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Insight Into the Sound Field During a Direct Field Acoustic Test (DFAT®)

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ABSTRACT

Over the past two decades, acoustic testing for the space industry has evolved from the ubiquitous reverberant chambers to using loudspeakers in what has been defined as Direct Field Acoustic Testing (DFAT). The initial need was to create a versatile system to provide a portable test facility to qualify space hardware on site as opposed to going to a dedicated test facility. Since that initial test carried out by MSI in the late ‘90s, equipment and control strategies have improved, and today it is possible to create an acoustic field with DFAT® which is very similar to that of a reverberant chamber and with even more control capability at low frequencies. Using a Multi-Input-Multi-Output (MIMO) control strategy has solved many of the initial issues. However, unlike tests in reverberant chambers, the acoustic field produced in a DFAT® test is dependent on the parameters used by the controller, its specific technology, and the whole sound generation system. This paper attempts to provide a qualitative overview and insight into the acoustic field generated by a set of loudspeakers around a test item. Focus is placed on the degree to which a test field approximates a diffuse field as this is a characteristic that is linked to the structural response of the device under test.

1. INTRODUCTION

Acoustic testing is a major milestone of a satellite mechanical environment qualification campaign (the others being the vibration test, the thermal-vacuum test, …). Since the space race began in the late 1950s, the space agencies have faced the issue of making sure that the severe noise caused by the rockets during launch and high-speed atmospheric flight would not damage the payload. As the environmental testing science evolved, the solution to test a satellite to the launch noise environment was found in using reverberant chambers. Specifically built to create a uniform acoustic field, these facilities are expensive to design, build (they have a floor isolated from the rest of the building and 500 mm thick walls) and operate (in order to reduce the sound absorption and maximize the noise, nitrogen or dry air is used to fill these chambers). These are big buildings and require large area for supporting equipment (Nitrogen storage, vaporizer and Pump)! In fact, the size is not only necessary to accommodate a large article, but to be able to create a uniform field at the lowest possible frequency. This frequency, referred to as the ‘cut-off’ frequency, is determined by the size of the chamber: the bigger the chamber, the lower is the frequency at which the acoustic field becomes uniform. The cutoff frequency of a reverberant chamber is typically set based on providing a minimum number of acoustic modes in the lowest 1/3 octave band of interest (perhaps 31.5 Hz) [1], and large chambers have volumes of 1000 m3, 2800 m3, or even more.

As the space conquest expanded from the national government (or agencies) to the commercial sector, the necessity of increasing the efficiency of a program pushed engineers to look at more efficient ways to complete the test schedule, of course without having to compromise on its result or validity. Because of several reasons, the US industry is leading the technology, use and development of DFAT® (also referred to as Direct Field Acoustic Noise, DFAN).

2. DIRECT FIELD ACOUSTIC TESTING

In a usual DFAT test, the speakers are set up in a circle around the test object. A number of microphones, 24 typically, are randomly positioned in the test volume. The digital MIMO controller makes sure that the field is uniform and diffuse over the test volume as prescribed by the satellite owner. It does so by producing N independent drives in an active control loop that ensures that each control microphone meets the target spectrum.

As just described, a DFAT® system is made of two main components: a digital control system and an acoustic excitation system with several sources. Albeit in need of an update, the NASA handbook 7010 [2] contains a good historical overview of the development of DFAT® technology. To avoid any repetitions, this paper will provide only a summary. Initially, the control of the sound field was done using a Single-Input-Single-Output (SISO) control technology. This ensured the necessary accuracy in the average spatial sense (the average of the microphones matched the acoustic profile very closely), but each of the microphones measured an SPL very different (>12 dB) from the others. Over the years a more accurate control strategy based on Multi-Input-Multi-Output (MIMO) has been developed. From a square control strategy [3] (that is there were an equal number of drive outputs and control channels) the algorithm has evolved to a rectangular controller and the results showed a significant improvement in the uniformity, especially at the control points. In particular, the system developed by MSI-DFAT uses a technology to control the coherence of the acoustic field [4,5].

Over the past years (after the publication of the NASA Handbook in 2016) there have been new attempts to perform DFAT® using different approaches. Alvarez *et al* [6] describe a method to overcome the limitations of the system in terms of maximum number of control microphones and drive signals. An optimization routine is used to choose the best subset of microphones (up to 12) out of a larger set on which to control the acoustic field.
The work in [7] is the newest and attempts to control the acoustic field using a well-established control strategy for reverberant chambers which does not use a narrow band control strategy.

This work proposes to use a new parameter to define the information, data and plots to look at when performing DFAT®: the Sinc Indicator Function (SIF). When added to the current requirements on homogeneity and average spectrum plots, the SIF will provide a more complete picture to test engineers about the quality of the test performed. Unlike acoustic testing in reverberant chambers, each DFAT® test might generate an acoustic field different from another. This paper attempts to provide engineers with a simple, qualitative metric to look at when conducting DFAT® tests.

3. DIFFUSE CHARACTER OF THE ACOUSTIC FIELD AND CI/SIF

In the quest for a metric to quantify how close a field is to a diffuse field, it is appropriate to start by defining this property. A definition is provided by the IEC [8]: “A diffuse sound field is a sound field which in a given region has statistically uniform energy density, for which the directions of propagation at any point are randomly distributed”. In such a field the waves travel with all the angles of incidence, so a microphone in a diffuse field measures the same magnitude regardless of orientation or location. Another take is that in a diffuse sound field the sound doesn't appear to have a single source.
For the first time in the space industry, the requirement for a diffuse field target is explicitly mentioned in some of the launcher’s user manuals. For example, the Ariane VI Users Manual [9] states “*Acoustic testing should be accomplished in a reverberant chamber. The volume of the chamber with respect to that of the spacecraft shall be sufficient so that the applied acoustic field is diffuse.*”

It can be argued that there are two main reasons for the requirement of diffusivity during the acoustic testing of space hardware: (a) historically (large) reverberant chambers have been the most common way of accommodating such large structures and producing sound levels above 145 dB, and they produce a good approximation of a diffuse field and (b) the analytical and numerical vibroacoustic models simplify greatly when the field is diffuse. For example, the formulation of the joint acceptance includes cross-pressure terms, and its expression becomes handier for both analytical and numerical predictions [10]; Yang [11] has also used numerical simulation to illustrate that a diffuse field provides the optimal excitation to the structure.

In 2000 Jacobsen and Roisin published a paper on the coherence of a reverberant chamber [12]. The paper sets out to define a way to measure the spatial coherence functions and relate these to their analytical expressions derived assuming a perfectly diffuse field. The authors start stating that *“The diffuse sound field is an idealized concept, and the sound field in any real room differs in fundamental respects from a diffuse field”* and then suggest that *“One possible way of testing the diffuseness of the sound field in a given room might be to compare theoretically predicted spatial correlation functions with measurements.”* In the study the authors find that when CSD and PSD spectra are measured in different locations of a reverberant chamber, between microphone pairs that are identically spaced, are spatially averaged and the resulting averaged PSDs and CSD are conventionally used to determine the resulting coherence between the microphone pairs, it matches closely the theoretical value. The match is not as good in a standard room.

For what concerns more specifically the space industry, there are some interesting scientific discussions on the nature of the acoustic field in the fairing during launch. Shi [13] presents the study done at JAXA which concludes that the acoustic field measured during launch is not entirely reverberant, but the nature of the field changes through the different phases of the launch. Similarly, Gardner [14] shows how the sound field measured and analyzed by NASA JPL during Cassini’s launch was not as diffuse as theoretically might be expected. The paper followed the same reasoning presented by Jacobsen and looked at the difference between the measured coherence and the theorical expression.

In a theoretically diffuse field, the coherence γ_{xy}^2 between two points at locations x and y is mathematically expressed by the sinc function squared

$$\gamma_{xy}^2 = \left(\frac{\sin\,(kr_{xy})}{kr_{xy}}\right)^2 \tag{1}$$

where r is the distance between x and y and k is the acoustic wavenumber [11-13].
At the same time, the coherence Γ_{xy}^2 can be computed from measured data (during a test) as

$$\Gamma_{xy}^2 = \frac{|S_{xy}|^2}{S_{xx}S_{yy}} \tag{2}$$

where S_{xy} is the Cross-Spectral-Density between the microphones at locations x and y and S_{xx} and S_{yy} are the (auto)Power Spectral Density (PSD) at each location [11].

By plotting these two functions that express the same physical quantity, Gardner showed that in the fairing, during launch, the measured coherence has quite some difference from the theoretical values, as shown in Fig.1. The principle of looking at the difference between the theoretical and experimental values is expressed in several references, as for example in [15-17].

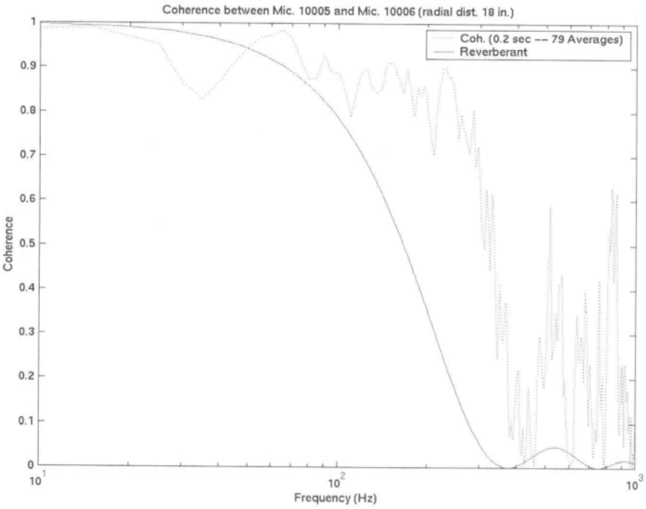

Figure1: Plot presented in Ref. [14] to show the difference between the coherence measured during launch (dotted line) and the theoretical (diffuse) value (solid line)

This paper proposes a method to quantify how closely the measured coherence of an acoustic field matches the coherence of an ideal diffuse field by looking at the difference between the measured coherence and the theoretical value of a diffuse field. For each pair of microphones used in the experiments (during DFAT® satellite testing 24 microphones is customary) this difference is a function of frequency, as shown as an example in Fig 2. Here is proposed to define a single curve, the Sinc Indicator Function (SIF), which is defined as

$$SIF(f) = 1 - \overline{\Delta\gamma^2} \tag{3}$$

where $\overline{\Delta\gamma^2} = \left|\overline{\gamma_{xy}^2(f) - \Gamma_{xy}^2(f)}\right|$ is the spatial mean error between the coherence of a theoretical diffuse field and that measured during a test (at each frequency line). As an example, a typical SIF is plotted in Fig.2 with a thick red line. The intent of this type of averaging in the paper is only to provide a function for relative comparison between two different fields, and it is not meant to produce a true average coherence curve.

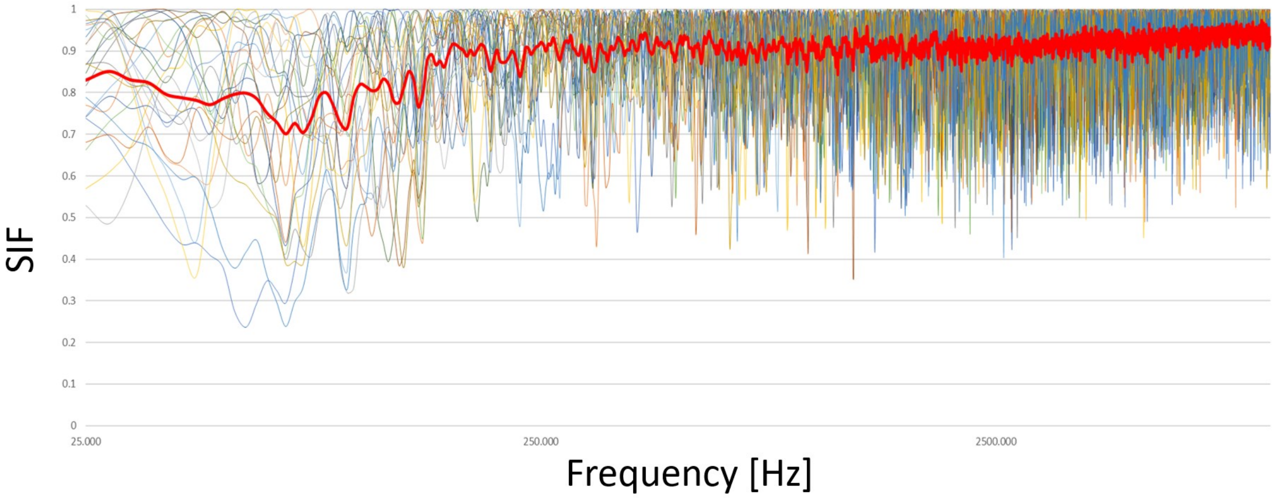

Figure 2: Plot of the difference between theoretical and experimental coherence for each pair of microphones and SIF (thick red line)

Finally, the SIF is averaged over the frequency range (usually 25-10000 Hz) to obtain the OverAll SIF (OASIF). As with all averages over a wide frequency band, the final averaging to a single, overall value does hide the specific spectral variation of the coherence curve.

$$\text{OverAllSinIndicatorFunction (OASIF)} = \text{Avg (SIF)} \tag{4}$$

Therefore $0 < \text{OASIF} < 1$ with $\text{OASIF} = 1$ indicating that the coherence of the measured field matches the coherence of a theoretically diffuse field. Note that $\text{OASIF} = 1$ is not proposed as sufficient to show that a field is diffuse, but rather to show that the measured coherence of the field matches the coherence of a diffuse field.

4. DIFFUSE CHARACTER OF A FIELD DURING ACOUSTIC QUALIFICATION TESTS

For this metric to be computed, the locations of the microphones must be known. This is necessary to compute the theoretical value of the coherence, Eqn. (1). Also, it is necessary to record and store the time histories of the microphones used in the experiments. These will be used to compute the experimental coherence expressed by Eqn. (2). With the two quantities available, the computation of the SIF given in Eqn. (3) becomes an algebraic exercise.

In this section the data measured using different experimental setups will be shown to demonstrate the efficacy of the newly defined SIF to show how close the measured coherence of an acoustic field is to that of a diffuse field, with particualr reference to those fields generated during Direct Field Acoustic Tests for space hardware.

The acoustic properties will be represented by 3 graphs for each case:

I. The spectrum in octave bands (full or 1/3 depending on the customer's requirements): This graph contains the target spectrum or reference, the average spectrum of all the control microphones and the spectrum of each microphone.
II. The homogenity of the field: This graph uses the criterion set forth by the Ariane 6 Users Manual [9], and plots the difference between each control microphone and their average at each octave band. The criterion requires that this difference doesn't exceed ±3 dB
III. The SIF

Reverberant Chamber: Figure 3 shows the plots generated from data measured in a large reverberant chamber. The SIF is in line with the expectations: an OASIF of 0.98 and a drop in OASIF in the lower frequency region (below the Schroeder frequency for this size of chamber [1]).

8 Drives setup – 0 Coherence: For the test shown in Figure 4, the field has been controlled on 24 microphones using 8 independent drives. Comparing it with the plots in Figure 2 it can be seen that the DFAT® system produces an acoustic field which is essentially equivalent to that in a reverberant chamber.

8 Drives setup – 0.6 Coherence: Figure 5 shows that whilst average control and uniformity are maintained, the SIF drops considerably over the entire frequency range, reaching an OASIF of 0.86.

Discussion and Future Directions

The SIF is a function of frequency that provides an immediate view of how close the measured coherence of a DFAT® field is to the coherence of a theoretical diffuse field (OASIF=1). The page limit doesn't allow plots for all the other cases which have been studied. One main conclusion of this work is that by using a MIMO control algorithm, MSI can generate different acoustic fields by changing the parameters of the controller. This leads to the conclusion that an acoustic field produced during a Direct Field Acoustic Test depends on the technology used. The SIF introduced here could provide the space test community with a metric for comparing one aspect of different fields produced with DFAT® other than the SPL spectrum. Importantly, this paper does not propose the OASIF as a single, sufficient measure of how closely a field approximates a diffuse field, and the authors are not aware of a single measure that can do this. However, the OASIF does provide a simple indication of how closely the measured coherence of a field matches the coherence of an ideal diffuse field. Attention must be paid when averaging and processing data from two different fields/measurements (e.g., number of microphone pairs, analysis bandwidth, etc.) [12]. It is noteworthy that the numerical value and number of significant digits (for which two significant digits have been arbitrarily chosen in this work) used are not yet fully explored and how the OASIF value is linked to the field will be object of further analysis. Also, there other 2 quantities that could be analyzed in relation their expression for a theoretical diffuse field: spatial homogeneity of SPL and phase. Areas of research will be on how data measured in different points (both vertically and horizontally spread) of the acoustic volume/field can be averaged and processed to provide a complete picture on the nature and type of the field.

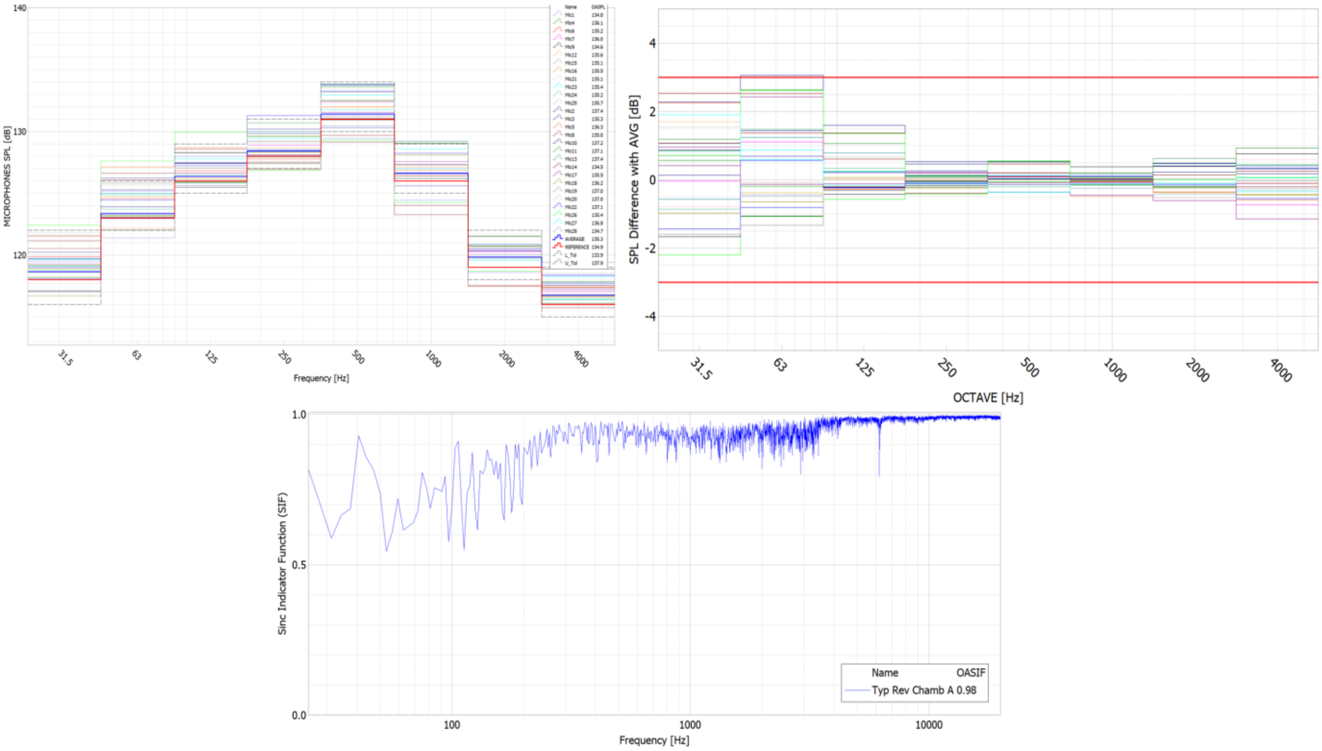

Figure 3: Acoustic Field in a Large Reverberant Chamber

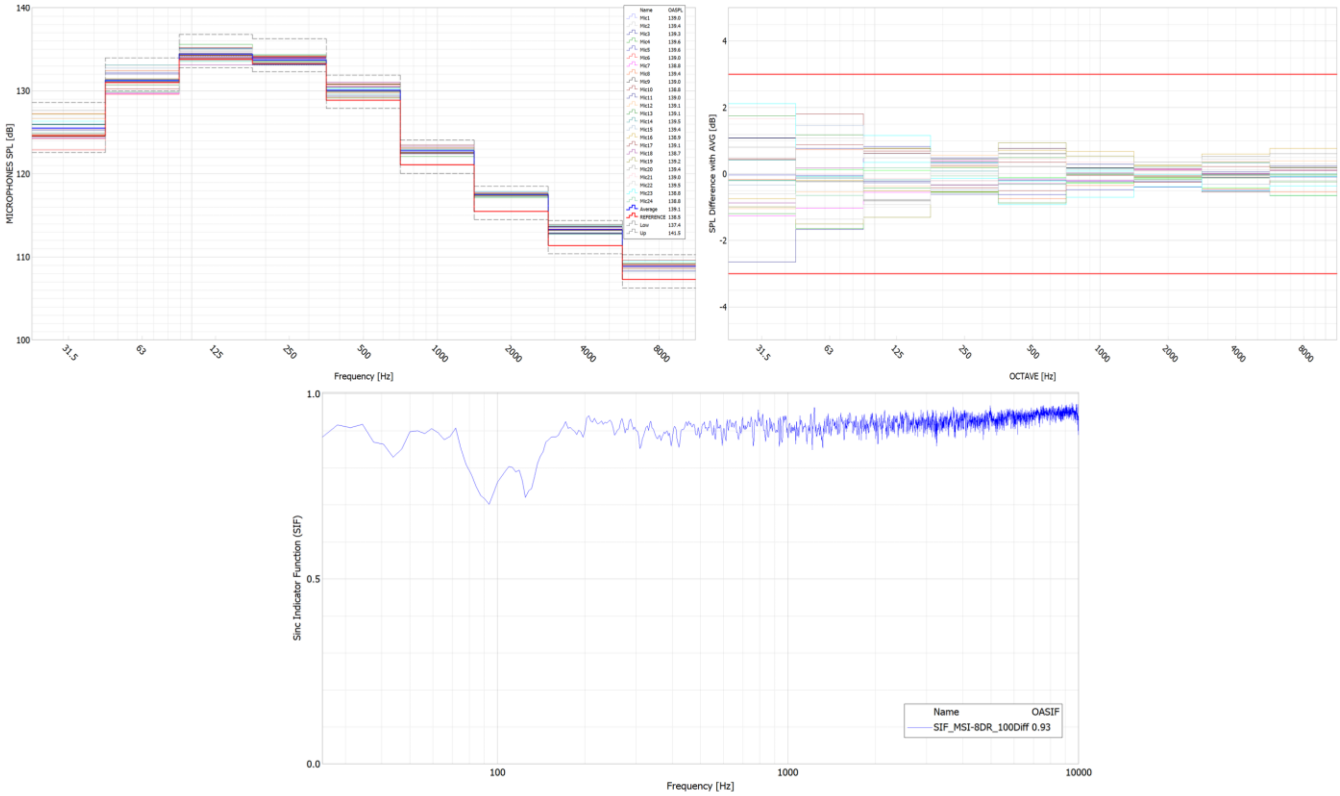

Figure 4: Acoustic Field Produced by MSI-DFAT with 8 Drives and 24 Control Microphones Set at 0% Coherence

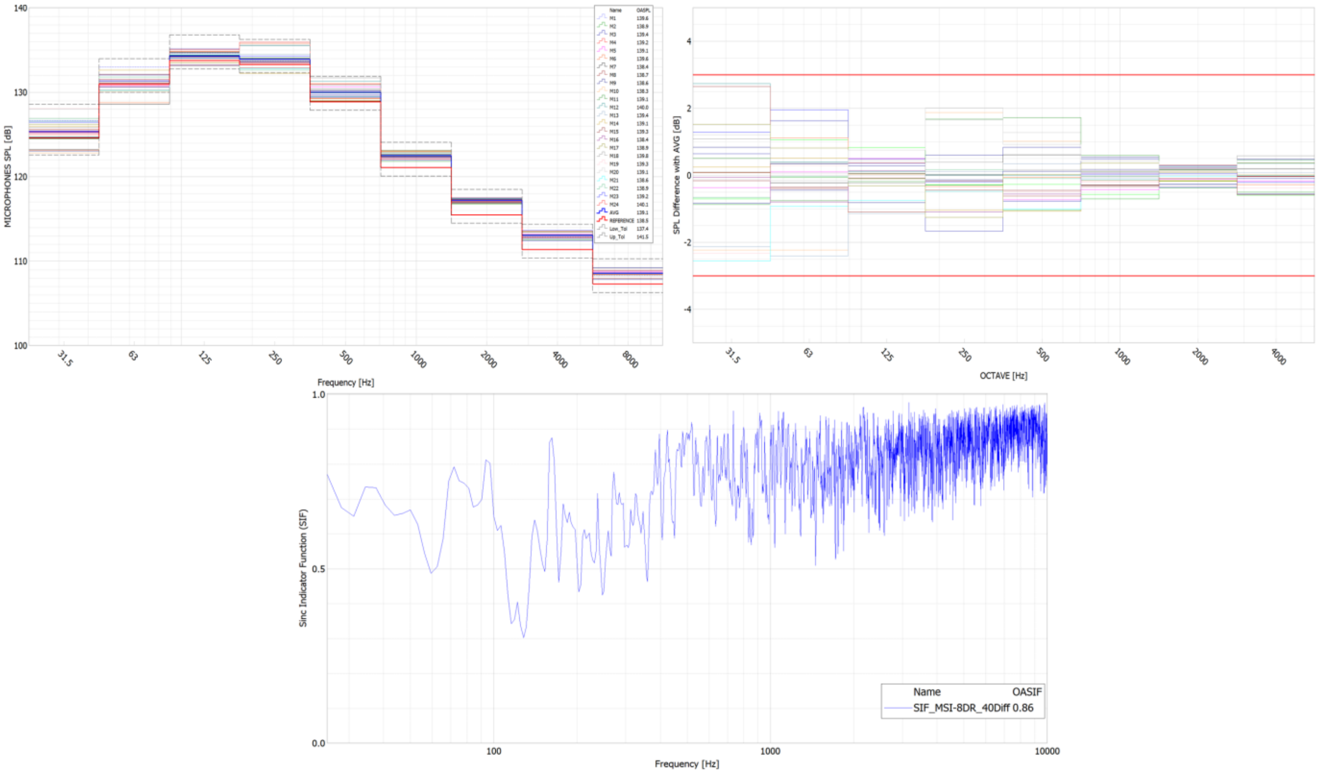

Figure 5: Acoustic Field Produced by MSI-DFAT with 8 Drives and 24 Control Microphones Set at 60% Coherence

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