

Advancements and Current Status of Direct Field Acoustic (DFA) Testing Since Inception

Ali R. Kolaini¹ and Dexter Johnson²

¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

²NASA Glenn Research Center at Lewis Field, 21000 Brookpark Rd, Cleveland, Ohio 44135

ABSTRACT

For several decades, large reverberant field acoustic (RFA) testing - and more recently, direct field acoustic (DFA) testing - have been employed in the aerospace industry to qualify spacecraft, payloads, and larger, low-surface-density structures such as solar arrays and reflectors. These tests are used to assess design integrity and detect potential faults in design and fabrication.

In general, the sound pressure levels in RFA testing are well understood; most chambers generate a diffuse field above the Schrödinger cut-off frequencies, although standing waves pose challenges by causing excessive structural excitations due to coupling. In contrast, DFA testing initially faced challenges related to non-homogeneity, standing waves, and other field inconsistencies. Over the past several years, significant progress has been made in control systems and speaker technology to mitigate some of these issues. This paper reviews the development of DFA testing since its inception (QuickSat), highlighting technical issues addressed and remaining challenges. Topics discussed include standing waves, field diffusivity, sound pressure levels (SPLs) measured by control and response microphone, placement of control microphones, and structural interactions that may alter the sound field.

KEY WORDS: Acoustics, vibro-acoustics, acoustic/structural coupling, direct acoustics, reverberant chambers, and loudspeakers.

INTRODUCTION

For most spacecraft and many of their components, acoustic testing is required to achieve flight qualification. For several decades, reverberant acoustic testing has been the standard method for qualifying flight hardware in acoustic environments. In most test chambers, the controlled acoustic field is predominantly diffuse, except at low frequencies. The diffusivity of a chamber can be assessed by evaluating the density of resonance peaks, which should be closely spaced relative to their associated bandwidth. The frequency below which this condition is not met - the cut-off frequency - can be estimated using the Schroeder equation. For instance, in the JPL acoustic chamber (~10,000 ft³), the estimated cut-off frequency is approximately 150 Hz, while in a smaller chamber (~1,000 ft³), it increases to ~350 Hz. Consequently, for frequencies below the cut-off, the accuracy of acoustic qualification is questionable due to the presence of standing waves. These standing waves can couple with acoustically responsive structural modes, leading to increased structural responses - a phenomenon explored in detail by Kolaini et al. in several studies [1-4].

In recent years, Direct Field Acoustic (DFA) testing has emerged as an alternative for flight hardware qualification. The first reported application was conducted by Scharton et al. during the QuikSCAT spacecraft qualification [5]. Due to scheduling constraints, an array of speakers was used to generate the required acoustic environment directly around the spacecraft. However, at the time, the

characteristics of the induced acoustic field were not thoroughly examined. Since then, DFA testing has been used in many flight qualification tests, primarily employing a Single-Input-Single-Output (SISO) control scheme [6].

DFA testing offers several advantages, particularly in scheduling, as it allows acoustic testing to be conducted at the spacecraft assembly site, eliminating the need for transportation to a separate test facility. However, the effectiveness of DFA testing is strongly influenced by the control strategy, test setup, speaker layout, microphone placement, and the hardware being tested [6]. Several DFA characterization studies conducted at JPL compared DFA-generated acoustic fields with those in a reverberant acoustic chamber. Significant differences in structural responses between the two methods led to efforts advocating for improvements in DFA control strategies [1,4]. These discussions, particularly with the DFA service provider, emphasized the need to transition from SISO to a Multi-Input-Multi-Output (MIMO) control approach [7]. At early stages of the DFA testing, often tests were conducted with limited knowledge of the generated acoustic field, ad hoc methods were frequently used to achieve the desired sound environment. The development of NASA-HDBK-7010, led by the author in collaboration with NASA and the broader space community, provided the first set of guidelines for DFA testing. This handbook, which compiles relevant research up to its publication date, is currently undergoing revision.

Since the release of NASA-HDBK-7010, numerous flight hardware qualification tests have been conducted with advancements in speaker technology and DFA control systems [8-14]. The traditional MIMO control approach has been further refined using modern optimal adaptive control, minimizing control errors in a least-mean-squared-error (LMSE) sense while optimizing the power drive spectral density matrix (SDM). Additionally, an adaptive MIMO vibration control system has been developed to modify the initial SDM reference specification [15-18]. A multi-SISO control scheme has also been implemented to enhance field diffusivity within the DFA test volume [19-20].

More recently, a new loudspeaker technology known as Neutron has been introduced, designed to independently achieve launch-level sound pressure levels while approximating an ideal diffuse acoustic field - akin to an infinite number of incoherent sources [13-14]. This system aims to produce a DFA test environment with high coherence and field uniformity. Recent studies have validated its ability to eliminate standing waves and further characterize the generated acoustic field, including vertical coherence and field uniformity.

This paper presents a review of structural responses and sound pressure levels obtained from DFA tests using earlier SISO (or MISO) control systems versus those conducted with MIMO control strategies. Additionally, it discusses the preliminary results of recent DFA tests conducted at JPL - initiated by the author and directed by Dr. Michael Van Dyke - in collaboration with two vendors. These tests, designed to independently assess the quality of the acoustic field and structural responses, highlight significant advancements in DFA testing. The results aim to provide the broader aerospace community with valuable data for independent assessment and decision-making. Finally, this paper outlines recent advancements in DFA testing and summarizes the benefits of the method, along with potential improvements applicable to both DFA and reverberant acoustic testing.

A Review of DFA Testing Results

For many years after its inception, DFA testing was performed using a SISO or Multiple-Input-Single-Output (MISO) control system. Several years ago, a series of tests were conducted at JPL using eight control microphones in different configurations. The sound field within the speaker array was

controlled to an overall sound pressure level (OASPL) of up to 145 dB, though most test runs were performed at 140 dB. In addition to the eight control microphones, another eight microphones were distributed within the test volume to measure spatial variations in sound pressure levels (SPLs). Furthermore, a 36-microphone array - quickly assembled for the tests - was deployed at multiple locations to capture detailed SPL variations within the test volume (Figure 1).

The microphone array consisted of a rubber net attached to a frame, with microphones secured to the net in an approximately 8×8-inch grid pattern (Figure 1c). Small neoprene pieces were used to hold the microphones in place, minimizing potential vibration-induced coupling effects and reducing extraneous noise.



Figure 1: (a) Speaker and woofer arrangement captured with a wide-angle camera, (b) speaker testing volume used in JPL tests, and (c) microphone array setup.

A simple test article was used to evaluate structural responses under both DFA and RFA conditions (Figure 2). The test article was instrumented with a series of triaxial accelerometers. Since the inception of DFA testing, concerns regarding the non-uniformity of sound pressure fields produced by loudspeaker arrays have been widely discussed within the community [1-7]. Figure 3 compares SPLs measured using several response microphones during DFA and RFA testing. Significant variations in SPLs, particularly from a few tens of Hz to several hundred Hz, were observed in DFA tests (Figure 3). These tests employed a SISO control system to regulate the DFA acoustic field (for more details, see references [1, 4, 6, 7]).

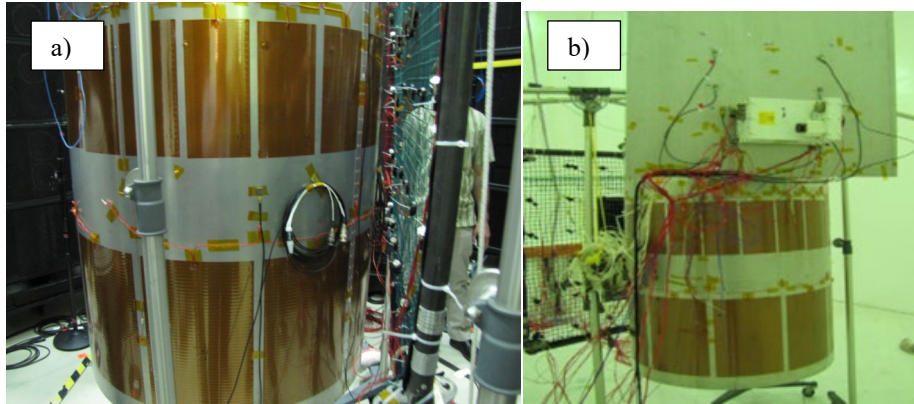


Figure 2: Aluminum panel with an electronics box and force gauges installed at the box/panel interfaces. A 3-ft cylindrical test article was also positioned within the speaker array for DFA testing (a) and later tested in JPL's reverberant chamber (b).

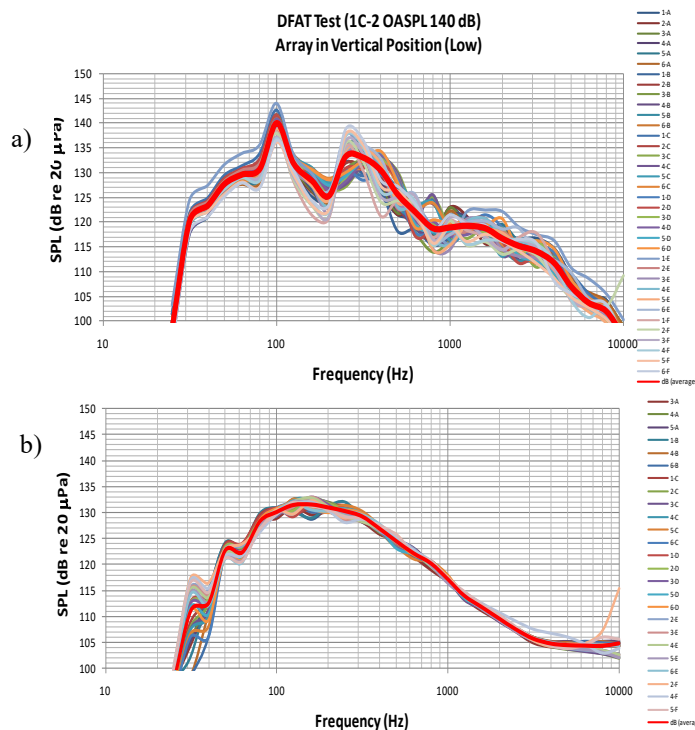


Figure 3: SPLs measured in DFA (a) and RFA (b) tests. The average SPL across all microphones in the array is also shown. The array was positioned identically with respect to the test articles in both tests.

Structural responses recorded from several accelerometers at different locations on the test article during SISO-controlled DFA and RFA testing are shown in Figures 4a and 4b, respectively. These results highlight key differences between the two acoustic test methods, which were extensively discussed in previous studies. The non-uniform SPL distribution observed in DFA testing (Figure 3a) led to significant variations in structural responses (Figures 4a and 4b). Notably, structural responses were significantly higher in DFA tests than in RFA tests for the same test articles and target SPLs. This discrepancy was primarily attributed to the presence of acoustic standing waves in DFA testing, as discussed in previous work by Kolaini [1-3]. These results ultimately led the author to advocate for

transitioning away from SISO control systems.

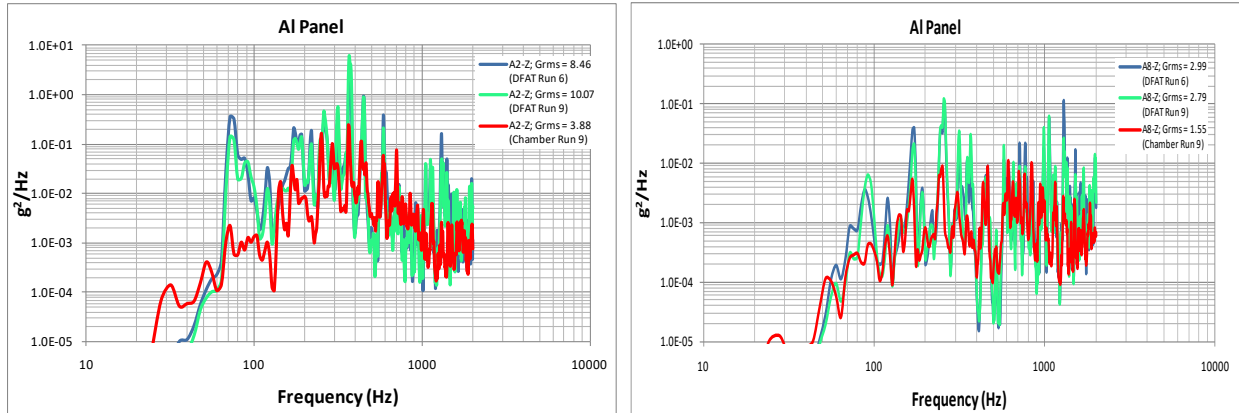


Figure 4: Structural acceleration responses measured at two locations in DFA testing (green and blue curves) and RFA testing (red curves). Clear differences between the two test methods under identical conditions are evident.

A second, more extensive DFA test campaign was conducted at the Johns Hopkins Applied Physics Laboratory (APL) from July 23-25, 2015. A third set of tests was later performed at APL using improved speaker technology and advanced control schemes [21-23]. In these tests, up to 16 control microphones were used in various configurations to regulate the sound field, achieving an OASPL of 140 dB. Additionally, eight monitor microphones were placed within the test volume to assess spatial SPL variations. A 36-microphone array was also deployed at multiple locations to capture detailed SPL distributions.

A key difference between the JPL and APL tests was the control system. The APL tests incorporated both SISO and MIMO control schemes [7], providing a more sophisticated approach to sound field generation. Figure 5 illustrates the DFA test cavity at APL, formed by the speakers, 36-microphone array, and linear microphone array. The 36-microphone array was used to assess spatial variations in the sound field for both SISO and MIMO control schemes, while the linear array was deployed to measure SPLs across the speaker arrangement and along the vertical axis.

Figure 6 compares the predicted first radial mode shape with measured acoustic standing waves at approximately 93 Hz (SISO) and 95 Hz (MIMO). Differences in mode shapes near the speakers in MIMO results likely stem from acoustic field distortions due to pressure measurements taken close to the sound sources. Additional measured and predicted acoustic standing waves for both MIMO and SISO control schemes are detailed in references [1, 4].

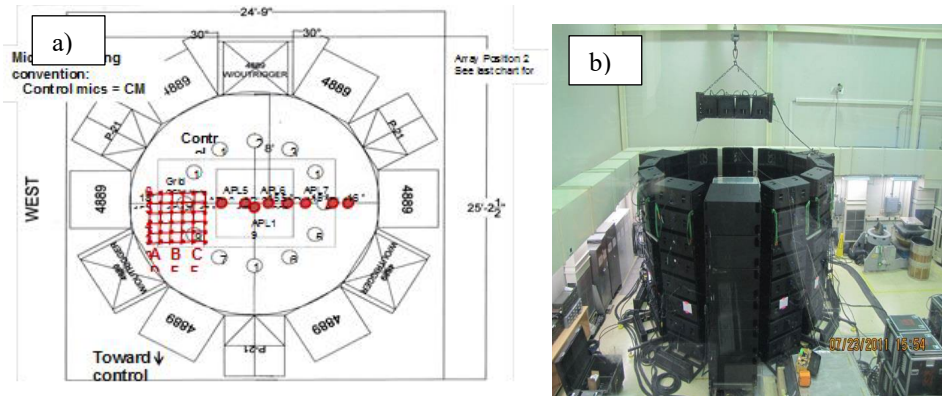


Figure 5: (a) APL speaker and woofer arrangement with control microphones, microphone array, and linear array. (b) Photograph of the APL DFA test setup.

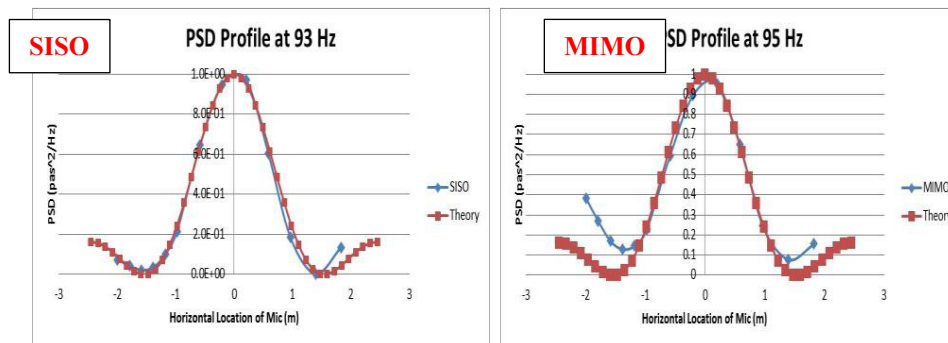


Figure 6: Predicted radial acoustic mode shape (~ 93 Hz) correlated with DFA test data obtained using SISO and MIMO control schemes.

In recent months, three additional acoustic tests were conducted at JPL. The primary objective was to characterize the acoustic field generated by loudspeaker arrays from two different vendors using current DFA methodologies. JPL specified the test space, test articles, test profiles, and data collection requirements to facilitate an independent assessment of recent advancements in DFA testing. These tests were also compared against reverberant chamber testing to evaluate progress over the past several years.

This paper presents high-level SPL and structural response data from these tests, with more detailed analysis reserved for future publications. Figures 7a and 7b show SPLs measured using control microphones and microphone arrays (with and without test articles) for vendor 1's setup, speaker technology, and control strategy. Figures 8a and Figure 8b present SPLs obtained from vendor 2's test configuration using their latest technologies. While both tests exhibit similar trends, particularly for control microphones, the measured SPLs have more scatter across all frequencies. Notably, Vendor 1's SPLs are below the nominal level, while Vendor 2's SPLs are higher above a couple of hundred Hz.

For comparison, Figure 9 presents SPLs measured in JPL's reverberant chamber. Above approximately 150 Hz, SPL scatter was lower than in DFA tests. However, the chamber did not fully meet the required SPL levels above ~ 2000 Hz. High-frequency limitations are common in acoustic chambers, though JPL has successfully addressed this issue by augmenting chamber testing with

additional loudspeakers positioned at the chamber's corners, separately controlled from the main voice coil system.

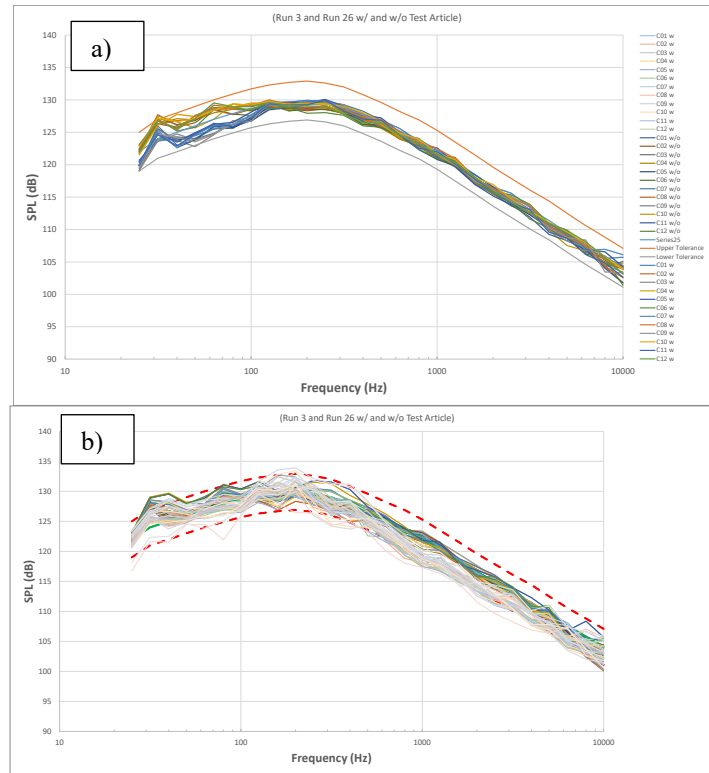


Figure 7: SPLs measured using control microphones using Vendor 1's test setup. (b) SPLs measured using a microphone array positioned at various locations within the DFA test volume.

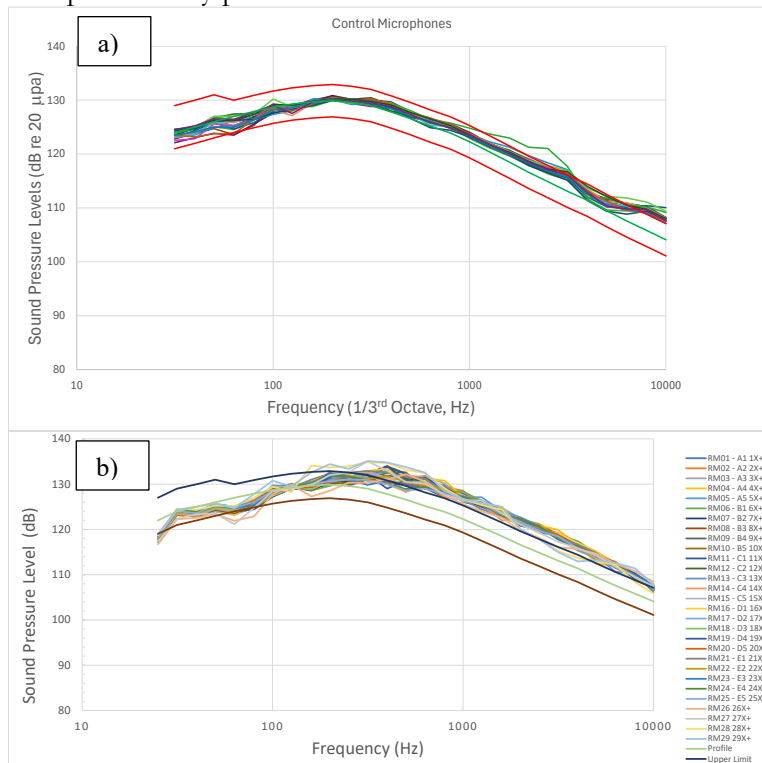


Figure 8: SPLs measured using control (a) and response (b) microphones using Vendor 2's test setup.

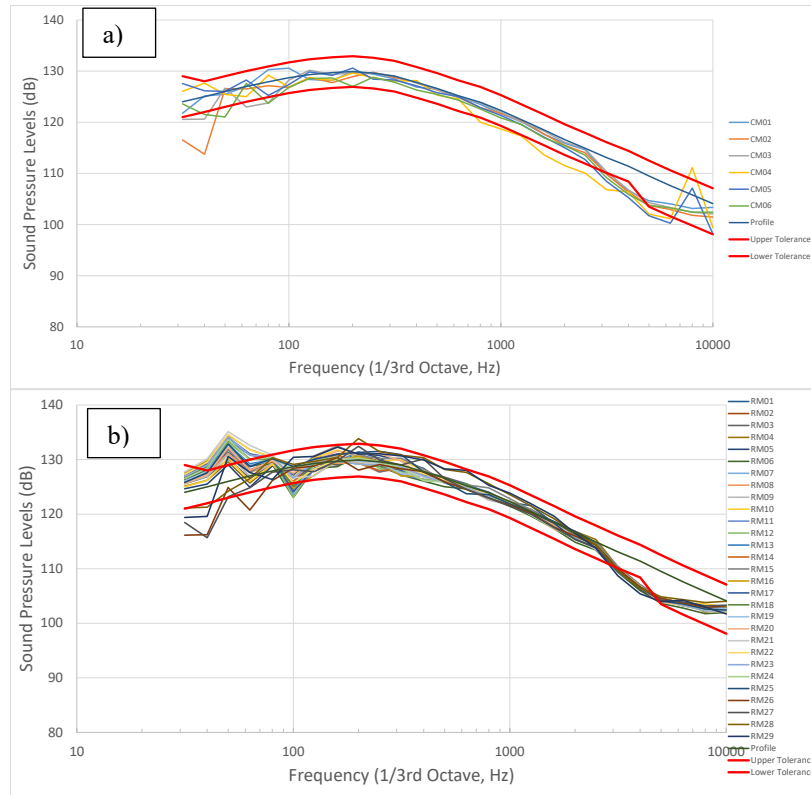


Figure 9: (a) SPLs measured using control microphones in JPL’s reverberant chamber. (b) SPLs measured using the response microphone array.

Finally, the structural responses from handful of accelerometers positioned on the test article are plotted in Figure 10. To compare the differences in structural responses, we computed maximum and minimum of all accelerometers on the test article for DFA as well as reverberant tests. As shown in this Figure the structural maximum and minimum responses show similar trend across all frequencies between three tests. The following observations are made from these plots: 1) the control microphone show a tight SPLs measured by all control microphones, including those at low-frequency region of the spectrum for two vendors’ DFA tests. Even though the scatter in SPLs below about 120 Hz are wider than higher frequencies, the results show standing waves within the acoustic field are minimized.

Based on a quick look at the recent JPL test data, the results demonstrate that modern DFA methods can generate sound fields and structural responses comparable to reverberant chamber testing. Additionally, DFA testing offers advantages in minimizing acoustic standing waves - previously a significant issue in SISO-controlled DFA tests and in reverberant chambers. Future publications will provide a more detailed analysis of these findings.

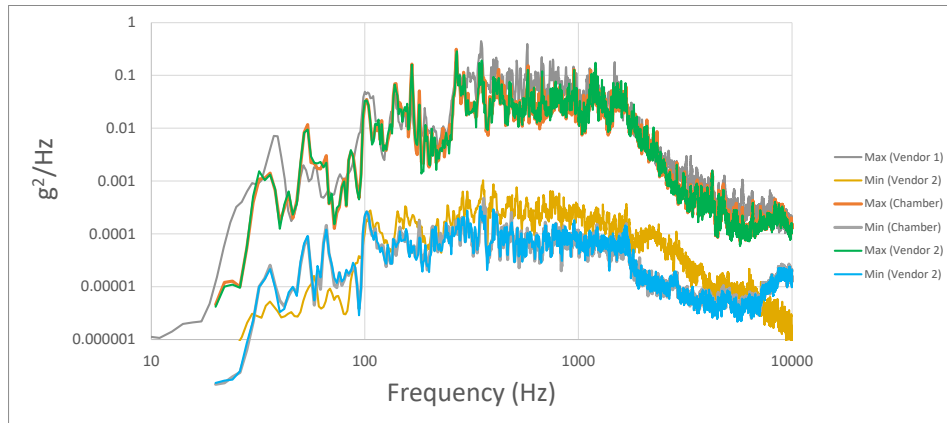


Figure 10: Maximum and minimum structural acceleration responses from Vendor 1, Vendor 2, and reverberant chamber tests.

SUMMARY

Since the inception of DFA testing, significant progress has been made in producing SPLs that instill confidence in using this method to qualify large flight hardware for acoustic environments. It is evident that the SISO control system does not provide acceptable SPLs and should no longer be used by the community. Since the JPL tests conducted several years ago, advancements in MIMO control systems have significantly improved DFA testing. More recent developments in loudspeaker technology and control methods have further enhanced DFA testing capabilities.

One of the most notable improvements is that, when properly controlled, acoustic standing waves in DFA test setups are minimized. This provides a distinct advantage over chamber testing, where reducing standing waves remains a significant challenge. Another key advantage is that DFA methods can generate sound fields at higher frequencies that meet most test requirements, whereas chamber testing may require additional techniques to achieve the same high-frequency coverage.

Despite these advancements, several questions remain. While chamber sound fields - despite their challenges - are well understood and typically diffuse above the Schroeder cut-off frequency, DFA-generated sound fields may not always provide the necessary level of diffuseness, and scattered sound fields may still persist. Another concern relates to structural responses: in some cases, SPLs have varied significantly, yet structural responses have remained similar. This contradicts the assumption that acoustic tests are linear - meaning that if the acoustic pressure changes, the structural response should change proportionally. These discrepancies warrant further investigation. Similarly, RFA testing has its own challenges, including minimizing standing waves and improving high-frequency control to meet requirements.

As part of the ongoing revision of Handbook 7010, one or two key parameters are being considered for inclusion to ensure consistent sound field and structural response characteristics across different control systems and technologies. Specifically, coherence in the radial and vertical directions, as well as the diffuseness of the sound field, will be evaluated. More detailed results from the three recent acoustic tests provide additional insights that may benefit the broader community.

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BIOGRAPHIES

Dr. Ali R. Kolaini has been a Member of the Technical Staff at JPL since 2005. He currently serves as a Principal Engineer and Group Supervisor of the Environment Requirement Engineering (ERE) group within the Reliability Engineering and Mission Environmental Assurance Office. Before his role as ERE Group Supervisor, he was the Supervisor of the Dynamics Environments Group in the Mechanical Systems Division for several years. Prior to joining JPL, Dr. Kolaini was an Engineering Specialist at The Aerospace Corporation and an Associate Professor at the University of Mississippi. He also holds the position of Deputy Tech Fellow for the NASA Engineering and Safety Center (NESC) Loads and Dynamics discipline. Dr. Kolaini earned his B.S. degree in Mechanical Engineering from Lawrence Technological University and his M.S. and Ph.D. in Mechanical Engineering from the University of California, Santa Barbara. He has more than 30 years of experience in the fields of vibration, shock, and acoustics.

Dr. Dexter Johnson is the NASA Technical Fellow for Loads and Dynamics, supporting the NASA Engineering and Safety Center. He works at the NASA Glenn Research Center (GRC) at Lewis Field in Cleveland, Ohio, though employed by the NASA Langley Research Center in Hampton, Virginia. He initially joined NASA in 1990 at the GRC as an Aerospace Research Engineer where he was involved in the development and application of Magnetic Suspension Technology to Advanced Aerospace Turbomachinery. He is the inventor of the Adaptive Variable Bias Control method for power-saving operation of Active Magnetic Suspension Systems. Later he held positions as the acting Deputy Chief of the Life Prediction Branch and the acting Chief of the Controls and Dynamics Technology Branch. In 2006, he became the Chief of the Structural Systems Dynamics Branch, and he served as the Chief of the Structural Dynamics Branch at GRC from 2014 – 2018. He became an American Institute of Aeronautics and Astronautics Associate Fellow in 2018. He graduated from the State University of New York at Buffalo with a B.S. in Aerospace Engineering in 1987, and a M.S. and a Ph.D. in Mechanical Engineering, in 1989 and 1995, respectively.