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DIRECT FIELD ACOUSTIC TESTING (DFAT)

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FOREWORD

This NASA Technical Handbook is published by the National Aeronautics and Space Administration (NASA) as a guidance document to provide engineering information; lessons learned; possible options to address technical issues; classification of similar items, materials, or processes; interpretative direction and techniques; and any other type of guidance information that may help the Government or its contractors in the design, construction, selection, management, support, or operation of systems, products, processes, or services.

This NASA Technical Handbook is approved for use by NASA Headquarters and NASA Centers and Facilities. It may also apply to the Jet Propulsion Laboratory and other contractors only to the extent specified or referenced in applicable contracts.

This NASA Technical Handbook establishes a common framework for consistent practices across NASA programs, addressing the application of the direct field acoustic test (DFAT) method for acoustic testing of spaceflight hardware.

DFAT is a relatively new aerospace acoustic testing method, first used for acoustic qualification of a spacecraft in the late 1990s. DFAT has certain advantages over the conventional reverberant field acoustic testing (RFAT) approach, in particular, reduced facilities development and maintenance costs and portability of the acoustic test equipment. The major disadvantages are a lack of coherent acoustic field that results in spatial variation; and the current technology limitation of not being able to produce sound pressure level (SPL) in excess of 147 dB. Even with the advancement of the control systems using DFAT for acoustic qualification testing, the pressure field and measured structural responses can differ significantly from an RFAT test, even if the control microphones are kept within the test tolerances specified. Significant advances in the DFAT control systems have been made in the last few years, which alleviate many of the previous concerns with this test method. However, application of DFAT varies widely among the NASA Centers and their contractors. Therefore, this NASA Technical Handbook provides the best current guidelines for implementation of the DFAT test method.

Requests for information should be submitted via "Feedback" at https://standards.nasa.gov. Requests for changes to this NASA Technical Handbook should be submitted via MSFC Form 4657, Change Request for a NASA Engineering Standard.

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Ralph R. Roe, Jr. NASA Chief Engineer	Approval Date

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DIRECT FIELD ACOUSTIC (DFAT) TESTING

1. SCOPE

1.1 Purpose

Direct field acoustic testing (DFAT) is a method of exposing space hardware to high intensity acoustic levels utilizing the direct field generated by an array of acoustic sources, typically loudspeakers. The DFAT methodology presents a number of significant logistical advantages over conventional RFAT in a dedicated acoustic chamber. However, certain technical limitations and nuances, variability in practice, and technical maturity relative to RFAT make it incumbent for a program to understand and carefully balance the benefits and limitations of the use of DFAT with the needs of the program.

The purpose of this NASA Technical Handbook is to provide information and guidelines on the applicability and use of DFAT testing. This NASA Technical Handbook is intended to provide an approach that may be consistently followed by those who choose to use this method for qualifying flight hardware for acoustic environments. The NASA Technical Handbook describes the following:

a. DFAT testing background.
b. Configuration.
c. Instrumentation, test control, and data acquisition and reduction.
d. Theoretical considerations for designing a DFAT test setup.
e. Guidelines for DFAT testing.

The information provided herein is intended to guide engineers and engineering managers in making more informed decisions in the planning and execution of DFAT test activities. Additionally, the fundamental basis is provided for the development of procedures to facilitate execution of the DFAT testing process based on standards and recommendations developed in the past decade.

1.2 Applicability

This NASA Technical Handbook is applicable to all acoustic tests using the DFAT method for National Aeronautics and Space Administration (NASA) flight and non-flight hardware, including but not limited to, built-up spacecraft, spacecraft experiments and components, aircraft and launch vehicle equipment, launch vehicle pads, and ground support equipment (GSE).

This NASA Technical Handbook provides baseline information for designing coherent and consistent test planning, setup, and implementation approach for DFAT testing. The use of this NASA Technical Handbook is recommended for engineers and managers within the NASA

Centers and NASA contractor organizations for acoustic acceptance, protoflight, or qualification testing using the DFAT test method. The applicability of this NASA Technical Handbook is to provide the means of planning and testing equipment and structures to wide-frequency acoustic induced vibration environments. The test equipment for acoustic testing, as well as details on test implementation are provided in this NASA Technical Handbook. It is expected that the user of this NASA Technical Handbook will have a mid- to high-level of understanding of acoustic testing techniques in the aerospace industry with commensurate education. The users of this NASA Technical Handbook are to apply the recommended steps with care and with an understanding of their purpose and limitations. Since the test equipment can be brought onto location without the necessity of transporting test articles, this method can present considerable cost savings and schedule flexibility where there is not the availability of an on-site acoustic chamber. Without the need of a reverberant chamber to produce the desired sound levels, DFAT testing can conveniently be performed to meet programmatic needs, if proper steps are taken to ensure this testing method provides the intended objectives and meets the flight hardware requirements.

Given the aerospace industry's body of knowledge and successful heritage based in RFAT, some comparisons will be presented between DFAT and RFAT. The primary purpose of this NASA Technical Handbook is to define the current state of DFAT and to highlight its strengths and potential technical problems that users need to know before making a decision to perform a DFAT test. Future revisions of this NASA Technical Handbook will provide updates to new developments and improvements, as the community continues to address technical issues with this method of acoustic testing.

This NASA Technical Handbook is approved for use by NASA Headquarters and NASA Centers and Facilities. It may also apply to the Jet Propulsion Laboratory (JPL) and other contractors only to the extent specified or referenced in applicable contracts.

This NASA Technical Handbook, or portions thereof, may be referenced in contract, program, and other Agency documents for guidance. When it contains procedural or process requirements, they may be cited in contract, program, and other Agency documents.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section are applicable to the guidance in this NASA Technical Handbook.

2.1.1 The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 Non-use of specifically designated versions shall be approved by the responsible Technical Authority.

The applicable documents are accessible at https://standards.nasa.gov or may be obtained directly from the Standards Developing Body or other document distributors.

2.2 Government Documents

NASA

NASA-STD-7001 Payload Vibroacoustic Test Criteria

2.3 Non-Government Documents

None.

See Appendix A for reference documents.

2.4 Order of Precedence

This NASA Technical Handbook provides guidance for the DFAT but does not supersede or waive established Agency requirements/guidance found in other documentation.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

APL	Applied Physics Laboratory
ASD	auto-spectral density
BEM	boundary element method
CG	center of gravity
DFAT	direct field acoustic testing
FEM	finite element modeling
GSE	ground support equipment
IEST	Institute of Environmental Sciences and Technology
JPL	Jet Propulsion Laboratory
MIMO	multi-input-multi-output
NASA	National Aeronautics and Space Administration
OASPL	over-all sound pressure level
PSD	power spectral density
RFAT	reverberant field acoustic testing
RMS	root mean square
SDM	spectral density matrix
SISO	single-input-single output
SMA	Safety and Mission Assurance
SPL	sound pressure level
STE	special test equipment

3.2 Definitions

Absorption Coefficient (Absorptivity of a Surface/Room): At a given frequency of a surface of an acoustically absorbing material, the fraction of the randomly incident sound power which is absorbed.

Acoustic or Sound Field: A region of elastic medium (such as air) containing fluctuating sound pressure waves generated by acoustic sources. Note: In general, an acoustic field is comprised of a superposition of waves arriving directly from the sources and those having undergone one or more reflections.

Antinodes: The loci (points, lines, or surfaces) in a standing wave system which have maximum amplitude of pressure or velocity.

Auto-Spectral Density (ASD): The Fourier transformation of the autocorrelation function. Note: The area under an auto spectrum represents the mean-square value of the signal.

Critical or Diffuse-Field Distance: Distance from the acoustic center of a sound source at which the mean-square sound pressure of the direct field in a specified direction is equal to the mean-square sound pressure of the reverberant sound in the room containing the source.

Diffuse Field: A sound field which has statistically uniform energy density and in which all directions of sound wave propagation are equally probable.

Direct Field: That portion of a sound field which arrives from the sound source without any reflections from boundaries, such as walls, ceilings, floors, or other reflective surfaces.

Direct Field Acoustic Test: A method of high intensity acoustic testing in which the direct field generated by an array of controlled acoustic sources is used to expose a test article to specified acoustic levels.

Far Field: At a given frequency, that part of a sound field a sufficient distance away from its source such that the phase difference between the acoustic particle velocity and the acoustic pressure is essentially zero. Note: Characteristically, the far field SPL, under free field conditions, decreases by 6 dB for each doubling of the distance from the source.

Free Field: Field in a homogeneous, isotropic medium (such as quiescent, isothermal air) free from boundaries.

Multi-Input-Multi-Output (MIMO): MIMO control scheme is the use of multiple channels at both the transmitter (speakers) and receivers (microphones) to improve the performance of the acoustic field within the DFAT volume.

Near Field: The region where the pressure and velocity are out of phase (i.e., energy is being sloshed back and forth). Note: The geometric near field occurs at distances comparable to the source dimensions and the spacing of multiple sources. The geometric near field is characterized by interference patterns created by constructive and destructive interference of pressure waves radiating from geometrically dispersed locations on the surfaces of the source.

Node: Point, line, or surface in a standing wave where some characteristic of the wave field has essentially zero amplitude (also see Partial Node).

Over-all Sound Pressure Level (OASPL): Ten times the base ten logarithm of the ratio of the sum of the time averaged mean-square pressure values, for all n^{th} octave bands over the entire test frequency range, to the square of the referenced pressure. It is expressed in dB relative to the reference sound pressure.

Partial Node: Point, line, or surface in a standing wave system where some characteristic of the wave field has a minimum amplitude differing from zero.

P95/50: The level of the maximum expected environment used that is not exceeded on at least 95 percent of flights, and estimated with 50-percent confidence (P95/50 level). Note: These statistical estimates are made assuming a lognormal flight-to-flight variability having a standard deviation of 3 dB, unless a different assumption can be justified. Considering the stated assumption, the P95/50 level estimate is 5 dB above the estimated mean (namely, the average of the logarithmic values of the spectral levels of data from all available flights).

Power Spectral Density (PSD): In statistical signal processing, the limit, as the frequency bandwidth approaches zero, of mean-square amplitude divided by bandwidth. Note: For typical discrete processing using finite window averaging, the constant frequency bandwidth ranges from 2 to 5 Hz. The oscillatory function may be any time-dependent parameter. For example, the unit for sound pressure spectral density is Pa^2/Hz (SI) or psi^2/Hz (English).

Random Incidence: Incidence of sound waves successively from all directions with equal probability.

Reverberant Field: That portion of a sound field that arrives from the sound source after going through multiple reflections from boundaries, such as walls, ceilings, floors, or other reflective surfaces. Note: A reverberant field is not necessarily diffuse. See definition for Diffuse Field and section 4.1.

Reverberant Field Acoustic Test: A method of acoustic testing in which the reverberant field within a chamber with highly reflective surfaces, generated by one or more acoustic sources, is used to expose a test article to specified acoustic levels. Note: In general, the reverberant field within the chamber consists of a superposition of the characteristic acoustic modal responses of the chamber.

Simulation: The reproduction of a physical event using artificial means in a laboratory environment.

Single-Input-Single-Output (SISO): SISO control scheme is the use of single channel at the transmitter (speakers) and single channel at the receiver (microphones) to control the acoustic field within the DFAT volume.

Sound Pressure: The total instantaneous pressure at a point in space, in the presence of a sound wave, minus the static pressure at that point.

Sound Pressure Level (SPL): The SPL, in decibels, is equal to 20 times the base 10 logarithm of the ratio of the time averaged root-mean-square (RMS) sound pressure to the reference pressure (reference = 20 μPa = 2.9E-9 psi).

Standing Wave: Periodic wave having a fixed amplitude distribution in space resulting from interference of progressive waves of the same frequency and kind. Note: Such waves are characterized by the existence of nodes or partial nodes and antinodes that are fixed in space.

Vibroacoustics: The term that describes acoustic- and hydrodynamic-induced vibrations in structures.

Wave Interference: Phenomenon that results when waves of the same or nearly the same frequency generated from multiple sources are superposed and is characterized by a spatial or temporal distribution of amplitude of some specified characteristic differing from that of the individual superposed waves.

White Noise: A sound wave whose spectrum is continuous and uniform as a function of frequency.

4. BACKGROUND

4.1 History

For most spacecraft and many of their acoustically responsive components, acoustic testing is required to attain flight qualification. Acoustic chambers provide a reverberant field with diffuse characteristics, except at low frequencies, and have been used to qualify flight hardware to launch acoustic environments for the past several decades. It has only been relatively recently that the DFAT testing method was first used for the qualification testing of the QuikSCAT spacecraft (Scharton and others, 1999). This method was first proposed by J. Van Houten (1966) for acoustic testing of large structures that would not fit in most conventional reverberant chambers. Since the QuikSCAT spacecraft test, DFAT testing has increasingly been used as an alternative to reverberant chamber testing, and significant advancements have been made in source acoustic power, test article size capability, and digital control technology (Larkin & Walen, 1999); (Lee, Y.A. & Lee, A.L, 2000; IEST, 2000); (Larkin, 2000); (Larkin & Smallwood, 2003, 2004). For example, the MIMO control technology used in state-of-the-art DFAT tests is a great improvement over the control used in the QuikSCAT test. DFAT testing is now often provided by vendors who supply test planning, equipment, power, and personnel for conducting a test at the client's site.

The DFAT testing has some advantages over RFAT testing such as the ease of access to and lower costs of equipment needed to generate the acoustic field, reduced facility and overall infrastructure costs, and schedule flexibility derived by the ability to set-up in a variety of locations (Larkin, 2000). However, the characteristics of a direct field in a given test are strongly affected by test setup factors, especially the physical arrangement of the acoustic sources, the control method, placement of control microphones, and the size and position of the test articles, some of these are frequency dependent (Van Dyke, 2008; Kolaini & O'Connell, 2008). Even though a very good approximation of the specified acoustic spectrum by the average of the discrete field points at the control microphone locations can be demonstrated, the ability to shape the characteristics of the entire acoustic field outside those discrete locations is limited. Detailed measurements have shown that there is a propensity for the existence of significant spatial gradients across the frequency spectrum due to what are believed to be the combined effects of wave interference and standing waves. (Kolaini & O'Connell, 2008; Kolaini and others, 2009; Maahs, 2009, 2010, 2012; Kolaini and others, 2012; Van Dyke & Peters, 2010; Larkin & Hayes, 2012; Rouse and others, 2011). Unlike RFAT testing, well-developed industry standard guidelines do not exist for direct DFAT testing. Recent advances in control methodology have been shown to mitigate the spatial effects of wave interference to a degree, but spatial variability is still prominent, particularly in certain frequency bands that are most likely associated with acoustic standing waves (Kolaini & O'Connell, 2008; Kolaini and others, 2012) and interference patterns (Van Dyke & Peters, 2010). 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 intended purpose of this NASA Technical Handbook is to provide testing guidelines for DFAT.

The structural responses induced by DFAT testing can differ significantly from those induced by a diffuse field, i.e., reverberant chamber testing (Kolaini & O'Connell, 2008; Kolaini and others, 2009, 2012). The differences in these two methods of acoustic testing are described by Kolaini and others (2012), where physical parameters attributed to them at lower frequencies are delineated. One of the parameters that strongly influences structural responses is the acoustic standing wave coupling with the structural modes (Kolaini & O'Connell, 2008; Kolaini and others, 2012; O'Connell & Hausle, 2005; O'Connell, 2007). The differences in the structural responses for a different case measured in RFAT and DFAT are reported to be insignificant, whereas the measured sound pressures between these methods of testing for this case were significant (Maahs, 2009, 2010, 2012). The contrast between these results and those discussed earlier may be due to the acoustically responsive structural modes not coupling with acoustic standing waves and/or the acoustically responsive structures being placed in less energetic part of the acoustic standing waves.

To discuss the acoustic field generated by loudspeakers using the SISO control system, a series of tests was performed at JPL with involvement from several institutions. A simple aluminum panel with an electronic box attached to it and an aluminum cylinder were used as test articles. These articles were also acoustic-tested at JPL's reverberant chamber to the same acoustic specification levels as in the loudspeakers' test. The differences in the acoustic fields generated by the speakers and reverberant acoustic fields and their impacts on the structural responses are significant and are discussed by Kolaini and others (2012). The SISO method is no longer recommended for DFAT testing.

Similar activities were repeated at Johns Hopkins University's Applied Physics Laboratory (APL) in 2010 and 2012. Significant improvements have been made in controlling the acoustic field within the speakers' volume using MIMO control scheme. This method of controlling the acoustic field is discussed in section 7 in some detail and by Larkin and Goldstein (2010). The recent development and the application of MIMO acoustic control applied to DFAT testing provide much improved methodology over the SISO control system (Larkin & Goldstein, 2010; Underwood & Keller, 2003). Even though the MIMO control system helps to reduce the interference patterns within the testing volume, the acoustic standing waves and their impact on the structural responses should be assessed during a pre-test field evaluation prior to qualification of flight hardware (see section 8).

4.2 Application

DFAT provides an option to qualify spacecraft for the flight acoustic environments while avoiding significant schedule impacts, handling risks, and costs associated with a RFAT. DFAT testing is currently used for nearly the same range of applications as reverberant chamber testing, from development testing for the purposes of structural response characterization and risk reduction testing of non-flight articles to qualification and acceptance testing of flight hardware. DFAT testing is applied at any level of assembly, from acoustically sensitive components, subassemblies, and instruments to entire space vehicles including both spacecraft and payload modules. The current DFAT technology is capable of producing broadband sound pressures (2020 kHz) with the OASPL of 145-147 dB for 30 seconds, 142-145 dB for 1 minute, 138-142 dB for an hour, and below 138 dB for 3 hours of continuous loudspeakers operation.

4.2.1 Development Testing

Development testing can be performed on non-flight engineering units either in situ, or at some other facility to investigate the susceptibility to acoustic excitation and can provide significant early design risk reduction value to a program. The portable nature of the DFAT equipment makes it available to anyone who has the facility for the equipment setup and electrical power and can ensure adequate protection of personnel from excessive noise exposure. Characterization of structural response to acoustic excitation is another useful application provided the spatial distribution of the acoustic field is sufficiently defined. By applying a known acoustic spectrum, a well-instrumented structure can be used to determine response of components, derive transfer functions, and extrapolate to higher levels or perform analysis/test model validation. However, response limiting in DFAT tests, conducted for the purpose of qualifying flight hardware, is not recommended until a more thorough development effort of this technique can be carried out.

5. DFAT SOUND GENERATION EQUIPMENT

The specific equipment to be used for each test is determined by the dimensions of the test article, shape and level of the target acoustic specifications, facility layout, and any unique aspects of the test. For example, limited footprint availability, overhead obstructions, other test equipment present, and workflow traffic patterns need to be taken into consideration when planning a test. A DFAT system can be customized to address most requirements.

5.1 Sound Generation Sources (Speakers, Woofers, and Horns)

The basic system components consist of a set of commercial speakers, stereo power amplifiers, and a control system. Early configurations used multiple sets of the "module" arrangement as shown in figure 1, One Speaker System Module (circa 1999 (Larkin & Walen, 1999)). Low-mid-high speakers are arranged into six VA4 (3-way, 80-1000 Hz) cabinets where each cabinet houses two 12-in low-frequency speakers, one 10-in mid-frequency speaker, and one high-frequency compression driver. Four additional SB1000 (Sub, 35-125 Hz) cabinets house two 18-in sub-woofers each and two M4 cabinets (horn, 200-800 Hz) each house a 7-in midfrequency compression driver and horn that is designed to supplement the 200-500 Hz range. The speakers use paper-Kevlar® composite cones, copper coil, and permanent magnet arrangements. The compression drivers use a 4-in diameter metallic diaphragm. All devices are manufactured and assembled to closely monitored tolerances to provide accurate and controlled excursions. In addition, most of the devices have some type of thermal dissipation built-in. Manufacturers all use various materials and driver configurations to provide cooling, increased damping, lower distortion, and reduced coil/magnet size.

Figure 1—One Speaker System Module (circa 1999 (Larkin & Walen, 1999))

Many configurations and much experimentation have taken place since the first DFAT was performed. The effectiveness of the low- to mid-frequency (25 to 700 Hz) devices is dependent on their location and orientation; and, therefore, analytical models should be used to determine their position, as discussed in section 8. In the mid- to high-frequency (~700 Hz to 10,000 Hz), acoustic pressure field measured at 1 m (39 in) directly in front of the cabinets can be as much as 3 to 6 dB higher than in the side fields. This has led to the use of 8 to 16 or more control microphones and special phase tuning for the speaker sets directly in front of a control microphone. The result has been consistent reproduction of uniform SPLs measured by control microphones around the test article. However, significant SPL variations were observed in the testing volume away from these locations. Figure 2, Typical Speaker System Arrangement (circa 2001 (Larkin, 2000)), shows a typical setup that was used in the 2000 to 2003 timeframe.

Figure 2—Typical Speaker System Arrangement (circa 2001 (Larkin, 2000))

The most current acoustic testing setup, figure 3, Current Speaker System Arrangements (Maahs, 2010, 2012), reflects both the newest advances in technology, as well as changes made to reduce the spatial variations observed in earlier DFAT testing. Speaker systems have advanced significantly in recent years, with an emphasis on combining components and enclosure design to produce the most uniform pressure field possible. In earlier DFAT configurations, speaker components were less efficient, and the enclosures that contained them were not designed to work together in the most efficient way possible, making smoothness and consistency of the sound output more difficult. Recent advancements include high frequency compression drivers incorporating beryllium diaphragms, low frequency drivers made with lighter and stronger permanent magnets with higher efficiency and better cooling and new rigid American National Standards Institute rated coupling systems (Larkin & Goldstein, 2010). These advances have provided consistency throughout the entire acoustic test range.

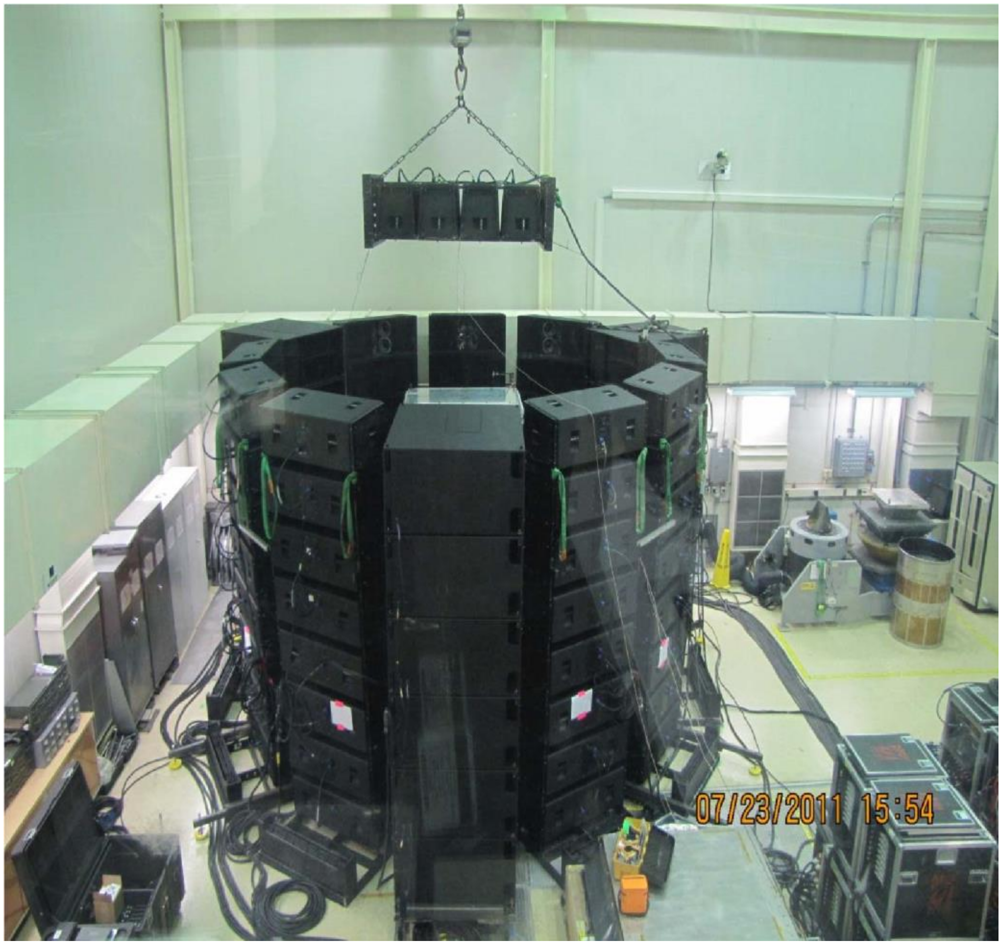


Figure 3—Current Speaker System Arrangements (Maahs, 2010, 2012)

5.2 Amplifiers and Mixers

Powering this set of acoustic sources (section 5.1) is a set of high-powered stereo amplifiers that are in the range of 3000 to 10,000 watts per channel. These amplifiers are controlled by a networked digital control system that monitors and limits the output voltage, power, and temperature of each amplifier. It can also provide various levels of input compression and signal phase delay. In addition, it provides the cross-over network for the speakers and compression drivers by filtering the drive signal and sending the selected frequency ranges to each device. Multiple filter types and shapes are available.

With the transition of sound systems to Class D switching amplifiers, greater performance was achieved over previous DFAT systems. New and more powerful digital amplifiers are capable of outputting more power than ever before (up to 20,000 watts per channel), while becoming increasingly lighter and more efficient (Larkin & Goldstein, 2010). Greater efficiency can also be gained by using more precise cross-over filter networks that generate less phase shift than earlier analog filter networks. In addition to phase, as before, output voltage, current, and temperature limits can be specified for each channel. When networked with a computer-based digital control system, digital amplifiers can be monitored in real-time through customized software specific to each acoustic test. All factors involved in performing a successful acoustic test can be closely monitored to ensure safety and consistent results. For the largest of tests, output power can easily exceed 1 million watts and may be channeled through hundreds of speaker components (Larkin & Goldstein, 2010).

Mixers usually provide a means for combining several inputs, with adjustable gain, into a single output, also with its own gain adjustment. Because of the multiple adjustments available with these devices, an end-to-end calibration is recommended to verify that the gain settings have not been changed before the test. A separate, independent monitoring system is also recommended.

Digital equalizers are usually used as band-pass filters to properly distribute frequency content to each driver or set of drivers. They can also be used to “pre-shape” the drive signal in situations where the controller may not have enough dynamic range, or to provide a more uniform control signal. Since these devices can also provide selective signal gain, it is recommended that an endto-end calibration be performed periodically during a test to verify settings and performance.

6. INSTRUMENTATION, DATA PROCESSING, AND CONTROL SYSTEMS

6.1 Acoustic Test Instrumentation

The types of acoustic and vibration measurement instrumentation used for RFAT testing can also be used for DFAT testing. In general, free-field omni-directional type microphones should be used. Microphones should be selected, positioned, and oriented with protection of the test article in mind. In all cases, instrumentation should be selected with the proper sensitivity and frequency response range required for the test. To do this, the background noise and maximum test SPL should be known and the corresponding transducer output should be matched to the selected signal conditioner.

6.2 Data Processing

All standard types of acoustic and vibration data processing hardware and software can be used for DFAT testing. The sound system contractor will generally provide the control and data acquisition for the control microphones. These data are to be stored as time histories and transformed in real time into the frequency domain. In addition, the data is also to be stored as PSDs and/or n^{th} octave SPLs. The time histories for each channel can then be restored for later post-test analysis and evaluation either in narrow-band or n^{th} octave-band. In addition, the time history data can be reprocessed using different averaging, windowing, blocking, etc. to see the effect on the resulting spectrum. It is also recommended that the data from at least one microphone be acquired by an independent system for verification purposes.

6.3 Sound Field Control Schemes

Control for the direct field environment can be provided by most typical acoustic control schemes. Narrowband and constant bandwidth, closed-loop, digital controllers are preferred.

Early DFAT control was performed by trial and error using a time average of multiple microphones and a manual 1/3rd octave equalizer. Setup was slow and the resulting acoustic field varied considerably, in particular with control microphone locations. Later, control was provided by a programmable Norsonic Real-Time Analyzer and Spectrum Shaper running as part of a closed-loop system. The resulting set-up time was reduced, but the field still varied considerably and the loop-time was long and increased with the number of microphones used. In 2003, a new random vibration controller (Underwood & Keller, 2003) was introduced to control an acoustic test. This led to further development of a front end to convert SPL to acoustic PSD and has the capability of reversing the process. This system allows normal acoustic parameters to be displayed, but the basic control is still provided by the narrow-band random control algorithms. The DFAT acoustic control system has thus evolved into a modern digital controller with all the standard features of a random vibration controller available for acoustic testing.

6.3.1 Control Instrumentation

Multiple control microphones are recommended. An adequate number of control microphones are to be positioned circumferentially around the test article at elevations obtained using analytical predictions. They should be placed no closer than 0.6 m (2 ft) from the test article surface and no closer than 0.9 m (3 ft) from the speakers. The number and spacing of the control microphones should be sufficient to provide an adequate representation of the sound field around the test article, including spatial sound level variations, so that the average sound level of the control microphone field points approximates the true spatial average of the test sound field to be controlled (see section 8 for recommendations). For a test area of similar size to that shown in figure 5, a minimum of 12 control microphones is recommended. Symmetric placement of the control microphones with respect to the loudspeaker array should be avoided in order to minimize the biasing effect of the microphones aligning with wave interference patterns within the test volume. It is also recommended that additional monitor microphones (not included in the control loop) and a microphone array be used to further characterize and document the sound field. These microphones can be moved around during the pre-test checkout to help fully characterize the sound field and to re-position control microphones and increase the number, if needed, to better control the acoustic field.

6.3.2 Narrow Band

It is recommended that users of the DFAT method become familiar and comfortable with the relationships between narrow-band and nth octave-band specifications. The acoustic specification is usually given and entered into the control system in terms of SPL, which, with the new controller, the SPL is internally converted and applied as a PSD. The conversion is to be confirmed and verified before the test. Therefore, the conversion is to be examined and understood by the control personnel so they may verify the PSD prior to testing.

6.3.3 Single-Input-Single-Output and Multi-Input-Multi-Output

Up to a few years ago, DFAT tests were performed using the SISO methodology. The SISO control methodology drives all sources in the loudspeaker array with the same signal. The fully correlated source array generated a highly coherent acoustic field, creating constructive and destructive wave interference patterns associated with any given frequency and resulting in significant spatial variation. The acoustic environment produced by this method is not suitable for diffuse field testing and is not recommended.

The recent development of the MIMO control method for controlling the acoustic field within the DFAT testing volume has provided a much-improved methodology over the earlier practice of using the SISO control approach. MIMO control employs multiple independent drive signals to control multiple reference points in the acoustic field. The control algorithm uses a fully populated spectral density matrix (SDM) that contains the PSD magnitude, phase, and coherence requirements to update all drives simultaneously based on the responses of the independent control channels. Using MIMO control, the user can input magnitude, phase, and coherence specifications with tolerance bands on each. This method is designed to control the response of each control microphone to meet its individual requirement based on the input it receives from each independent drive signal. Typical results from SISO and MIMO Acoustic tests using a mass simulator are shown in figure 4. These results show an incoherent field with minimum variation between control microphones in the case of MIMO control system (Larkin & Goldstein, 2010).

For all flight and GSE hardware acoustic testing using DFAT method, the existing or improved MIMO control method is recommended.

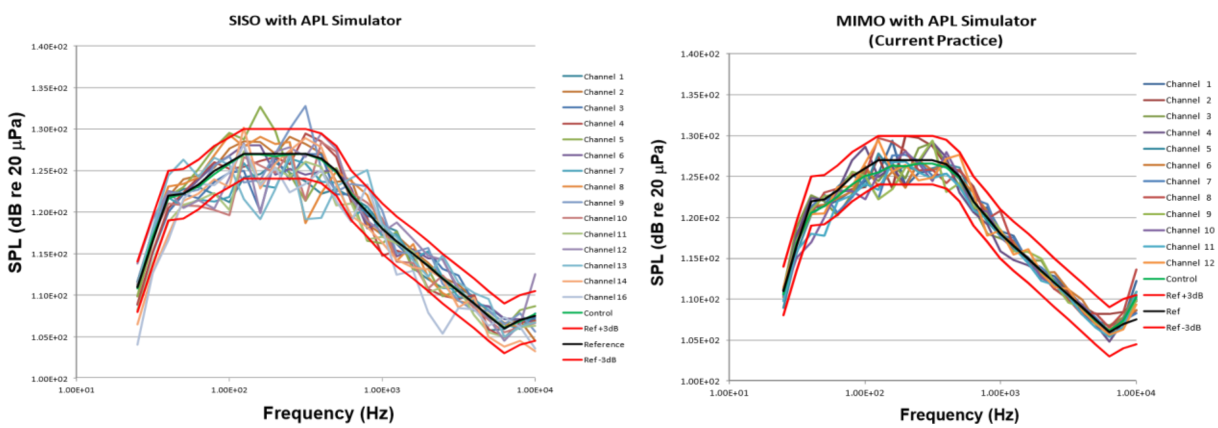


Figure 4—Typical Results from SISO and MIMO DFAT Acoustic Tests Using a Mass Simulator as the Test Article. The MIMO Control Provides an Incoherent Field with Minimum Variation Between Control Microphones.

7. TEST SETUP AND CHECKOUT PROCEDURES

7.1 General Configuration

Various arrangements of speaker cabinets can be used depending on the desired results. A basic configuration for exposing a generic test article on all sides to a specified acoustic environment is to place the test article on a stand, or suspend it from an overhead cable, at least 0.9 m (3 ft) above the floor and surround it with stacks of loudspeakers. Control microphones are to be placed at least 0.6 m (2 ft) away from the surface of the test article and at least 0.9 m (3 ft) away from the front face of the loudspeakers. This is to minimize the influence of test article surface effects and near-field effects from individual loudspeaker units on the control microphone measurements. A distance of at least 0.6 m (24 ft) is to be maintained between control microphones and large reflective surfaces. Outer limits on the distance of loudspeakers from the test article are determined analytically, as discussed in section 8, suitable for each test article.

An additional consideration in the loudspeaker configuration is the need to provide suitable acoustic environment coverage for the top of the test article, particularly if there are large horizontal surfaces on or near the top of the test article, or if acoustically responsive components, such as reflectors and panels, are placed at the top of spacecraft, and if these are not well-excited by grazing sound waves. One option to be considered is an overhead set of loudspeakers that can provide direct normal impingement on the top horizontal surfaces of the test article. An overhead loudspeaker can be supported by a building crane, a portable gantry crane, or a “cherry picker,” supported by a structure built up from the floor. However, according to at least one reference, this approach resulted in over-driving the response of the top surface of the test article in comparison with what would be experienced in a reverberant chamber (Maahs, 2012). According to the same reference, a better result was achieved without overhead loudspeakers by extending the height of the loudspeaker stacks 1.5 m (5 ft) above the height of the test article. In addition, tilting some of the upper level loudspeakers downward resulted in vibroacoustic efficiency closer to that of a reverberant field.

An approximate minimum facility floor space diameter of 7 m (22 ft) in addition to the test article diameter is needed to accommodate a DFAT test. Besides the distance of the loudspeakers from the test article, the additional 7 m (22 ft) includes room for the loudspeaker stacks and required rigging as well as walk space around the perimeter. The height of the facility should allow an additional 4 to 8 m (12 to 25 ft) above the speaker stacks to accommodate an overhead crane. In addition, there should be at least 37.1 to 46.5 m^2 (400 to 500 ft^2) of additional floor space available for amplifier racks, power distribution equipment, staging, and storage.

The control system and data acquisition station is to be located in an adjacent room capable of providing some significant degree of sound reduction. The amount of sound attenuation within the test room depends on a number of variables, and is generally dependent on distance from the source and the ratio of the room's volume to its sound reverberation time. The amount of sound attenuation within the test room depends on a number of variables, and is generally dependent on distance from the source and the ratio of the room's volume to its sound reverberation time. The sound attention from the DFAT setting and impact of the room's reverberation time on the measured sound field within the DFAT loudspeakers are recommended to be experimentally assessed on a case-by-case basis. All safety measures and procedures are recommended to be coordinated with the facility's Safety and Mission Assurance (SMA) office and carried out accordingly. Early coordination with SMA is strongly encouraged to ensure proper and sufficient application of safety measures and procedures.

7.2 Equipment Layout

Equipment positioning is critical for consistent results. Speaker and microphone positioning is to be done accurately and consistently to get repeatable SPL measurements. It is recommended that accurate dimensional measurements be made during the layout process and that speaker and microphone locations be outlined and taped to the floor before setting up any equipment. There are a number of possible speaker layouts depending on the size of the test article. Figure 5, Floor Plan Example for the Layout of a Test with a Loudspeaker Array Recently Used in DFAT Testing, shows an example of a circular loudspeaker array floor plan with the faces of the speakers positioned on a 4.9-m (16-ft) diameter circle for a test article diameter up to 2.4 m (8 ft). Figure 6, Example of a Test Setup for a Loudspeaker Array Diameter of 4.9 m (16 ft) (Maahs, 2010), shows a photograph of another setup of similar size.

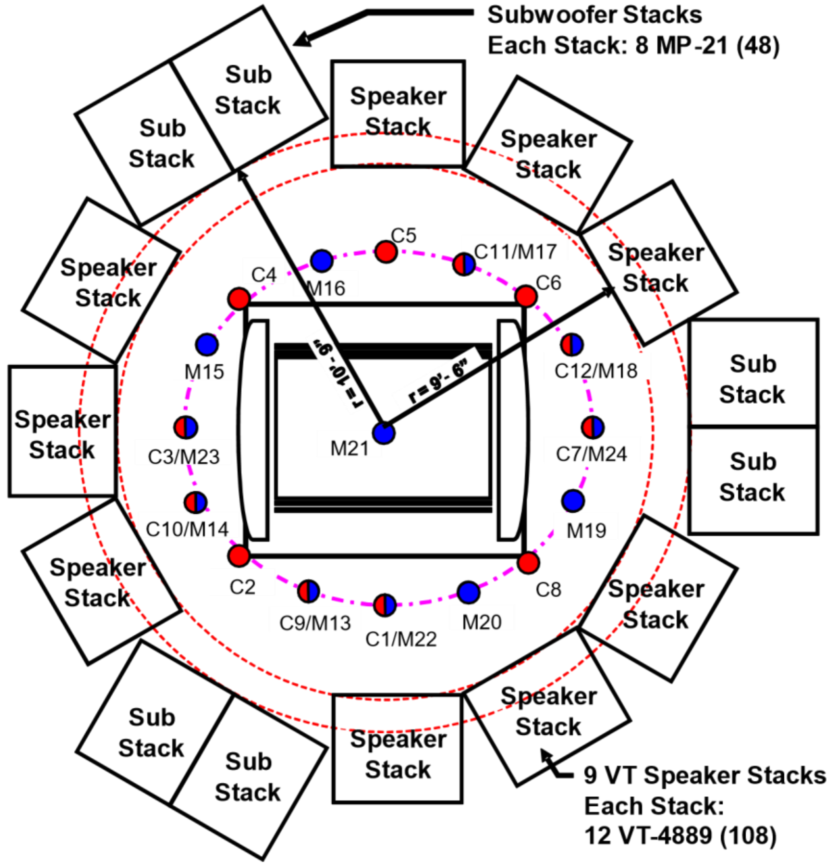


Figure 5—Floor Plan Example for the Layout of a Test with a Loudspeaker Array Recently Used in DFAT Testing (Speaker Stack and Sub Stack Distances from the Center are 9 ft – 6 in and 10 ft - 9 in, Respectively).

Figure 6—Example of a Test Setup for a Loudspeaker Array Diameter of 4.9 m (16 ft) (Maahs, 2010)

While the final configuration is made stable by tying all the stacks together, for tall test articles, the narrow base of a speaker stack relative to the height creates a possible over-turning issue during assembly. This can be mitigated by performing a stability analysis using a minimum lateral over-turning force of 0.25 g acting at the center of gravity (CG) of an individual stack. Weights can then be added to the base. Floor tie-downs or weights can be used to strap the CG of the stack at 45 degrees to the floor; or weights or outriggers can be attached to the base for stability. The recommended amount of weight or outrigger length is to be selected, so that the restoring moment is at least 1.2 times larger than the over-turning moment.

Ideally, the loudspeaker stacks should be mounted on support platforms with castors, so that one section of stacks can be easily moved out and then put back in place for the purpose of inserting or removing the test article.

The test article should be stored at a safe distance during the setup of the test equipment and performance of initial checkout runs and mockup testing. For tests with extensive dynamic response instrumentation and special test equipment (STE) for powering, commanding, and monitoring the test article, it is recommended that a patch panel be constructed to accompany the test article that provides a simple external connection for both dynamic data acquisition instrumentation and STE cabling. This will allow instrumentation of the test article to be completed prior to the arrival of the test equipment, and a standard interconnect will allow temporary disconnect and re-connect, if necessary, when moving the test article in and out of the test area, while minimizing the task and impact of reconnecting and checking the interfaces.

7.3 Power

A mid-size test can require a megawatt or more of electrical power to run the sound equipment. A viable option is to rent a portable generator, typically housed in a truck trailer, which can be parked outside the test facility. If the test is being performed by a test vendor, these services can likely be negotiated in the test contract.

7.4 Contamination Control

Since the test equipment being brought into the test facility or high bay area is generally not maintained under the rigors of contamination control required for flight hardware, and the test facility itself may not be a clean room, the test article is to be covered properly by contamination bagging. This is generally done either by creating a tent for the test article or loosely wrapping the test article with contamination bagging. However, post-test articles must be verified clean if required to the appropriate specification.

The presence of loosely hung contamination film with typical thickness of 50 to 75 microns (2 to 3 mils) has the side effect of attenuating the test acoustic field reaching the test article at high frequencies. Based on theory and documented results from flight space vehicle DFAT tests, attenuation below 1000 Hz is typically negligible, but above that, the acoustic sound power penetrating the film begins to roll off to a maximum reduction of 7-11 dB at 10,000 Hz (Van Dyke & Hackel, 2010). Figure 7, Theoretical Acoustic Attenuation of a Random Incidence Acoustic Field Through Polyester Film for Various Thicknesses as a Function of Frequency (Van Dyke & Hackel, 2010), shows theoretical attenuation for a random incidence acoustic field through various thicknesses of polyester film. A random incidence model appears to be more consistent with test observations than a normal incidence model, and provides a lower bound to test observations. Similar observations using DFAT testing are reported by Stasiunas and others (2012).

One potential approach to work around this effect would be to position the bagging so that it encompasses the control microphones. However, this may not be practical and may raise other logistical and technical issues, such as accessibility, proximity of the control microphones to the test article, contamination issues, etc. It is also reported in references cited above that attempts to manually compensate for the attenuated field with adjustments of the controls or reference specification are to be avoided, since this may have unforeseen negative consequences. It should be noted that in all test results documented in the above references, the attenuated field inside the bagging falls within the tolerances specified by NASA-STD-7001, Payload Vibroacoustic Test Criteria, i.e., ±3 dB between 50 and 3000 Hz, and best facility capability above 3000 Hz.

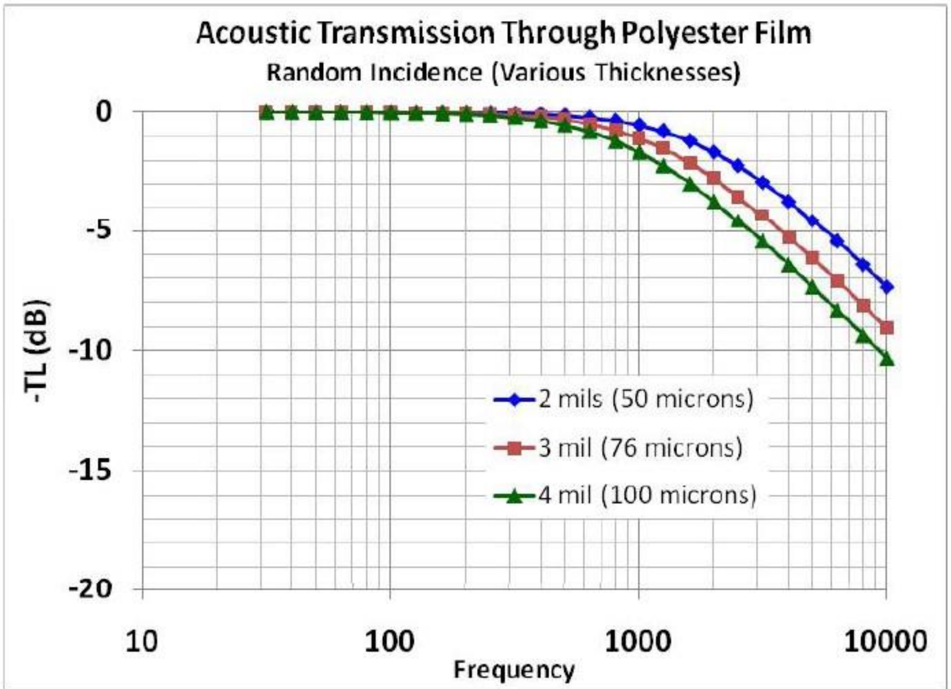


Figure 7—Theoretical Acoustic Attenuation of a Random Incidence Acoustic Field Through Polyester Film for Various Thicknesses as a Function of Frequency (Van Dyke & Hackel, 2010)

7.5 Microphone Calibration

Microphones are generally calibrated for some set period of time and are not to be used beyond that calibration period. In addition, it is recommended that an end-to-end calibration check also be performed on the test setup just prior to testing. This process will verify not only microphones but also cables, signal conditioning, other gain/attenuation stages, and all sensitivity settings.

7.6 Preliminary Mockup Testing

Since the direct sound field is significantly affected by the presence of the test article, it is highly recommended that before subjecting a flight article to the test environment, preliminary testing be performed with a volumetric mockup of the test article. The mockup, at a minimum, is to provide a roughly similar volume and geometric shape compared to the acoustically significant structural surfaces of the test article, and can be made of any number of available and constructed materials, including plywood. This provides an opportunity not only to spectrally shape the acoustic field, but also to evaluate the resulting test field to detect any problematic artifacts. Of particular interest is the existence of severe “hot” or “cold” spots that are spatially significant (SPLs falling outside the test tolerances) compared to the adjacent structural surfaces of the test article that could result in undesirable structural/acoustic coupling or otherwise result in over- or under-testing of the hardware. There is then opportunity to evaluate and weigh risks and plan for any mitigation measures to be implemented before the flight article is placed inside the testing volume. In section 8, analytical predictions of the acoustic field with the test article and speaker settings are recommended to be done before flight hardware undergoes DFAT testing.

For a proper evaluation, it is recommended that a sufficient number of monitor microphones independent from the control loop be used in order to observe the behavior of the acoustic field between the control microphones. A very effective practice is to use a planar array of microphones mounted on a portable frame that can be used to provide an SPL spatial map over various slices of the acoustic field. Figure 8, A Microphone Array Used to Obtain Spatial Mapping of the SPL in Various Slices of the Test Field, shows an example of a 6 x 6 matrix array of microphones with 20.3 cm (8 in) quadratic spacing; and its use is described by Kolaini and others (2012) and Van Dyke and Peters (2010). The 20.3 cm (8 in) spacing provides sufficient resolution to observe spatial gradients related to frequencies up to approximately 400 Hz.

Figure 8—A Microphone Array Used to Obtain Spatial Mapping of the SPL in Various Slices of the Test Field

7.7 Flight Hardware Test Startup

The testing is recommended to start with an initial signal above the background noise by at least 3 dB in each 1/3rd octave band. This usually results in a start-up level of around 120 dB OASPL. Below this level, the room noise floor will result in an overshoot of the specification in the first or second control loop. A test start level at -15 dB below full level is recommended with increasing level of increments +3 dB steps and at least 2 control loops at each level for initial testing. If the control is stable, the number of control loops can be reduced to 2 at startup and 1 at each intermediate level, and the increment can be increased to +6 dB steps. This will provide a compromise between speed and control. The goal is to get to level as fast as possible to minimize time on the system (and test article) without exceeding out-of-band tolerances.

During the initial runs, it is important to pre-tune the field for uniformity. Control microphones and monitor microphones placement should be studied at this time. Adjustments can be made to speaker locations, mass simulator locations, directions, and time alignments to provide a more uniform field at all microphones.

Always monitor the amplifier temperature during the test. It gives an indication of the more important speaker (cone/driver coil) temperature. Heat can melt the wire to cone bond and destroy the speaker.

7.8 Low-Level Field with Flight Hardware

Low-level runs are to be used for tuning and as a pre-test to ensure the required specification can be met, and the field is uniform around the test article, even after the field is characterized using a mass mockup. It is beneficial to analytically predict, map, and correlate the sound field and structure response as part of the pre-test analysis (see section 8). This test is an important part of providing for the safety of the test article and is to be used to characterize and map the sound field, locate places of reinforcement and cancellation of sound waves, identify acoustic standing waves that may couple with structural modes, and determine how to locate and orient the test article for safety and effectiveness. The orientation of the test hardware is to be decided by knowing the acoustic standing waves and the hardware structural coupling with these waves.

7.9 Segment Test Duration

The time duration limits of a test provider's equipment to sustain specified levels depends on the equipment and efficiency for which it is configured. The limitation lies with the potential overheating of the driver coils, and excessive power draw over extended periods of time, which can degrade or destroy the equipment. As the coil begins to heat up, the speaker performance is decreased, causing the controller to drive harder to meet the specification, which further worsens the coil heating. Cool down periods may be required between runs for long duration tests at high levels. With improvements in amplifier design enabling optimization of power distribution and control, this is becoming less of a limitation for DFAT testing than in the past. The capability of running a continuous test at an OASPL of 145 dB for 60 sec has been demonstrated a few years ago.

Nevertheless, the test provider's capability is to be researched as part of the test planning process, and full level and duration is to be demonstrated before subjecting a flight test article to the test, preferably using a mock-up of the test article. All input drive and control channels are to remain steady over the full level duration. If it is necessary to break the test up into segments for the purpose of allowing time for equipment cool-down, the duration of each test segment is to be no shorter than 20 sec, and the test duration is to be based on the total accumulated time at full level.

8. GUIDELINES FOR DFAT TESTING

It has been shown, even with the advancement of the control systems, using DFAT for acoustic qualification testing, the pressure field and measured structural responses can differ significantly from an RFAT test, even if the control microphones are kept within the test tolerances specified. Because of the non-uniformity that may exist in the acoustic field generated by DFAT testing, care is to be taken when performing this type of test to have sufficient instrumentation on the test article to prevent exceeding test article capability as the test level is increased and have an adequate number of microphones in place during the test to monitor the pressure field generated near critical items. It should also be noted that variability in the acoustic field generated by a DFAT test may result in under-testing as well as over-testing in specific frequency bands, and all efforts are to be made to map the acoustic field relative to acoustically sensitive hardware to ensure that an adequate test can be achieved and the intended requirements can be met.

The following guidelines are recommended for DFAT to address some of these technical issues:

a. Pre-test Preparation

(1) Before exposing the flight hardware to DFAT-generated acoustic field, model the acoustic field with and without the hardware using analytical and numerical tools outlined in section 8.1. The modeling results may provide useful knowledge about the acoustic standing waves and interference patterns within the testing volume. The pre-test analysis may also help optimize the location of the loudspeakers and control microphones to produce the most optimal acoustic field applicable to a specific spacecraft or other test article and will help identify empty DFAT volume fundamental acoustic modes below a few hundred Hz. The results also provide structural modes of the test article at low frequencies that may be susceptible to the acoustic standing pressure excitation. This exercise may also help orient/position the test article in the DFAT volume to minimize acoustic modal coupling impact (see section 8.2.1).

(2) Use the results from step (a. (1)) to design DFAT with locations of the speakers and the hardware to come up with an optimal configuration to help lower the impact of the acoustic standing and interference wave patterns. The space between speakers and the test specimen is to be no less than 1.5 m (5 ft).

(3) The modeling efforts in step (a. (1)) may help to identify the locations and number of microphones to be used in the test setup that yields the optimal acoustic field within the testing volume. A minimum of 16 control microphones spread throughout the testing volume and in critical locations are to be used to control the SPLs and these ARE NOT to be used to tailor a specified requirement (i.e., acoustic pressure limiting is not recommended). A minimum of eight additional microphones are recommended to be used for the verification of the sound field. The actual number of control and response microphones should be developed based on development testing. The recommended fixed locations for these

verification microphones are to be equally spaced around the circumference of a circle 0.6 m (2 ft) radially from and mid-elevation of the test article.

b. DFAT Test Setup Preparation

(1) The DFAT setup is to be designed with the information obtained from pre-test analysis. A simple mock-up test article and an acoustic array are required to map out the pressure field within the DFAT volume. The sound pressure variation within the test volume is to be identified using the microphone array and be minimized as much as practical below several hundred Hz (refer to sections 7.6 and 8.5).

A. The microphones shall be positioned around the test hardware within the DFAT volume at sufficient distances from all surfaces to minimize absorption and re-radiation effects. A distance from any surface of at least 1.5 m (5 ft) is recommended.

B. In facilities where this distance cannot be achieved, the microphones shall be located at least ¼ of wavelength from any light-weight acoustically responsive surfaces.

(2) The acoustic field near the top of the speakers' stacks exposed to the room should be measured and characterized. Steps are required to produce more uniform acoustic field if acoustically responsive surfaces, such as reflectors and panels, are located near the top of the DFAT speakers stack. This is the region where the acoustic energy egresses from the test volume, and may result in a lower SPL. If the SPL is too low at the top of the stack, speakers may need to be placed overhead or tilted, as shown in figures 2, 3, and 6. Conversely, if there is a big reflecting surface or cavity above the test item, e.g., the facility ceiling, there may be a standing wave resulting in higher pressure at the top of the test item.

(3) The SPLs from each control microphone are not to deviate by more than ±3 dB from the specification input SPLs.

(4) Perform an acoustic test with the mock up test article and thoroughly examine the acoustic standing waves at lower frequencies and acoustic field in the mid- to higher-frequency within the speaker circle.

c. Flight Hardware Test Setup Preparation

(1) Once steps (b. (1)) to (b.(4)) are completed and reviewed by dynamics engineers, the testing may continue with flight hardware. Perform a low-level acoustic test with the hardware and thoroughly examine the structural/acoustic modal coupling at lower frequencies.

(2) Re-orient test hardware in the DFAT volume, if necessary, to minimize coupling effects; i.e., move sensitive components away from pressure nodes/velocity

antinodes of the coupled frequencies. For example, the test item may need to be raised to minimize the impact of low-frequency pressure doubling near the floor of the DFAT volume.

(3) Examine low-level data (both sound pressure and acceleration/strain responses) by scaling to the full level (0 dB) and proceed if no structure capability issues are anticipated due to coupling.

(4) For large test hardware, where re-orientation may not be possible, use additional instrumentation to better gauge the coupling issue.

d. Summary of Additional Recommendations Discussed Throughout this NASA Technical Handbook

(1) Structural response limiting should not be applied until a more thorough development effort of this technique can be carried out (section 4.2).

(2) Preform an end-to-end calibration of mixers to verify the gain settings prior to testing (section 5.2).

(3) The SISO method is not recommended (section 6.3).

(4) Users to become familiar with the relationships between narrow-band and n^{th} octave-band SPL specifications (section 6.3).

(5) On a case-by-case basis, assess the sound attention from the DFAT setting and experimentally measure the impact of the room's reverberation time on the measured sound field within the DFAT loudspeakers (section 7.1).

(6) Make accurate measurements of the speaker and microphone locations (section 7.2).

(7) Perform speaker stack stability analysis using a minimum lateral over-turning force of 0.25 g acting at the CG of an individual stack (section 7.4).

(8) Calibrate all microphones and perform an end-to-end calibration check on the test setup prior to testing (section 7.5).

(9) Start the test with an initial signal above the background noise by at least 3 dB in each $1/3^{rd}$ octave band. This usually results in a start-up level of around 120 dB OASPL (section 7.7).

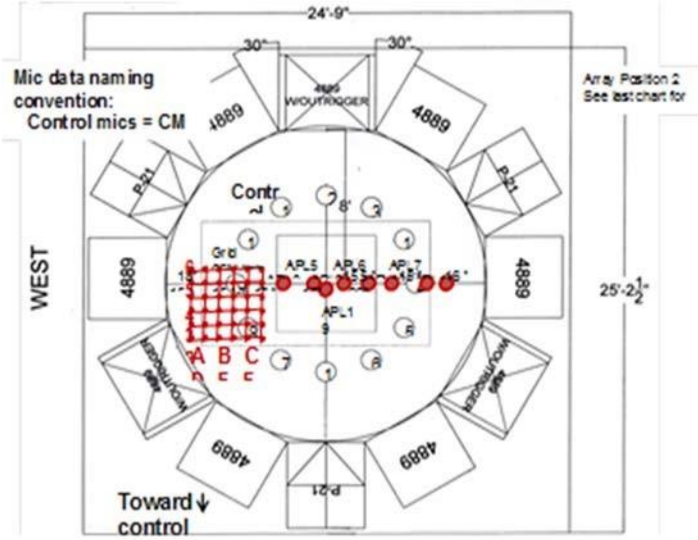
8.1 DFAT Test Setup Design and Acoustic Field Characterizations Using Analytical Models

This section provides three methods of analysis for preparation of DFAT testing and for predicting the SPLs within the DFAT volume, as follows: First, a simple mathematical model to predict acoustic modes within the speaker circles, with and without the test article, as outlined in section 8.2; second, a boundary element method/finite element modeling (BEM/FEM) analysis as summarized in section 8.3; and third, the coherent excitation as outlined in section 8.4. All three of these types of analysis provide valuable insights into the spatial distribution of DFAT sound fields, and the use of one or more of these methods is strongly recommended before proceeding with a DFAT.

8.2 Acoustic Standing Waves and Interference Patterns

The first extensive DFAT test to gain some understanding of the acoustic field generated by DFAT testing was performed at the JPL environmental test facility during March 2010 (Kolaini and others, 2012). The second, more elaborate DFAT test was performed at APL during July 2011 (Kolaini and others, 2012; Van Dyke & Peters, 2010; Larkin & Hayes, 2012; Maahs, 2009). The third such test was again performed at APL, where much-improved speaker technology and control schemes were employed (Maahs, 2010, 2012). The speakers, woofers, and control system for all three tests were provided by a vendor, which was responsible for setting up the testing configurations. Up to 16 control microphones were used in different configurations to generate the sound field between the speakers to an OASPL of 140 dB. In addition to using control microphones, another 8 monitor microphones were spread within the volume to measure the sound pressure spatial variations. Finally, an array of 36 microphones was positioned in several locations to measure the detailed sound pressure variation within the volume in these test setups. In the case of the APL tests, a linear array was positioned across the speakers and in the vertical direction to measure the possible standing waves within the volume between the speakers. The major difference between the JPL and APL tests was the control system, wherein the APL tests' improvement was made in the control system to generate sound field using both SISO and MIMO control schemes (Underwood & Keller, 2003). Part "a" of figure 9, The APL Speakers and Woofers Arrangement with Control Microphones, Microphone Array, and Linear Microphone Array, 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 SISO and MIMO and assess the spatial variation within the cavity, whereas the linear array was used to measure the SPLs across the speakers and along the height. Part "b" of figure 9 depicts the speaker setup used for acoustic field characterization using SISO and MIMO at APL's testing facility.

The linear array discussed above was used to measure acoustic standing waves in the radial and vertical directions. Figure 10, Sound Pressure Spectral Density Obtained from APL DFAT Test, depicts the pressure spectral density, identifying most acoustic modes measured using the 36microphone array. In this figure, both the interference wave patterns and acoustic standing waves (wavelengths corresponding to the dimensions of the DFAT setting) are identified. The interference wave patterns are critically dependent on the control system, and the MIMO control scheme has been shown to minimize the hot-cold acoustic field measured in DFAT testing (Van Dyke & Peters, 2010). The interference wave patterns are highly dependent on the control strategy and can be minimized, whereas the acoustic standing waves are related to the boundary conditions formed by speaker cabinets and the test article and have been shown to increase structural responses (Kolaini & O'Connell, 2008; Kolaini and others, 2009). 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 for this case.



(a)

(b)

Figure 9—(a) The APL Speakers and Woofers Arrangement with Control Microphones, Microphone Array, and Linear Microphone Array (b) Photo of the APL DFAT Setup (Kolaini and others, 2012)

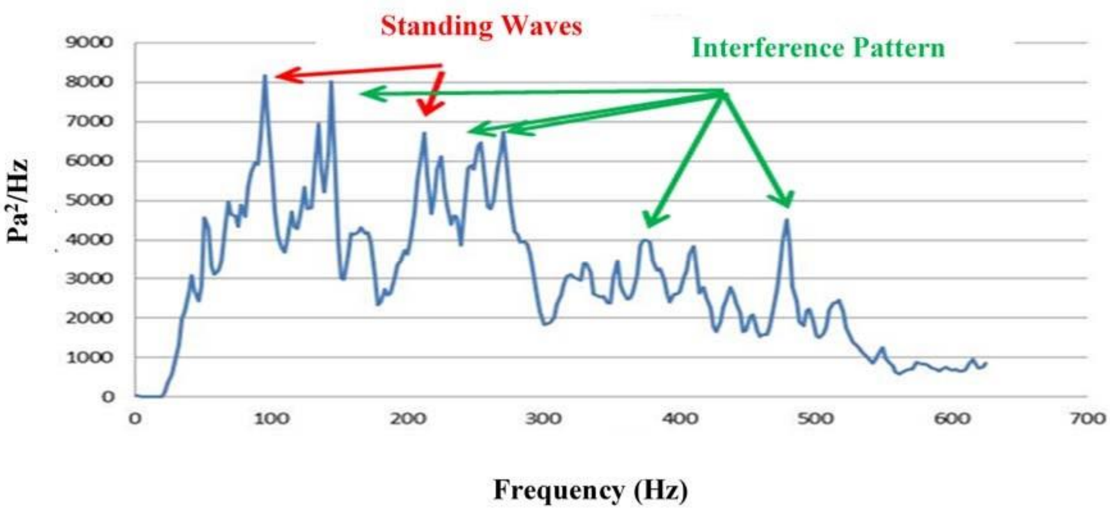


Figure 10—Sound Pressure Spectral Density Obtained from APL DFAT Test

NOTE: The acoustic modes identified in this plot are due to the acoustic standing waves and interference wave patterns (Kolaini and others, 2012). The acoustic standing waves are periodic waves with fixed amplitudes and wave lengths corresponding to the fixed dimensions of the DFAT setting.

8.2.1 Simple DFAT Analytical Model

To understand the acoustic standing waves of the cavity made up of the speakers in the DFAT test setup, 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 (Kolaini and others, 2012; Pierce, 1989). Figure 11, The Predicted Radial and Vertical Acoustic Mode Shapes at 88 Hz for the APL Speakers' Setup (Kolaini and others, 2012), shows predicted first radial standing wave with a frequency of 93 Hz (m= 0, and n = 1) and the first vertical mode with the same frequency (◌् =1) in the z-direction using the simple model described by Kolaini and others (2012). Figure 12, The Predicted Radial Acoustic Mode Shape with Frequency of ~93 Hz Correlated with Measured Data Obtained from DFAT Tests Using SISO and MIMO Controller Schemes (Kolaini and others, 2012), shows this predicted first radial mode shape compared with the measured acoustic standing waves at 93 Hz or 95 Hz, depending on whether the data were generated using SISO or MIMO control schemes. The differences in the mode shape that is 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 the acoustic sources (i.e., speakers). A few more predicted acoustic standing waves and correlation with the measured data for both MIMO and SISO control schemes are summarized by Kolaini and others (2012) and Cotoni and others (2012).

There is generally a difference between the peaks and valleys of the acoustic field within the cavity due to the interference patterns and due to acoustic standing waves. An exception is the case of the interference between waves traveling in opposite directions generated at the same frequency and phase by speakers directly opposing each other, as in the coherent source model (Van Dyke & Peters, 2010; Rouse and others, 2011). Standing waves impact the structural responses in a different and more significant way (Kolaini and others, 2009; Maahs, 2009) than do the interference patterns that characterize the geometric near field of spatially distributed sources. The next section discusses this further.

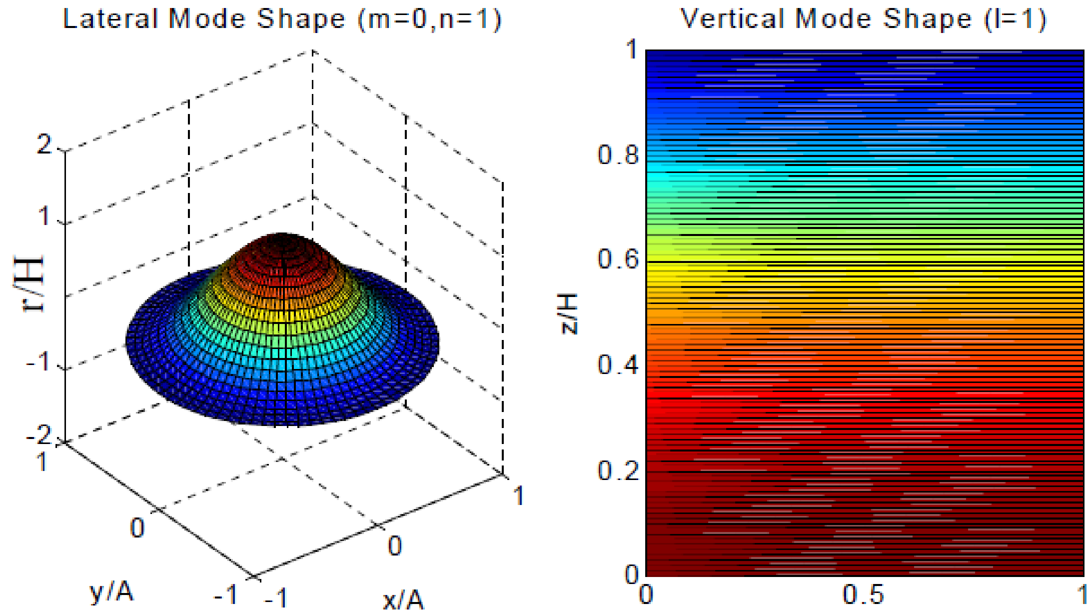


Figure 11—The Predicted Radial and Vertical Acoustic Radial and Vertical Mode Shapes at 88 Hz for the APL Speakers' Setup (Kolaini and others, 2012)

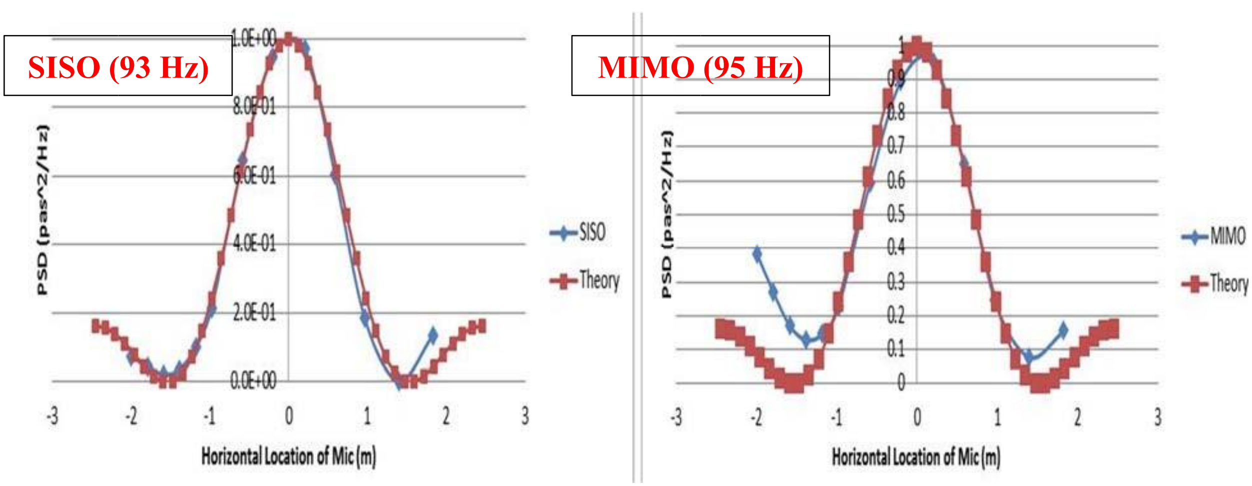


Figure 12—The Predicted Radial Acoustic Mode Shape with Frequency of ~93 Hz Correlated with Measured Data Obtained from DFAT Tests Using SISO and MIMO Controller Schemes (Kolaini and others, 2012)

8.2.2 Impact of Acoustic Standing Waves on Structural Responses

It has been demonstrated that the structure and acoustic mode coupling can result in an unanticipated overtest for some low mass to area structures like antennas, solar arrays, etc. (Kolaini & O'Connell, 2008; Kolaini and others, 2009). Recently, the reverberant chamber acoustic/structural coupling phenomenon was demonstrated by tailoring the dimensions of a 0.64 cm (1/4 in) 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 have shown to vary by more than 20 dB, when the panel structural mode coupled with one of the acoustic standing waves. These results, as discussed in some detail by Kolaini and O'Connell (2008) and Kolaini and others (2009), convey an important finding related to the coupling phenomenon. The observations from the test 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 simple aluminum panel acoustic test and similar observations made from a few flight hardware acoustic qualification tests (Kolaini & O'Connell, 2008) prove that the coupling phenomenon can significantly impact structural responses. The acoustic standing wave observations made from the APL DFAT tests 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 which could impact a lot of components susceptible to structural excitation in the mid-frequency region. This is in comparison to a reverberant acoustic chamber where, for a typical size chamber, the significant standing waves are mostly below ~100 Hz; therefore, in a relatively large acoustic chamber, the impact of the acoustic standing waves on a test article are much less than the same in DFAT testing.

8.3 Speaker Test Layout Design Using FEM/BEM

Predicting the spatial characteristics of the sound field generated by a DFAT test as it interacts with a given test article will be invaluable for pre-test analysis and test planning. Perhaps the most suitable modeling tool for predicting sound-structure interaction is BEM analysis or a hybrid combination of BEM and FEM. Some progress has recently been made in the development of capabilities applicable to modeling DFAT testing using BEM method (Cotoni and others, 2012; Gardner and others, 2013). The first attempt in modeling the DFAT test set up using BEM provided the testing volume modes with and without test article. The pressure field was modeled using various correlation schemes for the speakers (Cotoni and others, 2012). The BEM model of the speakers was idealized by assuming uniform velocity source on each speaker face. Figure 13, The BEM Predicted Radial and Axial Acoustic Mode Shapes with Frequency of ~90 Hz and 233 Hz Correlated with Measured Data Obtained from DFAT Tests Using MIMO Controller Schemes (Cotoni and others, 2012), shows the radial and axial acoustic modes predicted using the BEM model of the speakers and correlated with the measured data. The preliminary study of the BEM model with test article included the impact of the speaker model detail, test articles' sizes and geometry, their placement, and different correlation schemes for speakers. Figure 14, The BEM Predicted Acoustic Standing Waves Using Three Differently Sized Cylindrical Test Articles Placed in the Middle of Speakers (Gardner and others, 2013) shows the impact of the test article inside the DFAT test volume considering three different configurations. In these examples, idealized cylindrical geometries are considered. The DFAT BEM model is currently being improved by taking into account a detailed model of the speakers and test article geometries (Gardner and others, 2013).

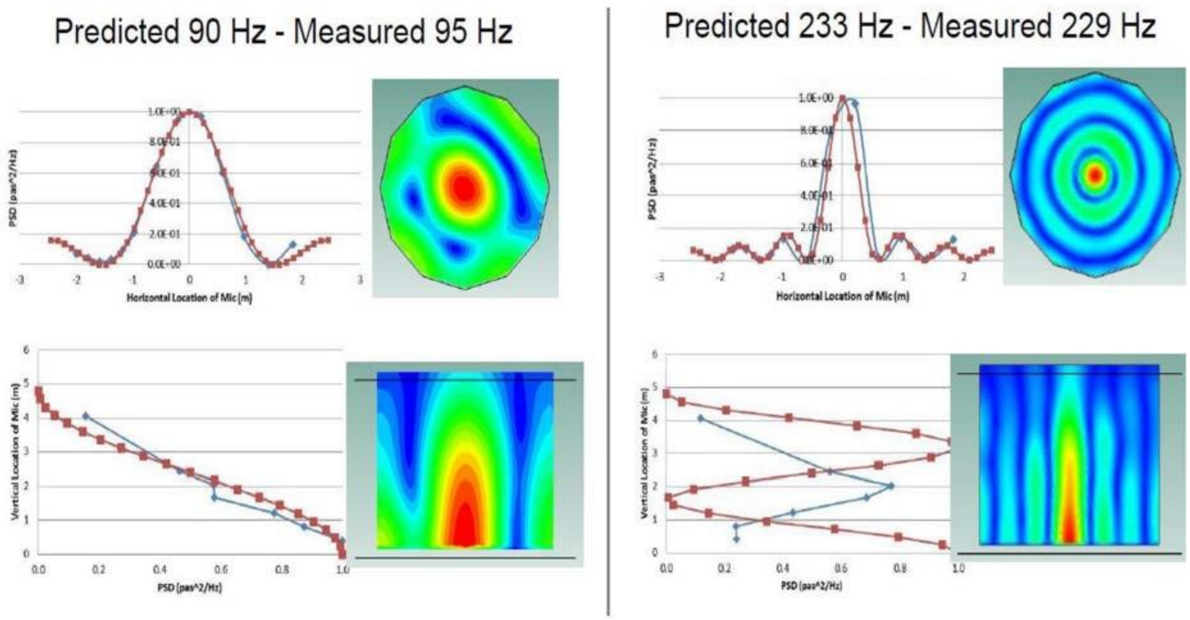


Figure 13—The BEM Predicted Radial and Axial Acoustic Mode Shapes with Frequency of ~90 Hz and 233 Hz Correlated with Measured Data Obtained from DFAT Tests Using MIMO Controller Schemes (Cotoni and others, 2012) (Blue Measured, Red Analysis)

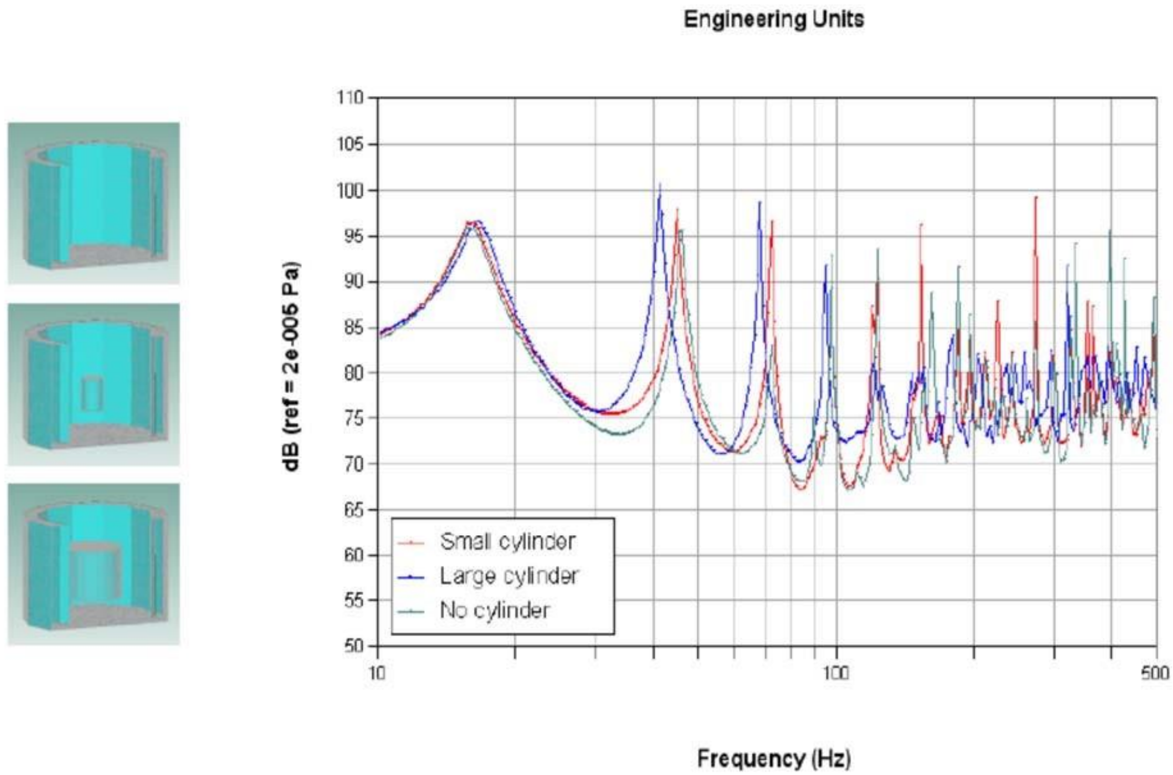


Figure 14—The BEM Predicted Acoustic Standing Waves Using Three Differently Sized Cylindrical Test Articles Placed in the Middle of Speakers (Gardner and others, 2013)

8.4 Simple Model for Speakers as Coherent Sources

Another simple modeling tool that may help prepare for the DFAT testing is to visualize spatial acoustic wave interference patterns resulting from an array of fully coherent sources that are used to approximate the acoustic field within DFAT volume. This approach is based on the observation that a simple model based on the free-field behavior of sound radiated from an array of simple coherent sources produces a very similar spatial pattern at modal frequencies as the standing wave mode shapes generated at characteristic modal frequencies of a cylindrical enclosure that is open on one end, as discussed in section 8.2. The reason for this is thought to be that the loudspeaker cones actually provide virtual pressure maximum boundaries so that the phasing of the superimposed sound waves creates an interference pattern very similar to the characteristic mode shapes of a rigid walled cylinder at the frequencies of the cylinder modes (Van Dyke & Peters, 2010; Rouse and others, 2011).

8.5 Control and Monitor Microphones

To fully characterize the acoustic field, the recommendation is to use a microphone array of the type shown in figure 8 to better map the sound circumferential and vertical variation within the test volume. The information from the array may be used to select the number and locations of the control microphones and also can be used to place the hardware to minimize the impact of acoustic standing waves and interference patterns discussed in section 8.2.

A few examples of control and monitor microphone setups and results, including the mapping of the acoustic field using the array in DFAT testing are provided by Kolaini and others (2012); Van Dyke and Peters (2010); Larkin and Hayes (2012); Maahs (2009, 2010, 2012); Rouse and others (2011); O'Connell and Hausle (2005); O'Connell (2007); and Larkin and Goldstein (2010). Spatial correlation in the time domain (coherence in the frequency domain) is higher most everywhere for a DFAT sound field than it is for a reverberant chamber sound field. The coherent nature of the DFAT sound field represents a challenge in the prediction of vibroacoustic structural responses. However, the differences in the DFAT and RFAT sound field characteristic and the corresponding structural responses are to be taken into consideration given that the development of acoustic specifications is traditionally based on a heritage of testing in the relatively uniform, incoherent sound fields characteristic of large reverberant chambers.

Given the potential for controlling the spatial characteristics of DFAT sound fields, it may be advantageous in the future to generate acoustic test specifications that more accurately reflect the spatial characteristics of the acoustic environments predicted for specific fairing and spacecraft configurations.

The control microphone placement is critical to a successful DFAT test, because of the known variance in the sound field. Early testing has shown several dB variations between control microphones and the monitor microphones in certain frequency bands (Maahs, 2009; Kolaini and others, 2012; Van Dyke & Peters, 2010; Larkin & Hayes, 2012; Maahs, 2009, 2010, 2012; Rouse and others, 2011). The inclusion of more control microphones randomly placed within the testing volume to obtain the control average is critical to narrow these variations. The number and best placement of the control microphones to be used for controlling the SPL within the testing volume with the test article present may be facilitated using analytical tools, such as discussed in this section. Subsequent characterization of the sound field with a mass simulator and adjustment of the control system, as necessary, is critical before flight hardware is exposed to the acoustic field.

APPENDIX A

GUIDANCE

A.1 Purpose

The purpose of this appendix is to provide guidance and is made available in the reference documents listed below.

A.2 Reference Documents

A.2.1 Government Documents

NASA

NASA-HDBK-7005	Dynamic Environmental Criteria
KSC-STD-164-B	Environmental Test Methods for GSE Standard

A.2.2 Non-Government Documents

Institute of Environmental Sciences and Technology (IEST)

IEST-RP-DTE040.1. (2000). “High Intensity Acoustic Testing.” Design, Test, and Evaluation Division Recommended Practices. Rolling Meadows, IL.

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