Developments in Direct-Field Acoustic Testing

Paul Larkin, Maryland Sound International, Baltimore, Maryland

Direct-field acoustic testing (DFAT®) has been developing to include new control schemes, hardware geometry and setup parameters in an effort to improve sound pressure uniformity. In addition, research is being conducted into the modeling and control of standing waves created by either room geometry or wave interference patterns in the DFAT sound field. Control schemes that use additional microphones or accelerometers in conjunction with nonsymmetry in the geometry of the setup to reduce the magnitude of standing waves is discussed. It will also be shown how control microphone placement and the type of control scheme can also heavily influence the creation of standing waves.

Direct-field acoustic testing (DFAT®) continues to increase in popularity as an alternative to more traditional reverberant acoustic testing due to its inherent advantages of reduced cost and schedule. The method uses combinations of direct-plane waves instead of a diffuse reverberant field and has been shown to produce similar structural excitation to that which is produced in reverberant chamber testing.[1] Specifics on the use and application of DFAT for aerospace testing can be found in MIL-STD-810G, Change 1 and the soon to be released NASA-HDBK-7010.

The advantages associated with DFAT are flexibility along with reduced cost, schedule, and risk. Program costs for off-site testing far exceed the costs of actually performing the acoustic tests. Since the DFAT system equipment is modular and portable, it can be brought on location and removed when the test is complete – eliminating several significant categories of costs and risks. There is no reverberant room needed for testing, no rigorous facility requirements, no maintenance, no operational costs, no storage and no additional personnel required on the part of the customer. As a result of its modularity, a typical DFAT system is highly configurable to most any testing circumstance that might be desired.

This flexibility further reduces the overall cost and risk associated with system level testing, because the system is configured and made ready in parallel to normal testing operations. Once the DFAT system has been prepared, the test article is usually required for only one day of testing, depending on the amount of test article instrumentation. This also lowers the cost associated with sustaining engineering teams standing by until the test is completed. Finally, the risks associated with packing and transporting the test article, additional handling operations in a remote facility, and return operations are eliminated. No transportation and remote operational costs are incurred, and no additional days are required.

The main difference between DFAT and reverberant chamber testing is that DFAT produces direct-field excitation of the test article rather than a diffuse field that exists in a chamber. A reverberant field is made up of theoretically infinite number of plane waves coming from all directions (equal intensity). This will excite the test article uniformly across the surface. DFAT produces a perpendicular (normal to the panel plane) field of plane waves directly on the test article. Depending on the geometry of the test article, this could produce large-magnitude variations creating local fluctuations on the test article surface due to phasing differences between the direct-plane waves. In the case of large surface area, low mass density test articles, the phasing difference may excite primary structural modes in a different way than the diffuse reverberant field. This fundamental difference and its impact on the structure must be weighed against the advantages of the DFAT method.

In addition to pressure coupling, a recent study has shown that structural coupling with peak acoustic velocity waves can also occur. Reference 10 gives examples of adverse coupling occurring in both the reverberant and direct fields due to peak pressure coupling as well as peak velocity coupling. The nature of the coupling being dependent on direct pressure vs oblique velocity waves interacting with unique structural panel properties.

Most DFAT tests performed before 2010 used the single-input-single-output (SISO) method. The SISO control system was first introduced around 2005-06 and used a narrow-band, real-time, closed-loop random vibration controller.[2] SISO control produced a well correlated sound field, since the same drive signal is delivered to all audio devices. However, a well-correlated sound field is not necessarily a good simulation of the flight environment for acoustic testing of aerospace components. Sound pressure level (SPL) variations due to wave interference patterns in the SISO field can be as large as ±12 dB from the average SPL due to constructive and destructive wave combinations.[3]

In addition, multiple-microphone averaging can exacerbate the problem by allowing large variations at the control points to result in an apparently well-controlled composite signal when compared to the required reference. Typical performance in the SISO environment is ±1 dB variation between the reference and the composite control average with ±5 dB of control microphone to control microphone variation and ±12 dB or more between monitor microphone locations. These characteristics do not describe an environment suitable for spacecraft testing, since the large variations could possibly result in an over/under test condition.

The more recent development by Spectral Dynamics (SD) and application by Maryland Sound of MIMO acoustic control in the DFAT process has been a major breakthrough creating a much improved methodology over earlier practice. MIMO control theory was developed as far back as the 1970s but had its first practical application to electro-dynamic shaker control in 2000-01 and recently to acoustic control in the 2009-10 time frame. MIMO control employs multiple independent drive signals to control multiple reference points in the acoustic field.

The control algorithm used by Spectral Dynamics actually uses a fully populated spectral density matrix (SDM) that contains magnitude (PSD), phase and coherence requirements to update all drives simultaneously based on the responses of the independent control channels. Using SD's Jaguar MIMO controller, the user can input magnitude, phase and coherence specifications with tolerance bands on each, at up to 16 independent control points. The system will use those constraints and the independent drives to produce a compliant acoustic environment at each control point. In effect, this method controls the response of each control microphone to meet its individual requirement based on the input it receives from each independent drive signal.

The result can be an incoherent field with minimum variation between control microphones. This represents a huge improvement in field uniformity (spatial variation) as well as providing a sound field with much lower coherence, similar to an actual launch vehicle. More details about the theory and practice of the Spectral Dynamics MIMO controller can be found in Reference 4. The MIMO acoustic control system block diagram is shown in Figure 1. Each microphone response is brought into the controller, converted to the frequency domain and individually compared to its own reference.

The reference for each microphone location is specified by *n*th octave-band or narrow-band magnitude, phase and coherence. The errors between the references and measurements are calculated and used to update each of the independent drives by solving an appropriate set of simultaneous equations. The drives are then converted back to the time domain, randomized and then distributed to each amplifier as analog signals.

In addition to the MIMO controller, a drive matrix switch (DMS)

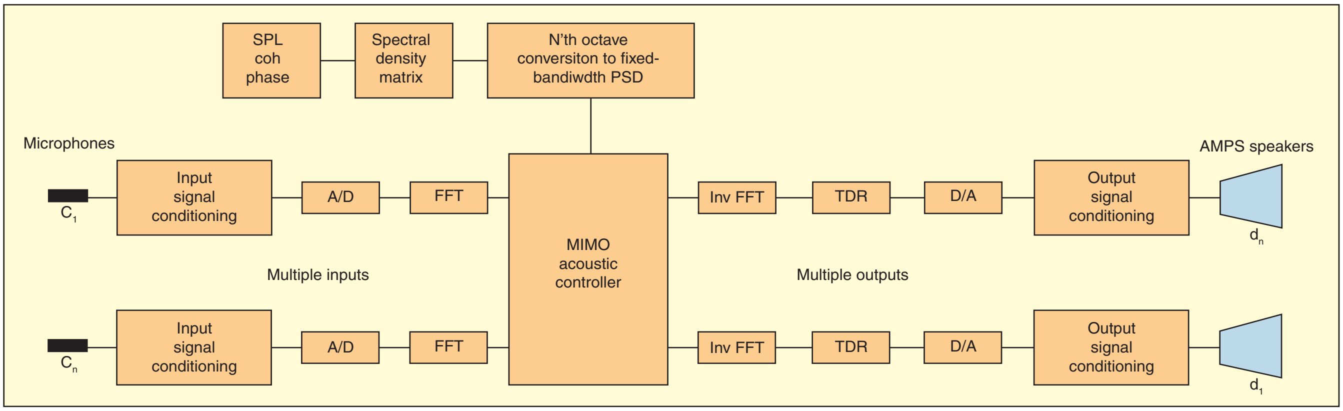

Figure 1. MIMO block diagram.

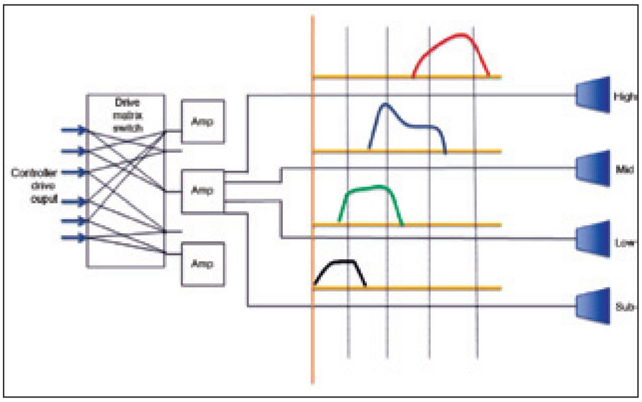

Figure 2. Drive matrix block diagram.

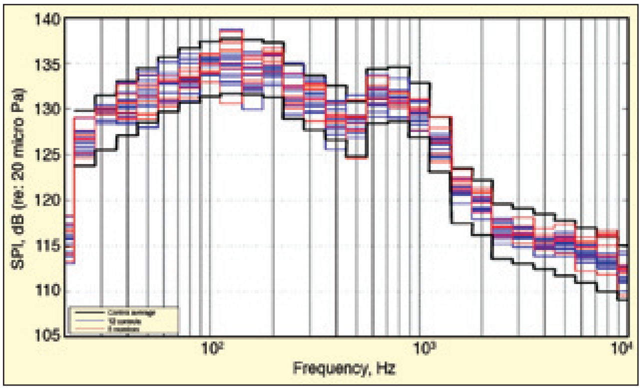

Figure 3. Current typical 1/3-octave MIMO mic response.

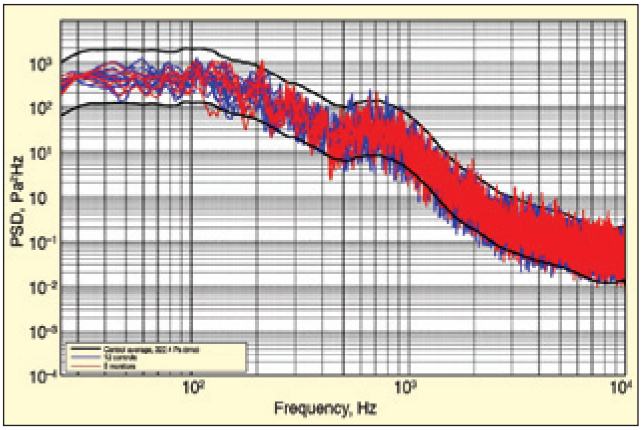

Figure 4. Current typical narrow-band MIMO mic response.

has been added to the control scheme. The DMS allows the multiple controller drive outputs to be switched to any combination of amplifier/speaker networks. The block diagram of the DMS is shown in Figure 2, which is placed between the controller and the amplifiers. The result is a more uniform, blended field with reduced coherence compared to the SISO system.

Results

Typical results from a MIMO acoustic test using the DMS are shown in the Figures 3 and 4. Figure 3 shows typical 1/3-octave results for control microphones and monitor microphones compared to ±3 dB tolerance lines on the SPL. The 12 control channels are shown in blue and the eight monitor channels are in red. Figure 4 presents the same data in terms of narrow-band (constant bandwidth) PSDs plotted with ±6 dB tolerance lines. Note that at certain frequencies, multiple microphones have similar maxima or minima.

It is believed that these locations are measuring some type of fixed wave patterns similar to what can occur in reverberant chambers.[5] However, unlike the uncontrolled modes of a reverberant chamber, these waves can be controlled by the MIMO system to be within or slightly above the specified tolerance limits. It is expected that over time, technology advancements will lead to even more uniform control. Additional details of the current technology, field uniformity, coherence, drive and control characteristics can be found in References 6 and 7. Data analysis of the time domain characteristics of the DFAT field can be found in Reference 8.

Standing Waves

As field control has continued to improve, attention has recently turned to concentrate on field uniformity. More specifically, standing wave patterns similar to those created by low-frequency reverberant chamber modes have come under recent investigation. To facilitate the investigation, a microphone array is now being used to identify and isolate standing wave patterns that may exist within the direct-field test volume created by wave interference patterns or the physical boundaries of the speaker circle.

A recent test configuration is shown in Figure 5 with a typical microphone array shown suspended above the test article. The array can be oriented in the vertical (shown) or rotated and suspended horizontally as well as raised or lowered to various locations within the test circle. Anywhere from 16 to 36 microphones have been used to cover a 0.8- to 1.5-square meter area.

Figure 6 shows a typical set of responses for 12 control microphones. Figure 7 shows the corresponding response of a 16-microphone array. These measurements were taken with the array vertical, between the speakers and the test article, and with the bottom microphone row about 1 meter from the floor and not near a control or monitor microphone. Responses at multiple vertical and horizontal locations within the annulus created by the speakers and test article were similar, with some slight shifting of frequency and amplitude. It can be observed from the two plots that the control average PSD is good, showing each control microphone response within ±6 dB.

Figure 7 shows the presence of some type of wave phenomenon that might be causing stationary waves to form at discrete locations within the field. As further investigation would reveal, some of these stationary maxima are caused by wave interaction or simply the summation of discrete frequency components at discrete loca-

Figure 5. A typical DFAT test configuration.

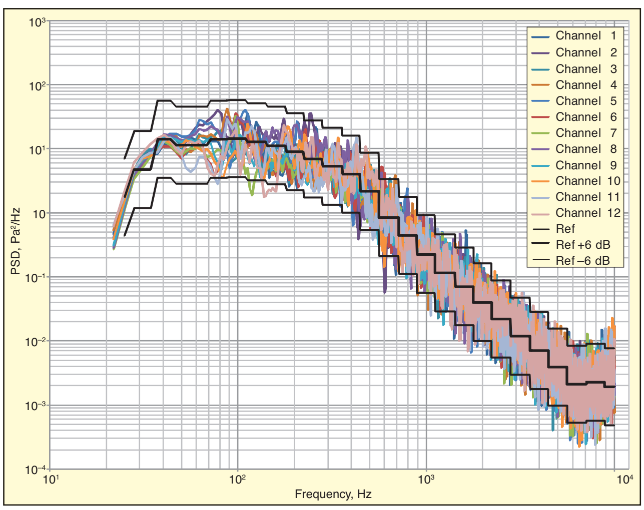

Figure 6. Typical DFAT control .

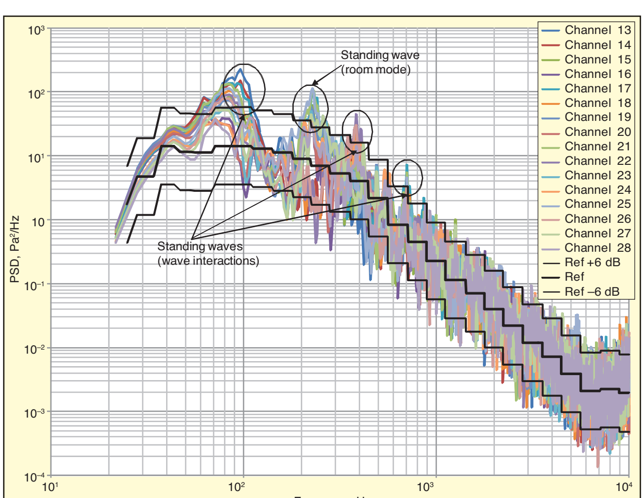

Figure 7. Typical array response.

tions, while other maxima are caused by the geometry and physical boundaries of the setup.

Figure 8 shows the control average and the average for the microphone array. This is a clear indicator that in this area of the simulated sound field deviations average slightly over 6 dB above the control and monitor locations in the 60-120 Hz range and again in the 200-300 Hz range. These narrow-band sound pressure excursions may have an impact on the test article and need to be investigated. It is recommended whenever performing a DFAT that a similar microphone array be used to assess the field

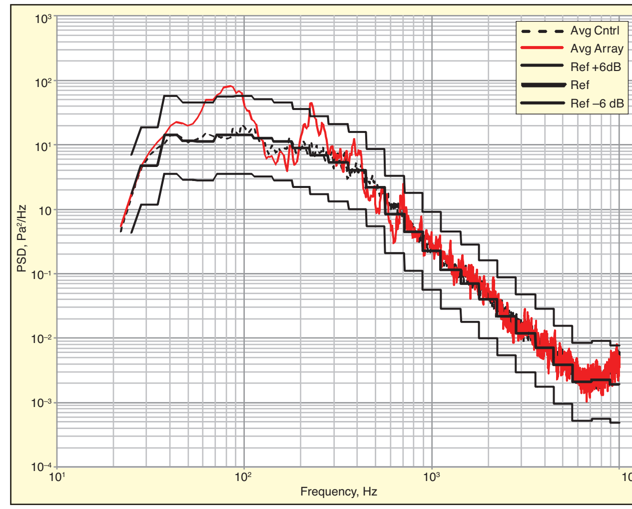

Figure 8. Average control and average array response.

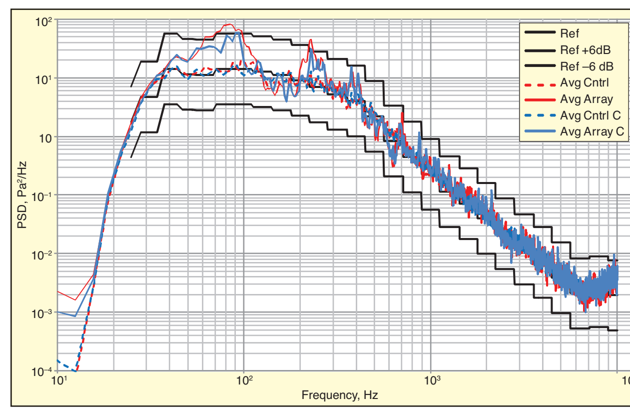

Figure 9. Move control mic (C4).

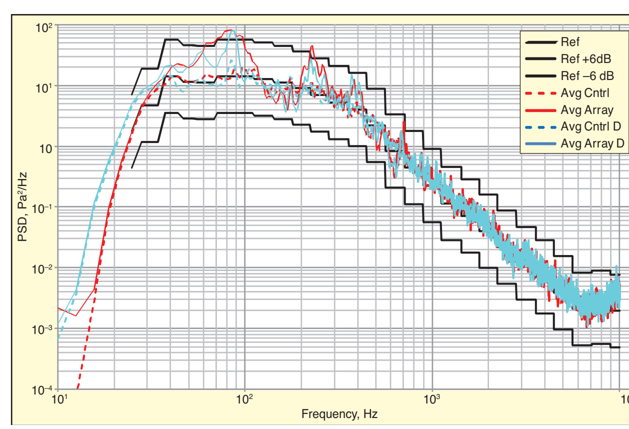

Figure 10. Move C4 and alter the reference (-6 dB at 70 hz).

and any potential impact it may have on the test article. However, if coupling is found to occur between the acoustic field and the structural modes, there are ways to mitigate the effects. Some of these methods are discussed subsequently.

Control of Standing Waves

Several methods for controlling the stationary wave magnitudes were investigated. Table 1 shows the various methods that were used and summarizes the results obtained. Measurement results are shown in Figures 9-14. Response limiting an accelerometer is a complex and controversial issue, and its overall effect on system response will be discussed in detail in a future article.

As often happens when looking for a solution to one problem, a significant discovery is made toward finding a solution to an unrelated problem. Such was the case with the next enhancement to DFAT. While making test runs toward optimizing crossover settings in an effort to produce more sound power output, the system

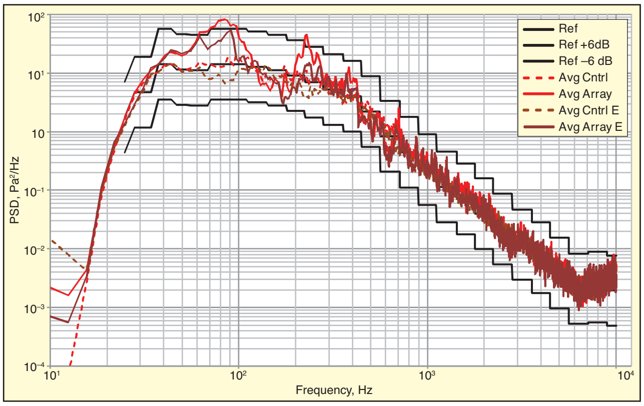

Figure 11. Add a control mic (C13-preferred).

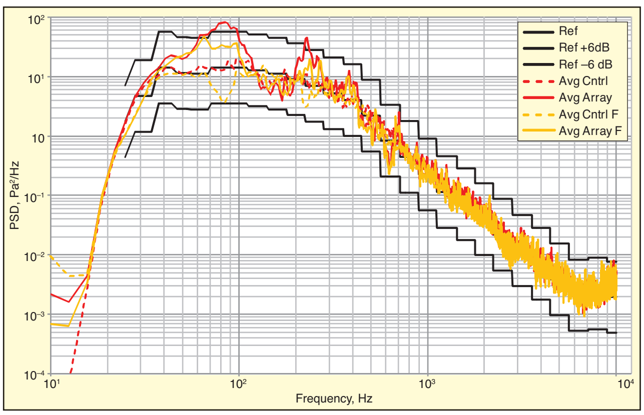

Figure 12. Response limit a monitor mic (M13).

time-alignment strategy was changed. Previous time alignment of the sub and three-way drivers was performed to a single point at the center of the circle. This ensured repeatability among setups and accounted for slight changes in geometry between setups.

To see the effect this alignment had on power usage, we attempted a test with NO time-alignment. Arrival times between sub stacks and three-way stacks were left completely random. The result was not good with respect to power consumption – nearly 2 dB more power was needed to reach a previous time-aligned condition, but the reduction in standing wave occurrence and magnitude was very good. A compromise solution was eventually found by experimenting with different time delays, and one was selected that minimized the power loss but gave acceptable reduction in the formation of standing waves due to wave interference patterns.

Note that not all patterns were reduced. As indicated between Figures 8 and Figure 13, three of the four peaks were significantly reduced. Those were the ones created by wave interferences. The fourth peak, in the 200-300 Hz range remained, and further investigation determined this to be created by the test geometry.

As was previously known, symmetry in the test setup can encourage the formation of stationary waves. However, unlike a reverberant chamber with fixed geometry, the DFAT geometry can be changed. It was again experimentally discovered that changes to

Table 1. Standing-wave control methods investigated.

Method	Description	Result	Figure
	Baseline		7,8
1	Move control mic (C4)	2 - 3-dB reduction	9
2	Alter reference (–6dB at 70 Hz	Useful for local reduction	10
3	Add control mic (C13 preferred)	3-dB reduction over multiple bands	11
4	Response limit monitor mic (M13)	Causes reduction in control avg	12
5	Response limit accelerometer	Effective in limiting structural response	N/A

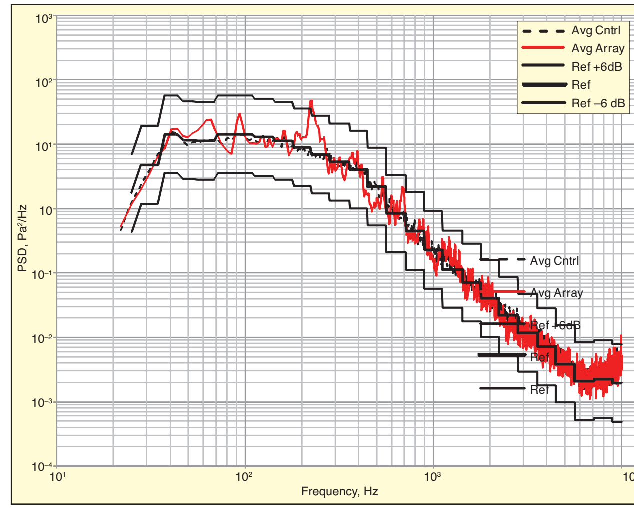

Figure 13. Eliminate wave interference, room/geometry mode remains.

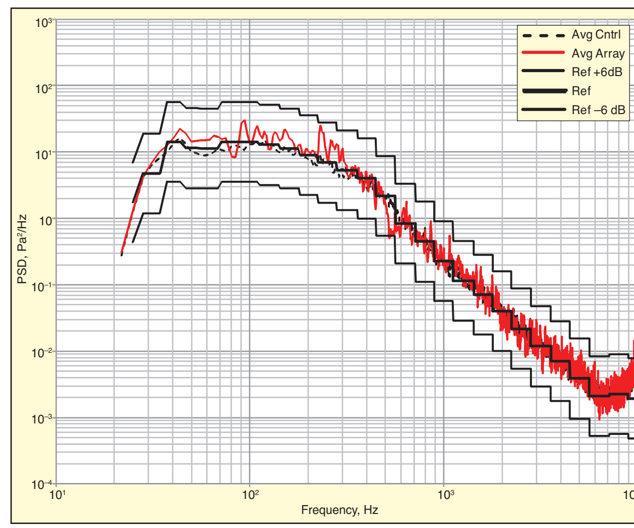

Figure 14. Current practice when controlling standing waves.

geometry, ovals instead of circles, skewed speaker stacks, random microphone placement, etc. All have an impact on the magnitude of standing waves in the DFAT environment. Table 2 lists the current methods of control in order of effectiveness.

The main point is that the DFAT methodology coupled with the narrow-band MIMO control system offers multiple strategies that can be used to control standing waves as well shaping the field in the DFAT environment. Using DFAT technology may even make

Table 2. Standing-wave strategies.

Method	Description	Result	Figure
	SISO	Shouldn't be used for uniform field testing	N/A
	Baseline	Standing waves exist in sound field	8
1	Time/alignment	Significant reduction in wave interference patterns	13
2	Random cntrl mic locations; avoid all symmetry	Significantly reduces room/geometry standing waves	14
3	Move control mic (C4)	2 - 3-dB reduction	9
4	Alter reference (–6 dB at 70 Hz)	Useful for local reduction	10
5	Add control mic (C13 preferred	3-dB reduction over multiple bands	11
6	Response limit monitor mic (M13)	Causes reduction in control avg	12
7	Response limit accelerometer	Effective in limiting structural response	N/A

it possible to create a much more flight-like environment than can be achieved by diffuse-field reverberant chamber testing.[9] The magnitude of the average improvement realized is demonstrated by comparing Figure 8 with Figure 14. The new time-alignment strategy as well as randomness in setup geometry has become standard practice since July of 2013.

On-Going and Future Work

Currently, work continues on defining a more detailed representation of the sound field through sound pressure measurements. To do this, in addition to the control microphones, more locations around the test article need to be measured as well as documenting all microphone array measurements. The acoustical intensity is also being measured at the surface of the sources to develop better models of the field.

The modeling effort is the next DFAT frontier to be explored. Finding a way to predict the sound field intensity and the response of the test article is essential for proving the viability of this new test method. A 3D representation of the field could be invaluable to planning, investigating and defining the test setup. In addition, the interactions between the acoustic field and the structure could then be easily obtained, and response predictions could be made prior to testing. Modeling with commercial products such as VA One and EASE could easily be adapted to predictive analysis using a DFAT sound generation module.

Currently several advanced DFAT applications are also under investigation. Chamber enhancement systems using low-frequency audio drivers with combined SISO, MIMO and conventional controllers have been designed and tested at the Naval Research Lab reverberant chamber. More details about chamber-enhancement methods and results will be discussed in a future article. Local tone excitations (whistles) have been investigated with some success.

Generally a separate drive must be reserved to contain the background reference with the tone superimposed. This can create a single tone at a particular location relative to the test article. An additional application is under study where a "collector" panel is excited acoustically to perform random vibration testing of components attached to it.

The advantage would be better-matched mechanical impedance between the test article and the driving surface. In addition, DFAT acoustic rooms are being developed with the intention of being made available for component testing. Finally, some preliminary work has been done in the area of field shaping. Current efforts have been concentrated in the horizontal (circumferential) plane, with results that indicate an overall average 0.5 dB/ft to 1.0 dB/ft gradient is achievable when attempting to vary the field.

Conclusions and Recommendations

It is very important to acknowledge that DFAT is not a replacement for traditional high-intensity acoustic testing (HIAT). Instead it is intended as a complementary alternative. After more research and modeling is done using the DFAT method, it might be understood to the point where it could become a primary testing method. The direct method provides primarily normal (perpendicular) wave impingement, and the magnitude of any incident waves is well below the magnitude of the normal waves.

The reverberant field provides equal wave intensity (magnitude and direction) at all points in the field. While the advent of new MIMO control schemes has made uniformity less of an issue, the MIMO control system still provides a finite number of independent drives and will always produce a partially coherent field.

Modeling the system will provide a means to better understand complex sound field interactions that are taking place and will lead to more efficient and higher performance designs. How the results of the DFAT method correlate with actual flight data must also be better understood for this to happen. Although DFAT has proven to be a valuable testing alternative, there is much to be learned from on-going and future investigations. The applicability of DFAT should be carefully evaluated before finalizing the test methodology. It is recommended that the sound field be measured and evaluated before testing any flight hardware, and monitoring of the sound field during the flight test should be a standard practice. It is also extremely important to determine if the sound field is driving structural response by correlating narrow-band microphone data with narrow-band accelerometer measurements.

This recommendation should be followed whether DFAT or reverberant testing is being performed, because adverse pressure and/or velocity coupling can occur in either environment. Always compare narrow-band microphone data with narrow-band accelerometer data during an acoustic test. This information should then be used to determine if response limiting should be employed and will provide justification for response limits. Response limiting identification, justification and implementation is a complex and controversial subject and will be discussed in a future article. In conclusion, DFAT has proved to be an advantageous solution for high intensity acoustical testing in many applications.

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The author may be reached at: plarkin@msihc.com.