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A Digital Twin for full-field monitoring in multi-channel control with applications to direct field acoustic testing

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Abstract

Direct field acoustic excitation (DFAX) is an increasingly adopted method to conduct environmental acoustic tests of space hardware which avoids the need of large reverberant rooms. Such tests are conducted by exciting the payload via direct acoustic radiations generated by a set of high-powered loudspeakers. Based on previous research, a comprehensive Digital Twin of the electro-acoustic plant is utilized to simulate the frequency responses of all the sub-systems in the plant, including digital audio processing, loudspeaker performance, sound propagation and structural response. In this paper, a model update approach is proposed to tune the electro-acoustic contributions in the simulation based on experimental data obtained during the test. Such model can be subsequently linked to the multiple-input multiple-output (MIMO) control loop to complement the physical responses obtained from the field sensors with simulated data. Consequently, the resultant Digital Twin enables test engineers to obtain the system responses at locations where no physical sensors are available, thus improving the control test performance via full-field monitoring.

Keywords: Direct Field Acoustic eXcitation, Digital Twin, Environmental testing, Multi-Input-Multi-Output, Vibro-acoustic Simulation.

1 Introduction

Environmental acoustic tests are conducted to assess the survivability of payloads against harsh noise conditions. In the space industry, the performance of such tests is part of the qualification campaign for satellites and spacecrafts which is carried out to ensure that the high sound pressure levels (SPL) generated during launch do not compromise their structural integrity or the operation of their components. The traditional method to test against such conditions is the use of large reverberant chambers in which the payload is excited by diffuse sound fields [1]. Although this approach has set the standards for environmental acoustic tests, the space industry is looking for more efficient techniques to alleviate the need of transporting the payload to such facilities. In this context, direct field acoustic excitation (DFAX) is gaining attraction in the recent years as a more flexible and cost-efficient approach to perform acoustic qualification tests of spacecraft without the necessity of an ad-hoc facility [2].

In DFAX tests, the payload is excited by the direct sound waves generated by arrays of high-powered loudspeakers installed around it. The electro-acoustic plant can be built at any conventional room large enough to house the set-up, with overall sound pressure levels over 145 dB being reported [3]. In order to achieve similar acoustic fields as in reverberant chambers, advanced multiple-input multiple-output (MIMO) control systems are usually put in place to replicate the test references provided by the launcher authority, as shown by Larkin [4]. Indeed, the design of the test set-up and the selection of control parameters play a huge role in the ability of the control system to represent efficiently the acoustic references, thus much care must be put to avoid costly, and risky, trial and error iterations. To mitigate such issues, different methods have been proposed in the past years to automatically define key parameters of the MIMO control system, such as the pre-test analysis proposed by Alvarez Blanco et al. [5].

Given all these challenges associated to the realization of efficient DFAX tests, different simulation approaches are being introduced to support test engineers in the design and dimensioning of the electro-acoustic plant, see for instance [6] or [7]. Depending on the detail of the (vibro-)acoustic model, engineers can get from a rough estimation of the structural responses in the payload subjected to the acoustic excitation, to a full simulation of all the system responses in the MIMO control test. In order to achieve the latter, a Digital Twin containing all the transfer functions of the system must be generated, i.e. including the responses of the electro-acoustic actuators as well as a proper description of the waves propagating, scattering and reflecting in between the loudspeaker stacks and off the payload, as described for instance in a previous work by de Miguel et al. [8].

Based on the models proposed in the latter work, in this research we generated a full Digital Twin of a small-scale DFAX set-up which has been built in the facilities of Siemens in Leuven (Belgium). The simulation model accounts for the dynamics of the electro-acoustic transducers through well-known lumped-parameter models [9], and the wave propagation in the test volume is numerically calculated via a state-of-the-art vibro-acoustic solver based on adaptive order finite elements, described in the work of Bériot et al. [10]. This paper proposes to reuse such model to estimate full-field responses in a physical DFAX test. By complementing the experimentally measured transfer functions with numerical ones coming from the Digital Twin, test engineers can visualize all the system responses, e.g. the pressure fields, in locations were no physical sensors are placed. Such technology has the potential change the way this type of MIMO control tests are performed, as much more information can be make available to evaluate the performance of the acoustic test. In addition, in order to increase the confidence on the model accuracy, a model update technique is introduced to reduce the error of the numerical model with respect to the measured acoustic responses on-site.

The paper is structure as follows: first, the small-scall DFAX plant used in the current research is presented in Section 2. Then, Section 3 introduces the Digital Twin of the physical set-up, including a brief description of the models employed. Section 4 aims at describing the approach followed to generate full-field solutions during the MIMO control test. The results are discussed in Section 5, focusing mainly on the correlation levels achieved by the Digital Twin. Finally, the conclusions are drawn in Section 6.

2 Electro-acoustic system

The proposed DFAX set-up is shown in Fig. 1. It consisted of a total of 45 small-size loudspeakers stacked in a cylindrical configuration of 9 columns. Such arrangement was introduced to mimic the typical layout of the electro-acoustic plants utilized in full-scale DFAX tests for qualification and acceptance of space components. The test set-up had a inner diameter of 66 cm and a maximum height of 76 cm at the top of the speaker stack. For each column, the loudspeakers were stacked on top of each other and attached to a metallic beam structure to ensure they stayed aligned in the vertical direction.

The loudspeaker model was the Control 1 Pro by JBL, a compact 2-way cabinet with a specified frequency range of 80 - 20000 Hz. This model's cabinet contains a 135mm diameter low frequency woofer and a 19 mm tweeter, and features a crossover frequency of 4.2 kHz. The input signal to the loudspeakers was delivered by an Audio Toolbox by Auvitran [11], which provides signal processing and power amplification.

The DFAX system was instrumented with 24 free-field array 1/4-inch microphones to acquire the acoustic responses inside the test volume. The microphones were placed randomly at different locations in between the loudspeaker stacks, hanging from a metallic grid which is placed on top of the beams that sustain the speakers, as depicted in Fig. 1. Such configuration was implemented to avoid introducing any stands in the test volume, as the microphones were hanging from their SMB cables directly.

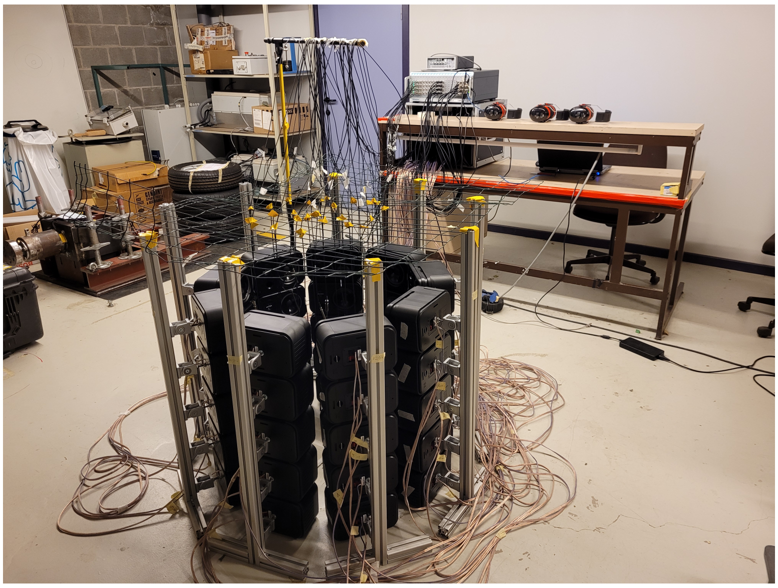

Figure 1: Picture of the small-scale DFAX setup.

In addition, a rectangular plate of dimensions 27.3 × 32.8 cm was installed at the center of the test volume with the aim of simulating the payload in real DFAX tests. The structure was made of a thin layer (approximately 1 mm) of Aluminum and was hanging with elastic cords from two large stands placed on opposite sides of the set-up.

The signal generation and data acquisition in the test was done with a Simcenter SCADAS Lab hardware [12] and the control algorithm was provided by the software Simcenter Testlab MIMO Random Control [13]. The test specification was introduced in the software in the form of a third-octave band spectrum profile of constant value with an overall SPL (OASPL) of 90 dB between 50 and 10000 Hz. 9 independent drive signals (one per column) were set to control the acoustic fields, which were characterized by the 24 microphones aforementioned. An automatic selection of 12 control sensors was performed based on the pre-test analysis [5], leaving another 12 microphones for monitoring purposes.

3 Digital Twin

The Digital Twin was generated in the simulation platform Simcenter 3D [14]. The aim of the model was to simulate as accurately as possible the system responses in the MIMO test, thus all the main components of the electro-acoustic plant were modelled, namely: signal processor, electro-dynamic transducers, the acoustic media in which the sound waves propagate and the plate structure. An illustration of the 3D vibro-acoustic model created in this work is included in Fig. 2.

In a DFAX configuration, the pressure responses measured at the field sensors are defined by the direct acoustic radiation from the loudspeakers as well as the reflections off the stacks and the structural item. Indeed, it has been observed that standing waves appear due to wave interference patterns in the test volume as well as the room geometry [4]. In order to capture such complex responses, a full 3D numerical model of the acoustic media was generated using state-of-the-art acoustic solvers. The acoustic domain covered the entire test set-up from the ground and it is discretized using the adaptive order finite element method, also known as FEMAO [10]. This method solves numerically the acoustic propagation problem described by the Helmholtz equation in a very efficient manner by adjusting locally the interpolation order of the finite elements for different frequencies and element sizes.

Free-field conditions were applied over the air external surfaces via the so-called Automatically Marched Layer

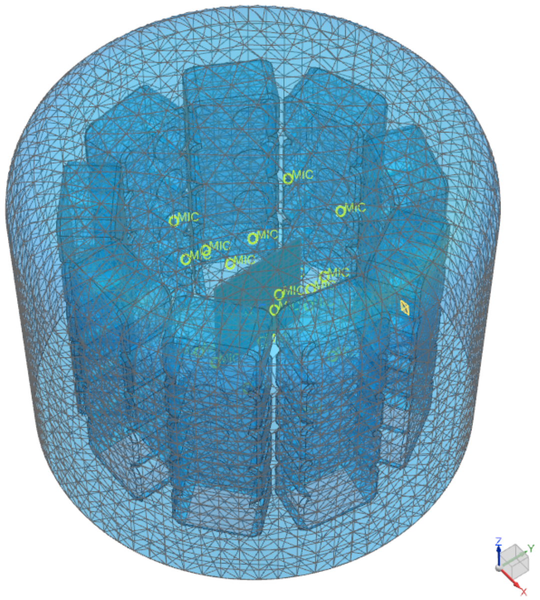

Figure 2: Illustration of the vibro-acoustic model of the DFAX plant generated in Simcenter 3D.

(AML), which efficiently absorbs outgoing waves in the convex boundary [15]. The ground was modelled as an acoustically rigid surface and the fluid-structure interaction with the structural component is represented with two-way coupling. The targeted frequency range was 50 - 1000 Hz, with a resolution of 3.125 Hz. The maximum number of degrees of freedom of the acoustic model were 113,334, and the computation lasted slightly less than 5 min in a laptop of 64 Gb of RAM using 4 parallel processes.

The radiation from the loudspeakers was introduced as acoustic velocity loads applied on the driver's faces. The response of the electro-acoustic transducers was estimated via lumped-parameter models, which provided an analytical representation of the actuator response based on the Thiele-Small parameters [16]. The level of correlation achieved by the loudspeaker model is depicted in Fig. 3, which shows a comparison of the velocity measured with a laser Doppler vibrometer (LDV) at the center of the membrane against the estimation of the lumped-parameter model. Finally, the voltage amplification functions were also measured and added to the electro-dynamic response in the model.

The resulting model can be used to perform virtual testing activities in the early stages of the test campaign, which can be extremely useful for test engineers to design of the acoustic set-up according to the target references, perform what-if scenarios and optimize various parameters of the MIMO test via numerical analyses. In this context, recent works [7, 17] have proposed the application of pre-test algorithms in the Digital Twin to simulate the behavior of the control system and optimize relevant parameters such as the selection of control sensors.

4 Full-field monitoring in MIMO control acoustic tests

Another use which can be given to the Digital Twin presented in the previous section is to augment the space of physical responses available in the test with virtual solutions. Indeed, the FRF matrix generated by the simulation has the same form as that generated by the control software from the non-parametric model of the

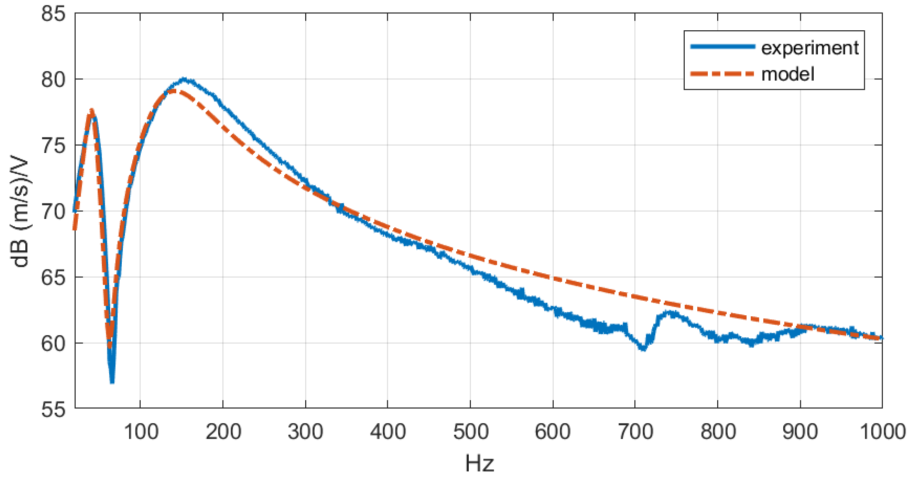

Figure 3: Acoustic velocity measured at the center of the woofer (blue line) and estimated by the lumped-parameter model (dashed red line).

system, i.e.

$$\boldsymbol{p} = \boldsymbol{H}\,\boldsymbol{v} \tag{1}$$

where $\boldsymbol{H} \in \mathbb{C}^{m \times d}$ is the transfer matrix between the drive signals $\boldsymbol{v} \in \mathbb{C}^{d}$ and the pressure responses $\boldsymbol{p} \in \mathbb{C}^{m}$. Note that all the operations hereinafter are performed per frequency line. By substituting the experimental transfer matrix with the one obtained from the simulation model, for any given set of values of the drive signals one can estimate the full-field responses as

$$\boldsymbol{p_s} = \boldsymbol{H_s}\,\boldsymbol{v} \tag{2}$$

where $\boldsymbol{H_s} \in \mathbb{C}^{n \times d}$ contains the simulated FRF at n virtual senors and $\boldsymbol{p_s} \in \mathbb{C}^{n}$ are the corresponding complex pressures. Note that in the model, one can introduce as many virtual sensors as desired, see Fig. 4, thus enabling the computation of full-field responses during the test.

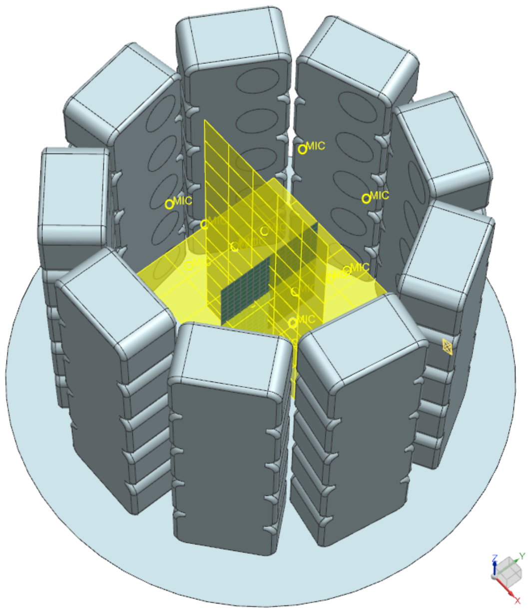

Figure 4: 3D model of the DFAX set-up including the modelled microphone sensors in yellow.

In closed-loop MIMO random tests, the role of the controller is to compute the voltage signal values that minimize the error between the test targets and the measured acoustic responses. The estimated drive signals are in a first step provided in the form of a spectral density matrix (SDM), $\boldsymbol{S_{vv}} \in C^{d\times d}$, which contains the power spectral densities (PSD) and cross-power spectral densities (CSD). Once available, this matrix can be retrieved and used to estimate the responses at the virtual sensors as follows

$$\boldsymbol{S_{pp}} = \boldsymbol{H_s}\, \boldsymbol{S_{vv}}\, \boldsymbol{H_s}^H, \tag{3}$$

where $\boldsymbol{S_{pp}} \in C^{n\times n}$ contains the spectral terms of the virtual responses. Such approach allows test engineers to visualize the pressure values achieved at the test in locations where no physical sensors are placed. In DFAX tests, such capabilities can be used to get a complete view of the properties of the acoustic fields generated by the control system at any desired location of the test volume.

4.1. FRF update

Due to various uncertainties and assumptions in the model, one should expect a certain level of error when correlating the simulated FRFs with those measured at the physical plant. If this error is too high, the confidence in the virtual solutions computed via Eq. 3 would be reduced and the value of the full-field monitoring to extract quantitative metrics might be heavily compromised. In this paper, we propose a simple method to improve the correlation of the model outputs with respect to the experimentally identified FRFs of the system. The underlying idea is to adjust the contribution of the boundary conditions, which in the current modeling framework correspond to the electro-acoustic functions described in Section 3, based on a comparison of the simulated and measured functions at a subset of observation microphones, o, for which there is geometrical correspondence. Mathematically, such operation can be written as

$$\boldsymbol{H^o} = \boldsymbol{H_s^o}\, \boldsymbol{E} \tag{4}$$

where $\boldsymbol{H^o}$ and $\boldsymbol{H_s^o} \in \mathbb{C}^{o\times d}$ are the experimental and simulated transfer matrices, respectively, at the observation sensors, and $\boldsymbol{E} \in \mathbb{C}^{d\times d}$ is a complex matrix containing the correction factors of the electro-acoustic loads. The values of $\boldsymbol{E}$ can be computed in different manners based on the model update choice, but, in general, one can assume that the number of observation sensors is greater than the columns of $\boldsymbol{H_s^o}$, i.e. the number of drive signals, leading to an over-determined system of linear equations which can be solved via least-squares. Once $\boldsymbol{E}$ is computed, the full updated matrix of FRFs can be recovered as

$$\boldsymbol{H_{upd}} = \boldsymbol{H_s}\, \boldsymbol{E} \tag{5}$$

The performance of the model update can be checked by evaluating the correlation between the responses obtained at the remaining physical sensors, $k = m - o$, and their virtual twins. Such checks provide the test engineers with very important information on how well the improved model is representing the physical system in locations which are not utilized during the model update process.

5 Results

The results included in the present section follow two purposes: first, the validation of the numerical models via correlation analysis with the measured FRF values; and secondly, to show the visualization of virtual data at measured and unmeasured locations in the MIMO random control test.

5.1. FRF correlation

The experimental transfer functions were obtained from a low-level open-loop test using 9 uncorrelated pseudo random signals. Figure 5 shows the FRF values [Pa/V] in dB obtained at one of the microphone sensors from:

the test (solid blue line), the original model described in Section 3 (dashed red line), and the updated model based on the method described in Section 4 (dash-dotted yellow line). The selected sensor, microphone 24, is located at the point 15.3 cm × 10.65 cm × 55 cm with respect to a coordinate system placed on the ground at the center of the set-up, and the FRF is calculated with respect to the drive signal number 5 (fifth column of the $\boldsymbol{H}$ matrices).

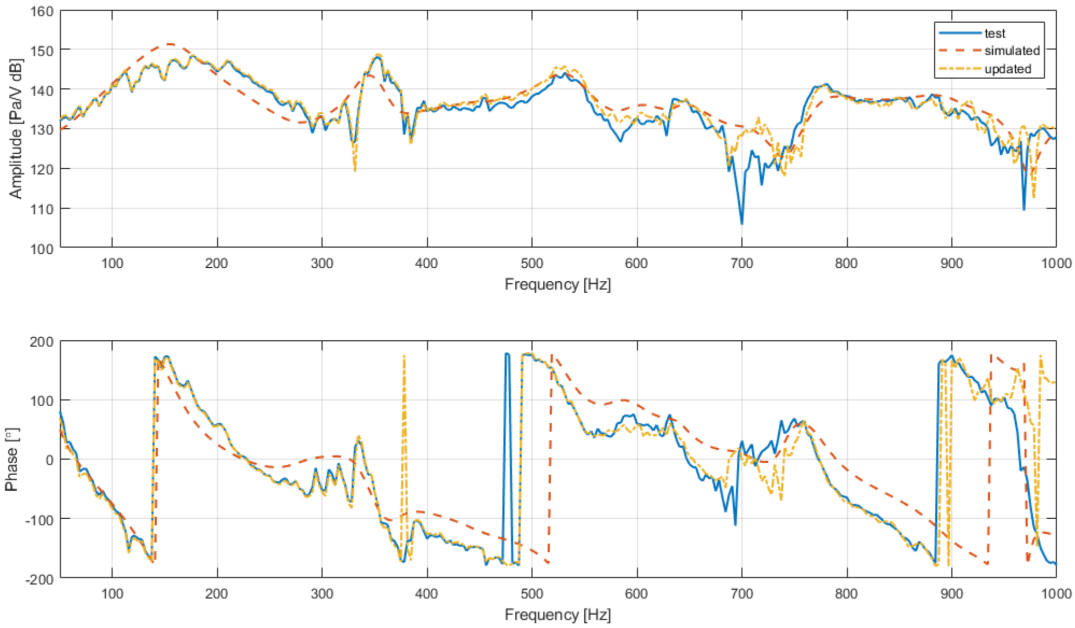

Figure 5: Amplitude and phase values of the FRF at microphone 24 obtained at the test and from the simulated and updated models.

Regarding the original model, one can observe that the direct frequency simulation estimates fairly well the transfer function identified in the test, both in amplitude (top graph) and phase (bottom graph). As expected in this type of acoustic measurements, the experimental curves are noisier than that provided by the model, which does not simulate certain effects such as reflections from the room and surrounding objects. However, it is clear that the main dynamics of the system are well captured. Also, a small delay is noticed in the phase response, which is probably due to a latency in the electro-acoustic system not properly represented in the lumped-parameter model.

The updated FRFs are computed using a total of 15 microphones as observation sensors (microphones 1 to 15), thus leaving 9 sensors for validation purposes. It is noted that the selection of the observation sensors for the model update is independent of the choice of control/monitoring microphones for the MIMO test. The results shown in Fig. 5 correspond to one of the latter set. It is clear from the plot that the FRF values are considerably improved over the entire frequency range considered (50 Hz - 1000 Hz), especially at low frequencies where the values are almost on top of the experimental ones. Another aspect to note is that the phase delay observed in the original model is effectively corrected. Figure 6 includes the correlation with respect to the experimental values based on the root mean square error (RMSE) for all 24 microphones. As expected, the error is reduced at the observation sensors when the FRF update is performed. Also, the correlation in all validation microphones (microphones 16 to 24) improves considerably, although slightly less than in the observation sensors which are used to update the model. These results indicate that there is a good level of confidence in the virtual responses provided by the updated Digital Twin at any other point within the test volume.

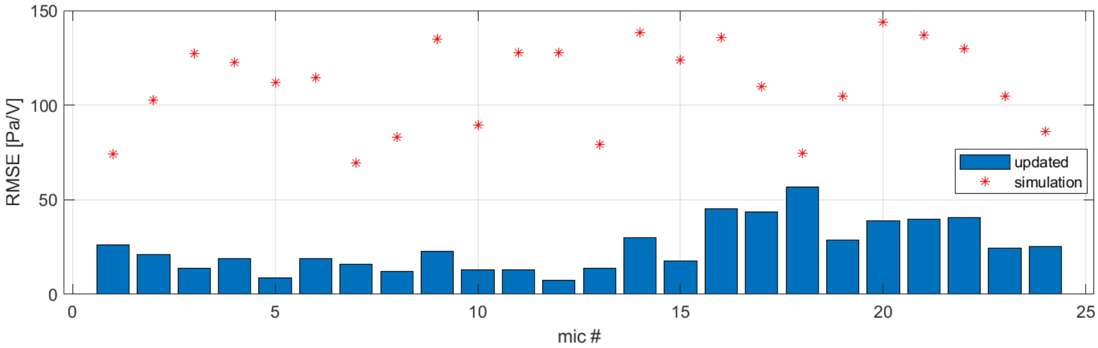

Figure 6: Comparison of the correlation error (RMSE) with respect the test references at all 24 microphones for one of the drive signals.

5.2. Full-field monitoring

The MIMO control test was performed using the SPL profile depicted in Section 2, a flat third-octave band spectrum of 90 dB OASPL between 50 and 10000 Hz, as reference at all the control sensors. Once the SDM of the drive signals were computed by the controller, the matrix of simulated FRFs can be used to obtain the acoustic responses at all virtual channels via Eq. 3. Figure 7 shows a plot of the PSD data obtained in Simcenter Testlab at one of the control sensors (microphone 20), which is used in this exercise for validation of the model update. The curves correspond to the targeted pressure values (green line), the measured response (red line) and the virtual response at the same location (blue line). As before, the agreement between physical and simulated solutions is very good, in particular at low frequencies, which gives us further confidence in the full-field data.

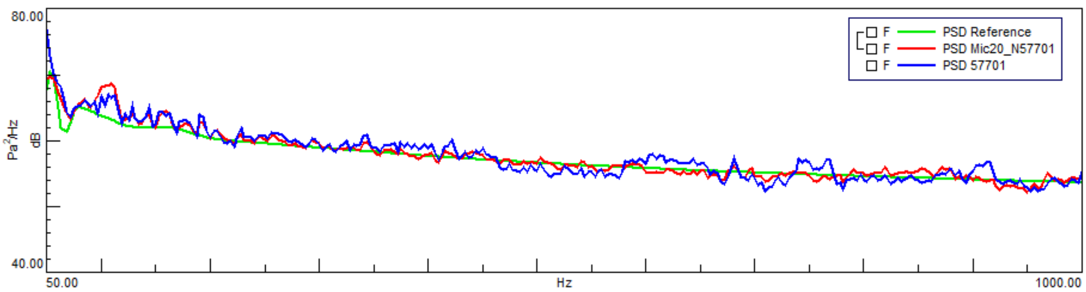

Figure 7: PSD values measured (label Mic20_N57701) and predicted (label 57701) at one of the control sensors during the MIMO control test. The acoustic reference is also included.

Other than the virtual measurements at the observation and validation microphones, the main goal of the proposed Digital Twin is to provide an estimation of the system responses in unmeasured locations, anywhere in the test volume were there are no physical sensors in place. As an example, Fig. 8 illustrates these full-field monitoring capabilities of the proposed approach for MIMO control tests. The image shows the contour plots of the PSD curve at 50 Hz over the microphone planes included in the model of Fig. 4. These virtual solutions provide the test engineers with highly useful information regarding for instance the capabilities of the control system to achieve the acoustic references, as well as the eventual presence of high pressure areas or reflection patterns which might be uncontrolled. Corrective actions to improve the environmental acoustic test campaign might be taken onsite based on the extra information provided by the Digital Twin.

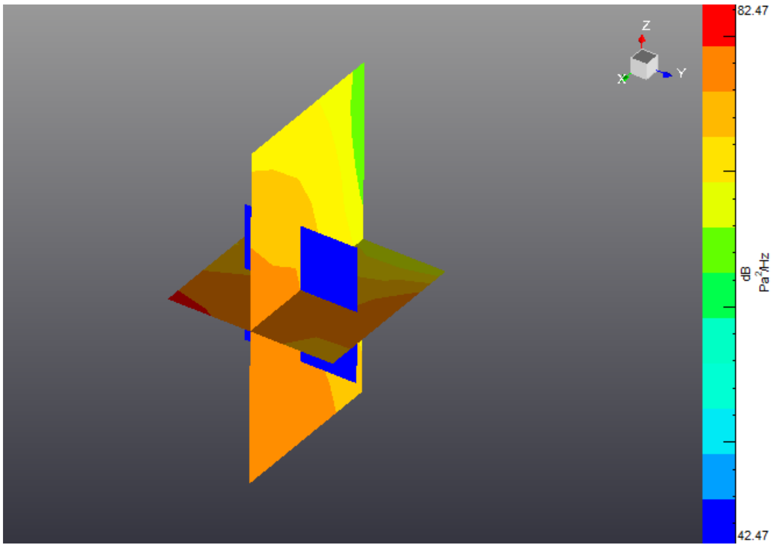

Figure 8: Visualization in Simcenter Testlab of full-field PSD solutions in two planes intersecting the plate used as test specimen.

6 Conclusions

The present work introduces a comprehensive Digital Twin of a small-scale DFAX for the estimation of full-field responses in MIMO control tests. The electro-acoustic plant under study consisted of a reduced size DFAX set-up with 45 small loudspeakers pointed at the center of the cylindrical configuration and driven by 9 independent signals routed to each speaker column. A full simulation of the MIMO set-up was created by modelling all the relevant transfer functions of the control system in between the signal generation and the sensor measurements. Such model is then used during the test to evaluate the acoustic fields in locations where no physical microphones are available.

The possibility of visualizing full-field data on-site has the potential to change the current procedure to conduct environmental tests as far more information is available through the Digital Twin for engineers to evaluate the performance and efficiency of the control strategy. In order to increase the confidence in the simulation, a simple model update procedure is introduced to improve on-site the correlation of the numerically computed FRFs, once the system transfer functions have been identified in the test. The proposed method, which is based on the correction of the electro-acoustic loadings in the model, has proven to be very effective in reducing the error of the virtual estimations for the problem under study. Future works will be focused in validating the method in more realistic environmental acoustic tests. Furthermore, on-going research is dedicated to the implementation of more comprehensive model update methods which go beyond the limiting assumptions of the current approach, for instance based on machine learning techniques or Kalman filtering methods.

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