the BEM modeling

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approach. The correlated results shown in Figures 6 to 9 reconfirm the hypothesis that acoustic standing waves exist in reverberant chamber as described in References[1-2] and the DFAT testing.

There is a clear distinction between the peaks and valleys of the acoustic field within the cavity due to the interference patterns and acoustic standing waves. The latter impacts the structural responses in a significant way and is discussed in the next section in some detail.

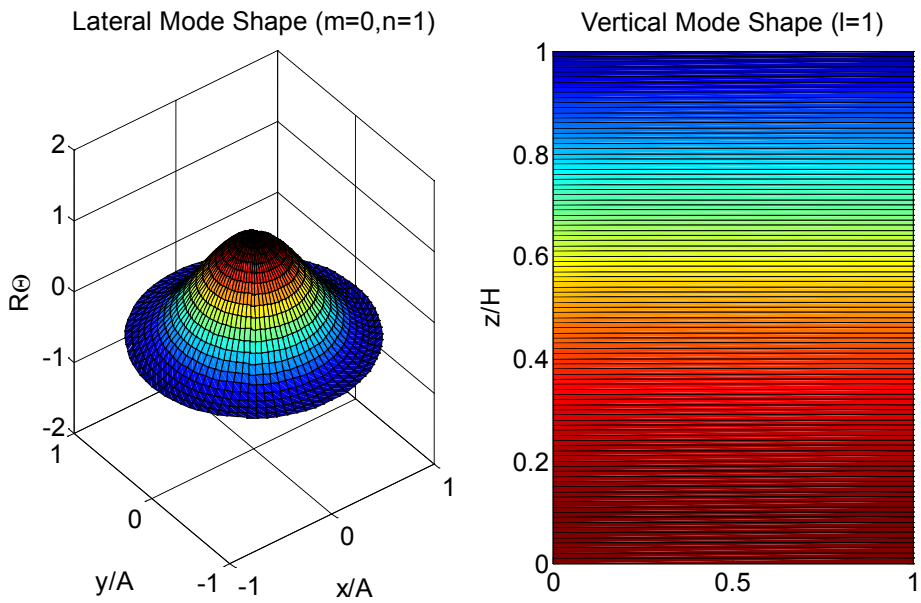

Figure 4: The predicted radial and vertical acoustic standing wave modes both at 88 Hz for the APL speakers setup.

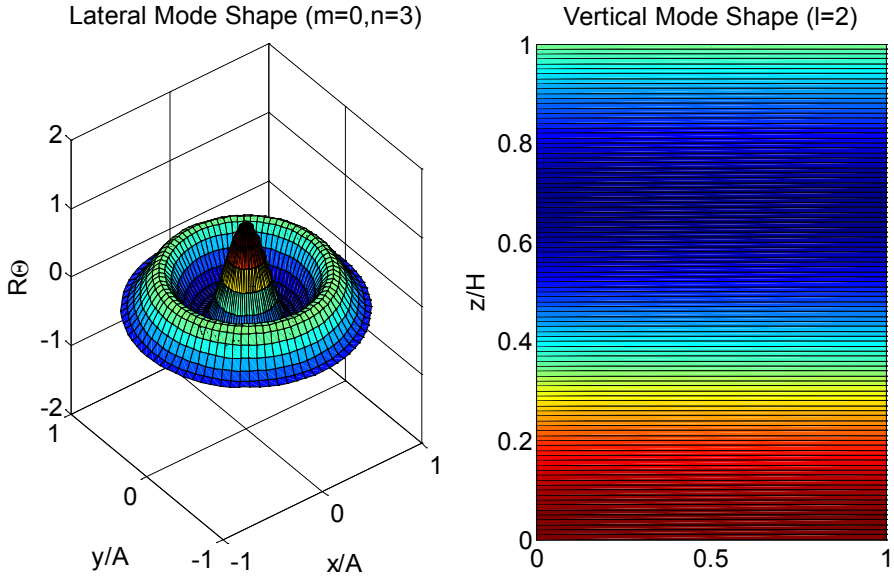

Figure 5: The predicted radial and vertical acoustic standing wave modes of 203 Hz and 237 Hz respectively for the APL speakers setup.

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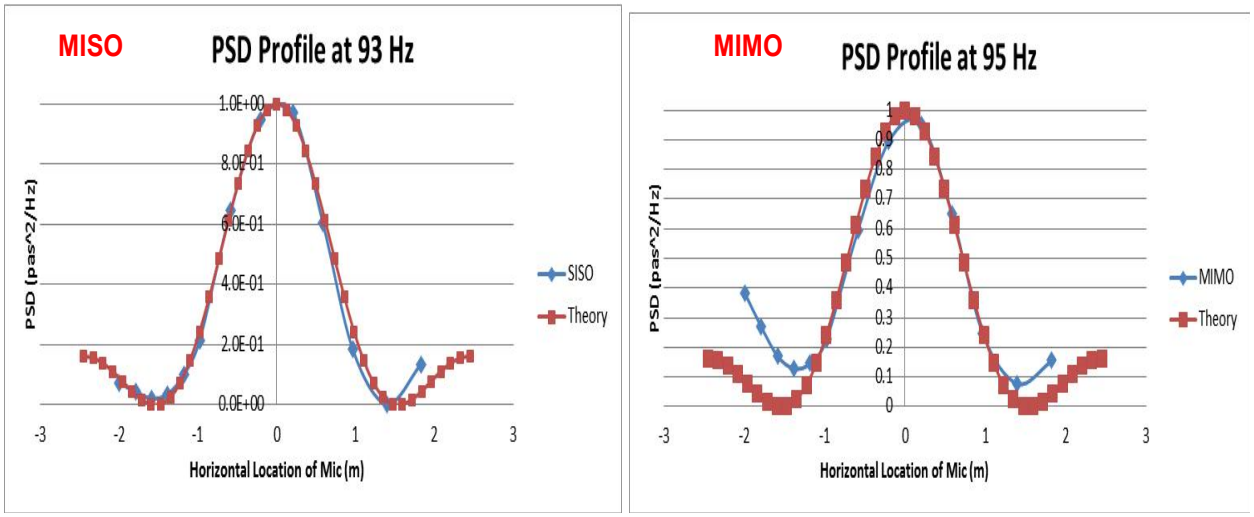

Figure 6: The predicted radial acoustic standing modes with frequency of ~93 Hz correlated with measured data obtained from DFAT tests using MISO and MIMO controller schemes.

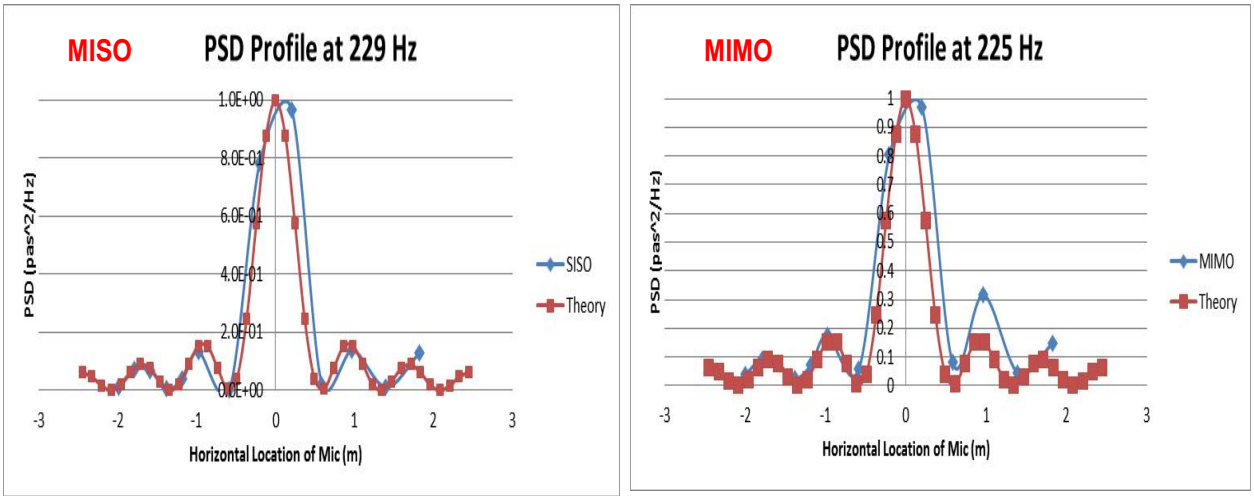

Figure 7: The predicted radial acoustic standing modes with frequency of ~225 Hz correlated with measured data obtained from DFAT tests using MISO and MIMO controller schemes.

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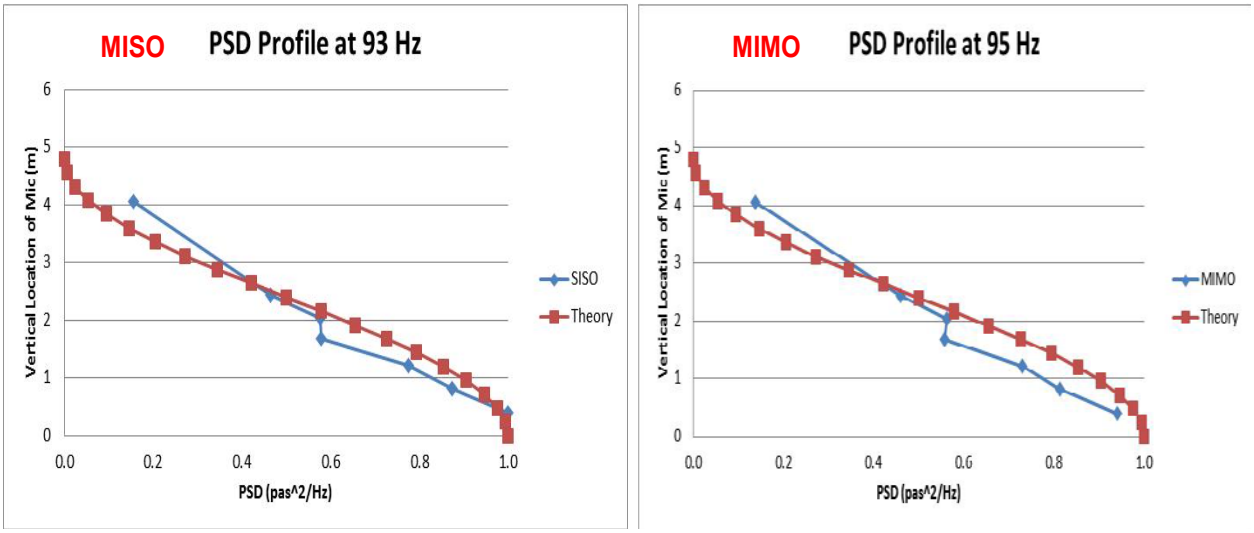

Figure 8: The predicted vertical acoustic standing modes with frequency of ~95 Hz correlated with measured data obtained from DFAT test using MISO and MIMO controller schemes.

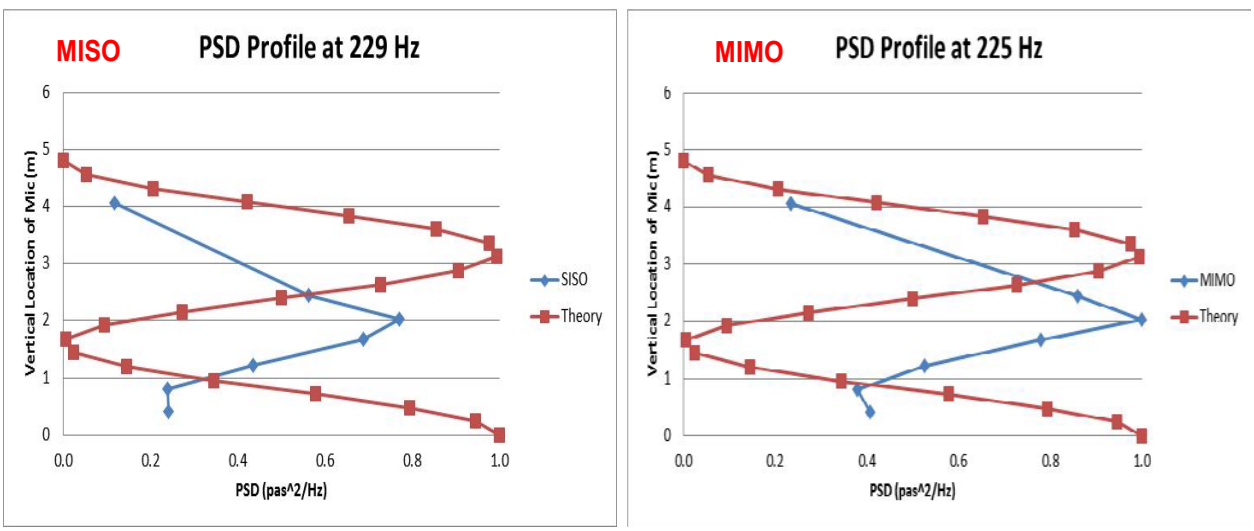

Figure 9: The predicted vertical acoustic standing modes with frequency of ~225 Hz correlated with measured data obtained from MISO and MIMO controller schemes.

ACOUSTIC STANDING WAVES AND STRUCTURAL MODAL COUPLING

It has been demonstrated that the structure and acoustic mode coupling can result in an un-anticipated overtest for some low mass to area structures like antennas, solar arrays, etc[1-2]. 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. 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, are shown in Figure 10 for each of the three panel locations. This figure conveys a

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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 less 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[1]. 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 differences of 20 dB. 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; 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.

In the case of the structural response comparisons between DFAT and RAT tests under similar conditions an example from Al panel responses are shown in Figure 11. The DFAT results were obtained from MISO control scheme. This figure indicates significant differences between the structural responses measured using the DFAT and RAT methods of testing. Efforts are underway to quantify the differences between RAT and DFAT using the MIMO control scheme.

The simple aluminum panel acoustic test described above and similar observations made from a few flight hardware acoustic qualification tests[1-2] prove that the coupling phenomenon can significantly impact structural responses. The acoustic standing wave observations made from the APL DFAT test discussed above clearly indicate that a DFAT setup with inherent acoustic standing waves will impact structural responses when the structural modes couple with them. The acoustic standing waves in DFAT testing are particularly important since these modes extend to a few hundred Hz that could impact a lot of components susceptible to structural excitation in the mid-frequency region. This effect in DFAT testing will be further examined and will be reported in future publications.

CONCLUSIONS

The existence of acoustic standing waves in reverberant acoustic testing has shown to impact structural responses in a significant way. The detail reverberant chamber acoustic/structural coupling phenomenon using a 1/4-inch aluminum panel demonstrated structural excitations in excess of 20 dB when such coupling occurs. The detailed acoustic standing waves measured from APL DFAT tests and correlated with a simple model indicate these waves exist in the DFAT testing. Any of these waves, unlike the wave interference patterns, if coupled with structural modes will provide significant increase in the structural excitation. The excitation

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frequencies in DFAT tests may fall in the mid-frequency range where most components are susceptible to excessive excitation.

BEM analyses are being considered to numerically design DFAT test setups that will minimize the impact of such coupling. Results from this activity will be presented in future meetings.

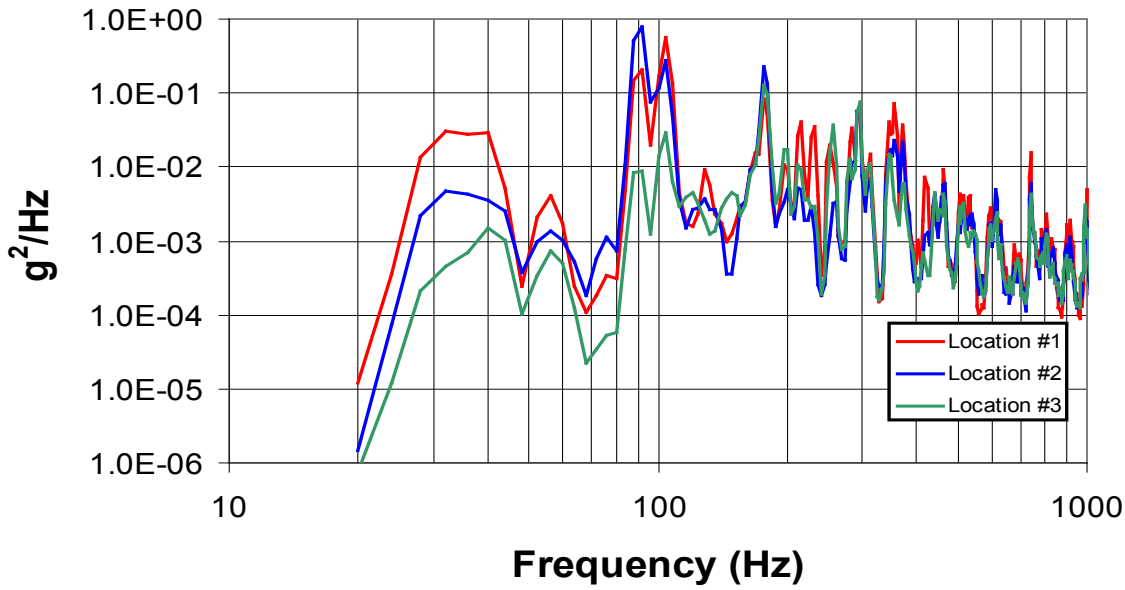

Figure 10: Al panel structural responses measured by one of the accelerometers at its corner with panel placed at three locations in JPL reverberant acoustic chamber.

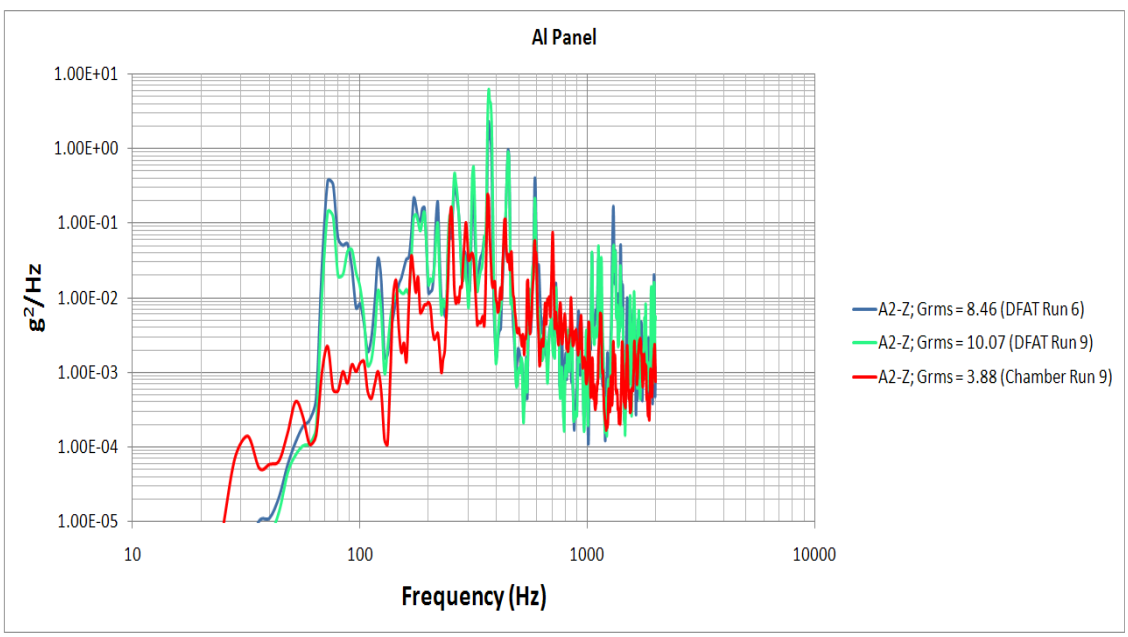

Figure 11: Al panel structural responses measured on Al panel both in JPL reverberant and DFAT tests. The DFAT tests were performed at JPL using MISO control scheme.

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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 in the Dynamics Environments group of the Mechanical Systems Division. Prior to joining JPL, Dr. Kolaini was an Engineering Specialist at The Aerospace Corporation and previously 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 20 years of experience in the fields of vibration, shock, and acoustics.

Benjamin J. Doty has over 10 years of experience in the field of vibro-acoustics. Currently, Mr. Doty holds the position of Structural Engineer III as a member of the Dynamics Environments group at JPL, where he serves as a lab expert on vibration, shock, and acoustics. In this role, he defines project dynamic requirements, directs dynamics testing, and conducts ad hoc dynamic analysis and testing to support hardware design or technology development. Mr. Doty has a B.E. degree in Mechanical Engineering from Vanderbilt University, an M.S. in Acoustics from Penn State, and an MBA from Pepperdine University. While working for NAVAIR, he served as the technical manager of SBIR contracts developing hearing protection technology for Navy flight deck crew. As a graduate assistant at Penn State, he conducted experiments for the NAVY to characterize acoustic-structural interaction underwater. At JPL, in addition to conducting acoustic qualification testing of flight hardware, Mr. Doty has supported research to improve acoustic test methodology, and helped develop the Wireless Acoustic Electric Feed through, a patented technology.

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