



## Cabin noise measurements with microphone arrays and sound intensity probes

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### ABSTRACT

Aircraft cabin noise measurements in flight are used to identify the noise sources and entry points of acoustic energy into the cabin and to quantify the respective noise levels.

The aim of an ongoing project of the partners GfAI and DLR is to develop a handheld measurement system suitable for cabin noise in-flight measurements. In the current study an optical tracking system and two measuring principles of the sound intensity are combined in order to measure the sound intensity with focus of developing a MEMS microphone array based system. Suitable MEMS microphones were tested and calibrated and a MEMS microphone array was developed to measure the sound intensity.

**Keywords:** MEMS-microphone array, cabin noise measurements, MEMS intensity array

**I-INCE Classification of Subject Number:** 72

### 1. INTRODUCTION

Aircraft cabin noise measurements in flight are used to characterize the sound field within the cabin and identify the main entry point of acoustic energy into the cabin. The objectives of these measurements are to quantify the acoustic environment of the passengers and the cabin crew with regard to the acoustic comfort, the speech comprehension of the cabin announcements and the fulfilling of the regulations regarding noise within the cabin.

Up-to-now sound intensity measurements are the state-of-the-art measurement technique for this task. The cabin noise measurements performed during a test flight to identify the acoustic entry points can be done following the recommendation of ISO 9614-1. Additional sound absorbing material is used to suppress the interfering reflections of the cabin walls. Nevertheless, due to the tight spatial environment and the expensive flight time cabin noise measurements are still challenging and costly.

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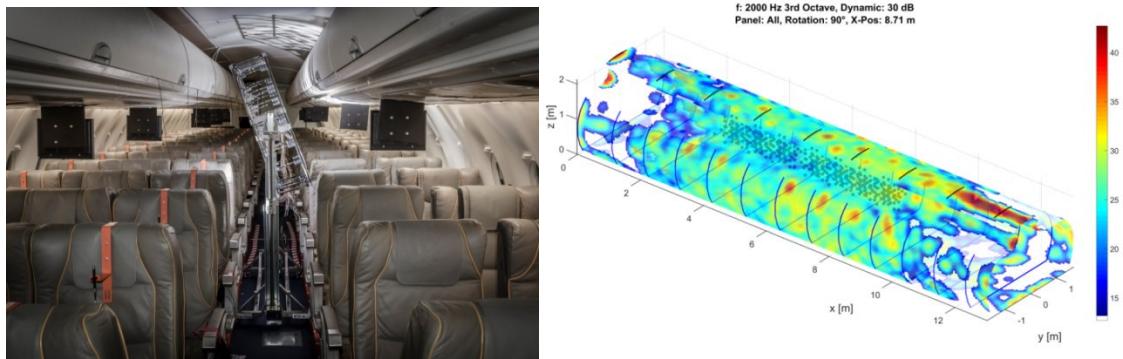
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The development and feasibility of microphone array measurements for cabin noise was shown in previous work [1], [2], [3] and [4]. First measurements during flight were performed in 2013 with a microphone array system traversable on rails mounted on the seat retainer of the cabin [1], similar to Figure 1, left. Here a microphone array was traversed to previously determined positions (in flight direction, x-direction) and additionally rotated at every x-position along the x-axis. With this system it was possible to traverse the microphone array 4300 mm in x-direction and determine the sound field inside this cabin section within 30 minutes. Nevertheless the preparation and mainly the installation of the rail system (to secure the microphone array during flight) is time consuming.

The aim of the latest study [4] was to evaluate the accuracy of the measured acoustic intensity of the different cabin panel elements. This was performed by comparing the standard intensity method to beamforming techniques. As in [1], in this study the rail system was used to secure the microphone array system in-flight as well as to determine the position and rotation of the microphone array within the cabin (see Figure 1, left). Additionally to the evaluation of the accuracy this study showed that with a large (virtual) microphone array consisting of 420 microphones it was possible to detect the sound sources within the lining (see Figure 1, right).



*Figure 1: (left) Array measurement setup inside the ground-based Dornier 728 cabin noise simulator, (right) Source maps at 3rd –Octave band 2 kHz with DAMAS [4].*

The goal of the ongoing project is there to develop a handheld microphone array system suitable for cabin measurements in flight test. Within this development there are two main challenges:

1. the feasibility of beamforming inside the reverberant environment of the cabin
2. the determination of exact position of the handheld array while moving through the cabin

Thus the aim of this study is to test an optical tracking system (depth camera) in combination with acoustic measurement systems based on beamforming and sound intensity measurements.

Section 2 presents preliminary sensor tests; section 3 describes the measurement setup followed by the description of the data processing in section 4. Section 5 gives an overview of the measurement results.

## 2. MEMS SENSORS AND PRELIMINARY TESTS

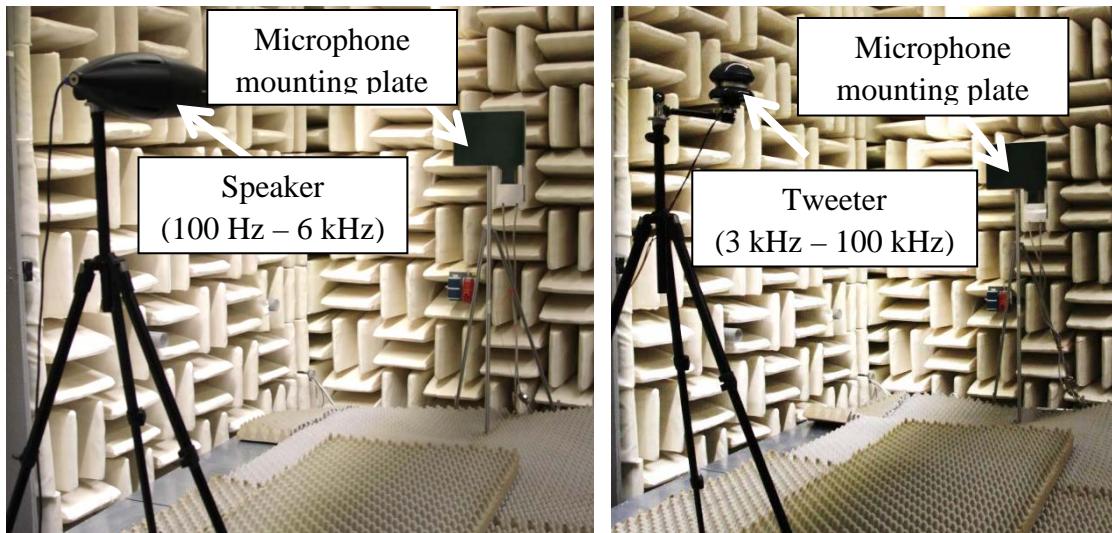
### 2.1 Sensors

For a handheld array, in terms of weight and size, it is convenient when the sensors are very small. Therefore MEMS microphones of type InvenSense ICS 40618 were chosen. These sensors have very small dimensions (3.5 mm x 2.65 mm x 0.98 mm). For our measurements the frequency response and the acoustic overload point is very important. The datasheet indicate a linear frequency response from 100 Hz to 10 kHz and an AOP of 10% at 132 dB [5]. However, for high quality measurements, the AOP below 2% or 3% is important. The frequency response and the AOP of the ICS 40618 sensors were measured as shown below [5].

## 2.2 Frequency response

The frequency response was tested in the anechoic room of the SAG laboratory of DLR Göttingen. This was performed using either a calibration speaker for the low frequency range (100 Hz to 6 kHz) or calibration tweeter for the high frequency range (3 Hz to 100 kHz) in front of a rectangular aluminum plate as depicted in Figure 2. In the center of the plate the MEMS sensors were flush mounted. For statistical reasons a total of 48 sensors of the type ICS 40618 were tested. The frequency response was calculated by the comparison to a reference microphone (B&K Type 4944), also flush-mounted in the plate at the identical position. For the frequency response over the entire frequency range the results from the speaker and the tweeter where merged with a weighted average within 3 kHz to 6 kHz for each sensor.

Figure 3 shows the mean frequency response of all sensors, the standard deviation is represented by the dotted lines. The frequency responses show an almost linear behavior within an interval of 300 Hz to 20 kHz. Remarkable, the standard deviation is almost negligible, significant deviations are only visible in a small region around the anti-resonance (50 kHz). Due to this low standard deviation the sensor offers a suitable for beamforming and sound intensity applications.



*Figure 2: Measurement setup for the frequency response measurement of the MEMS sensors.*

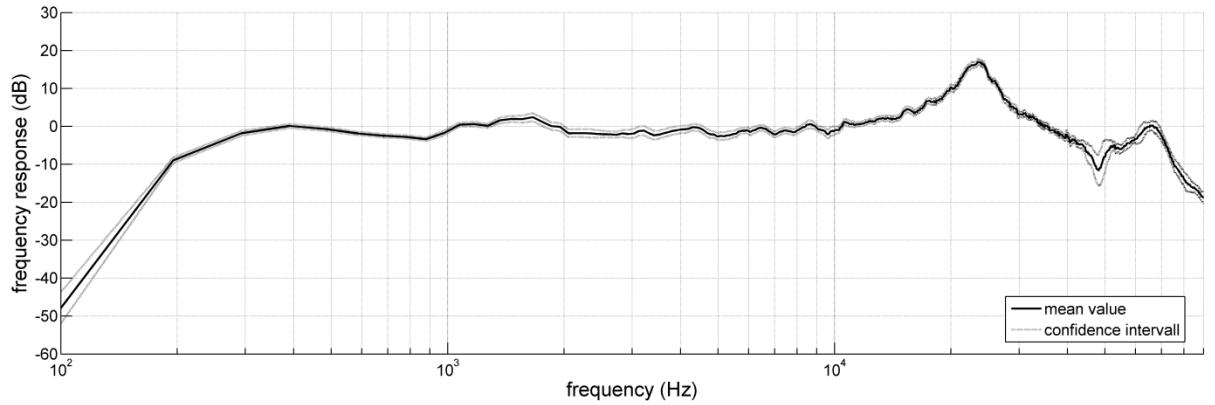


Figure 3: Frequency response of the ICS 40618 MEMS sensors.

### 2.3 Total harmonic distortion

The THD was determined approximately instead of the AOP. Therefore a test bench for the measurement of the total harmonic distortion (THD) has been accomplished. Figure 4 shows the THD test bench. It mainly consists of a modified Oberst-Tube [6] setup which can provide very high sound pressure levels provided by a speaker with a very low level of distortion.

Figure 5 shows the THD (%) for different sensors: two reference sensors and a high-pressure MEMS sensor. As can be seen, the distortion factor for both reference sensors up to excitation levels of 170 dB is below 3%. The ICS 40618 MEMS sensor shows a significant increase of the distortion factor for levels over 125 dB, the 2% distortion appears at 122 dB. This is completely sufficient for the cabin noise measurements but also for future applications the application range is thus determined.

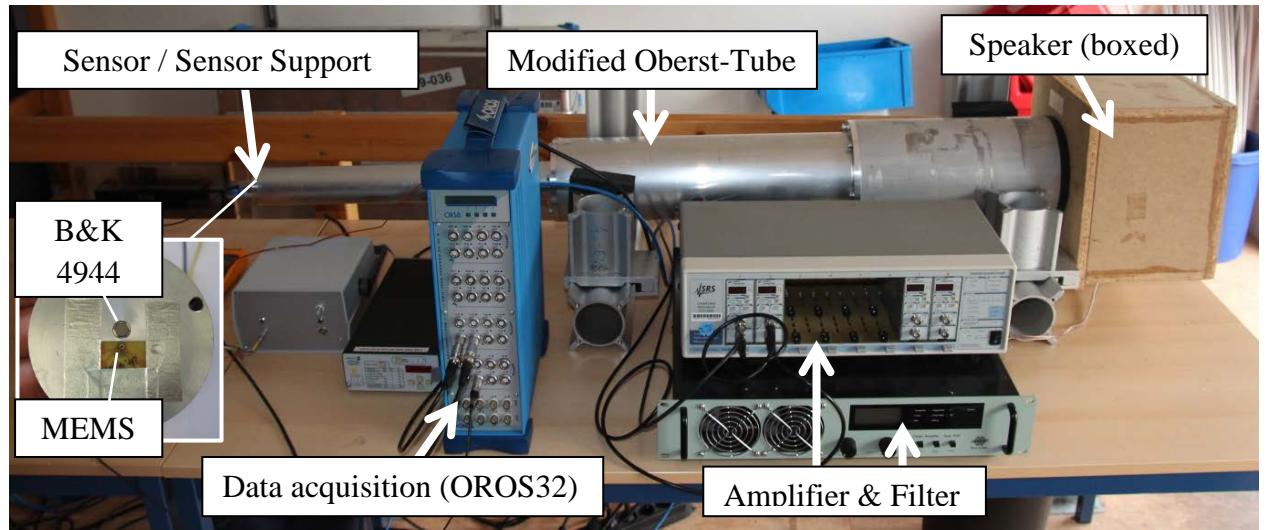


Figure 4: Measurement setup for the THD measurement of the MEMS sensors.

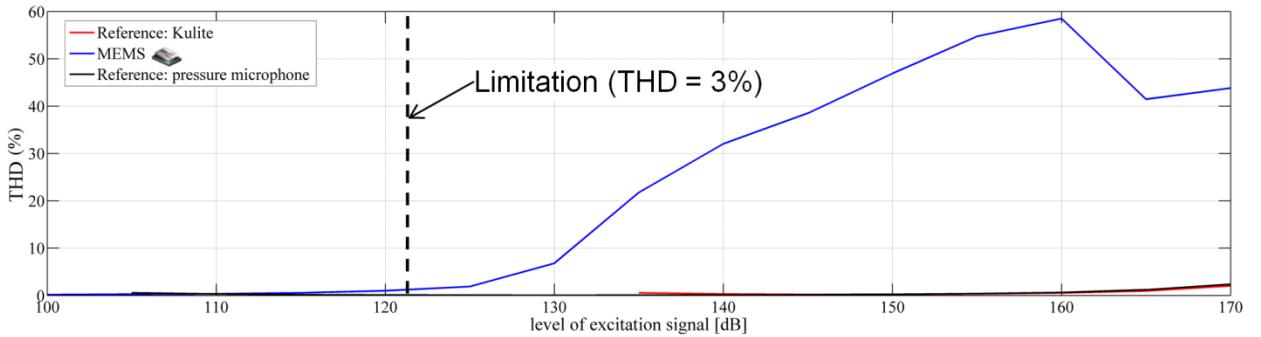


Figure 5: Total harmonic distortion over excitation level for ICS 40618 MEMS sensor and two reference sensors.

### 3. MEASUREMENT SETUP

#### 3.1 Measurement Environment

The measurements were conducted in the anechoic chamber of the aeroacoustic laboratory in Göttingen (SAG). Important for the assessment of the new measurement systems this provides an ideal environment for sound intensity measurements.

As a reference sound source an omnidirectional loudspeaker (Brüel & Kjaer, type 4295) was used for all measurements. In this speaker a single high-power speaker radiates through a cylindrical orifice. The loudspeaker in the anechoic chamber is displayed in *Figure 6*. For simplified data acquisition using the optical tracking system, the speaker geometry was highlighted using white tape. During the tests the loudspeaker emitted white noise in the frequency range of 80 Hz to 6.3 kHz.

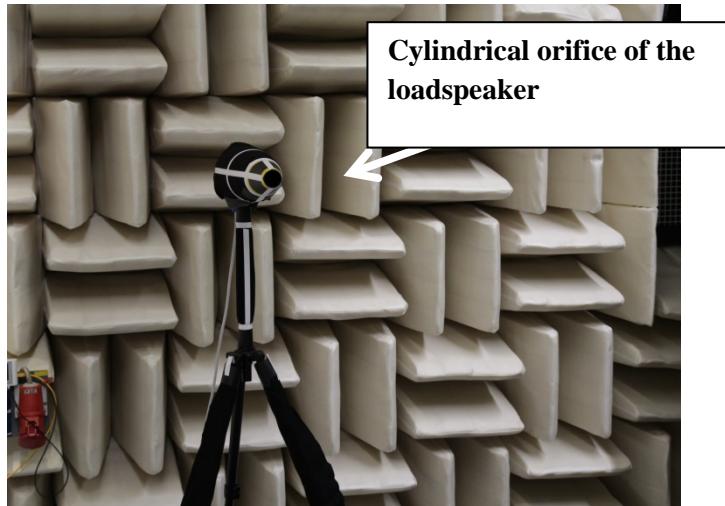
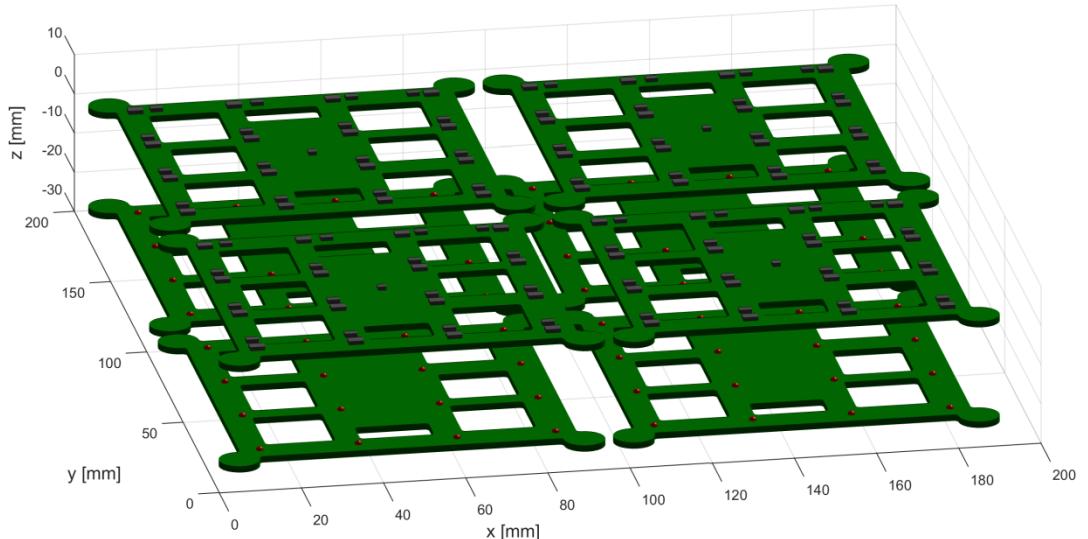


Figure 6: Omnidirectional loudspeaker (Brüel & Kjaer, type 4925) within the anechoic chamber of the aeroacoustic calibration (AKG) at the DLR site in Göttingen.

#### 3.2 Analog MEMS Array

For combined beamforming and intensity measurements, a microphone array consists of 8 printed circuit boards with 16 analog MEMS microphones (InvenSense ICS 40618) each were designed and constructed. The microphones were positioned in two facing planes with an equidistant pattern ( $2 \times 8 \times 8 = 128$  microphones) as depicted in *Figure 7*. The analog signals measured by the MEMS Array microphones were recorded with a gbm Viper-HDR data-acquisition system.



*Figure 7: The eight printed circuit boards with the MEMS microphones arranged in two facing planes.*

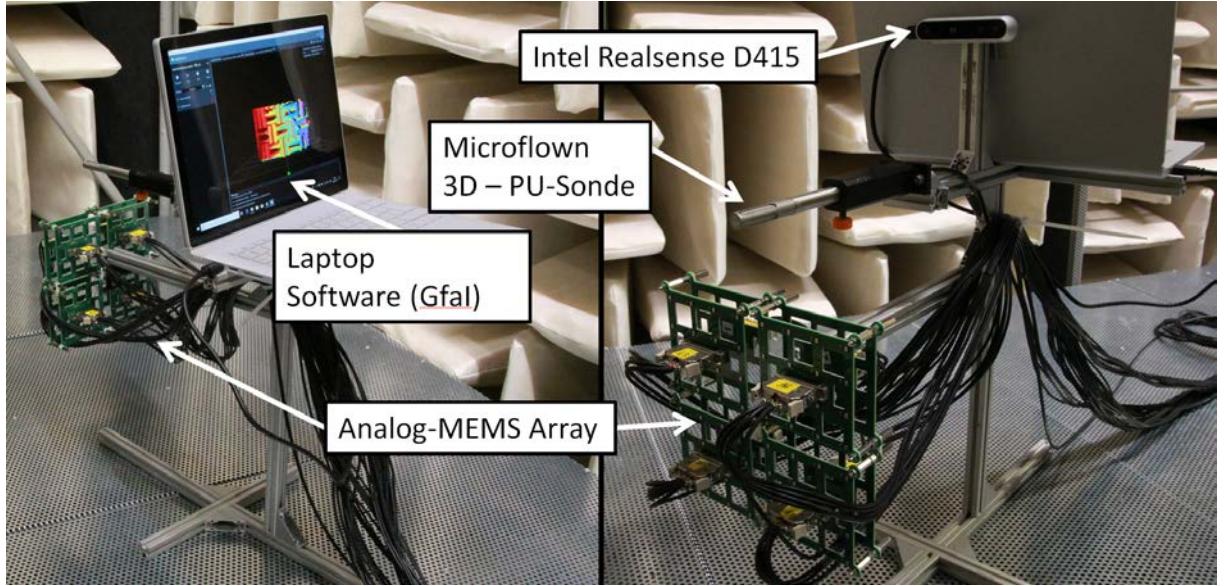
### 3.3 Intensity Probe

For the direct measurement of the sound intensity a 3D *pu*-probe by Microflown (1/2" inch 3D AVS - Acoustic Vector Sensor) was used. This probe acquires the pressure  $p$  with a microphone and the vector of particle velocities  $u$  with hot wire sensors. According to the manufacturer the frequency range of this probe is 20 Hz to 20 kHz. As well as for the MEMS-Array the analog signals measured by the *pu*-probe were recorded with a gbm Viper-HDR data-acquisition system.

### 3.4 Array localization

The main goal of this study is the assembly of the optical and the acoustical system to enable a handheld acoustical cabin system, either with sound intensity or microphone array technology. For the 3D optical tracking an Intel Realsense Depth Camera D415 was used. The tracking software was provided by GfAI. The output of this software are a three dimensional model of the scanned environment and the time dependent camera ( $x, y, z$ )-positions and the respective rotation angles within the surrounding measurement environment.

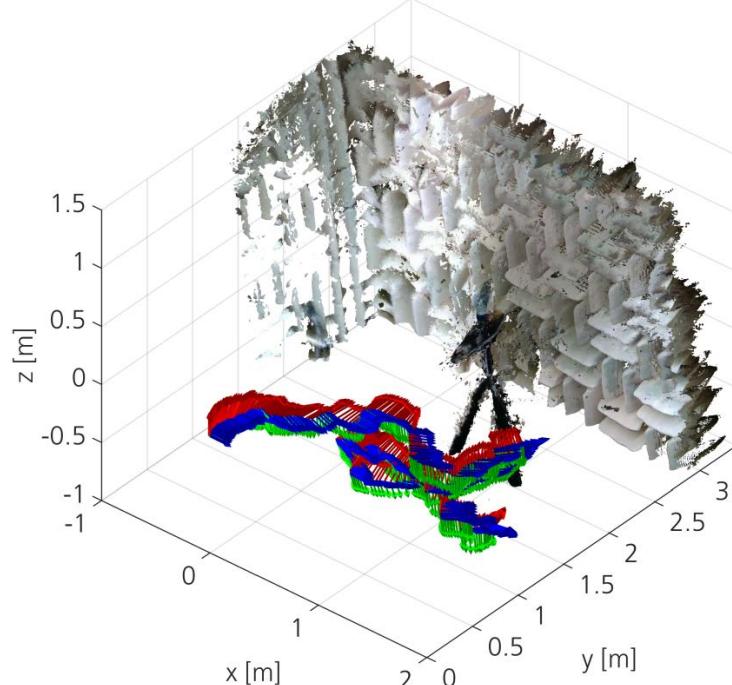
This optical tracking system has to be time-synchronous with the used data-acquisition system in order to allocate the measurement results to the position and rotation of the microphone array or *pu*-probe moving through the cabin.



*Figure 8: First prototype with combined setup of the MEMS-microphone array, the pu-probe and the depth camera.*

*Figure 8* shows photos of the combined setup with the MEMS-Array, the intensity probe and the depth camera. The MEMS-Array, the *pu*-probe and the depth camera are rigidly connected thus the microphone positions can be calculated from the camera position.

*Figure 9* shows the raw data of the camera scan of model and environment and the trajectory of the camera coordinates. The loudspeaker and the anechoic chamber are visible in the scanned environment model. In the current evaluation of the results the camera data are only used for orientation and localization of the microphones.

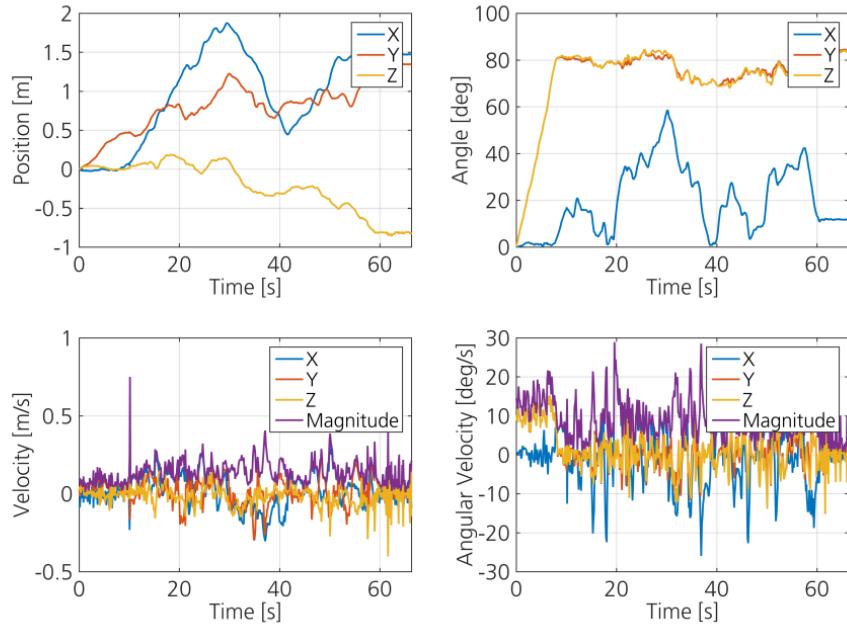


*Figure 9: Raw data; reconstructed 3D-model of the loudspeaker inside the anechoic chamber and the trajectory of the camera position.*

The camera position and the respective rotation angle together with the velocity and the angular velocity are displayed in *Figure 10*.

For practical use it is recommended to move the camera system with slow movements as can be seen in the Figure 10 with velocities of less the 1m/s. The angular velocity was also kept low which can be seen by the small changes of the angle over the 60 s measurement time. The camera-array system was moved within an area of approximately 2 m x 2 m in front of the loudspeaker.

The necessary accuracy was estimated to be 100 ms resulting in an accuracy of the position of less than 10 cm and of the rotation angle of 3 deg.



*Figure 10:* Time depended camera movement within global coordinate system; [upper left] camera-position,[upper right] rotation of the camera, [lower left] camera velocity, [lower right] angular velocity.

#### 4. DATA PROCESSING

The sound intensity measured with the *pu*-probe was calculated directly using the three-dimensional particle velocity.

With the MEMS microphone array the sound intensity was calculated using finite differences of the pressure to calculate the particle velocity. The mean value of each 4 microphones of the 6 cube surfaces was used to calculate the sound pressure for three (virtual) microphone pairs. The cross power spectrum  $C_{i,j}(\omega)$  of these three intensity pairs ( $i,j$ ) was calculated using a FFT-blocksize of 2048 samples. The sound intensity  $I_{i,j}(\omega)$  is then calculated by the following formula:

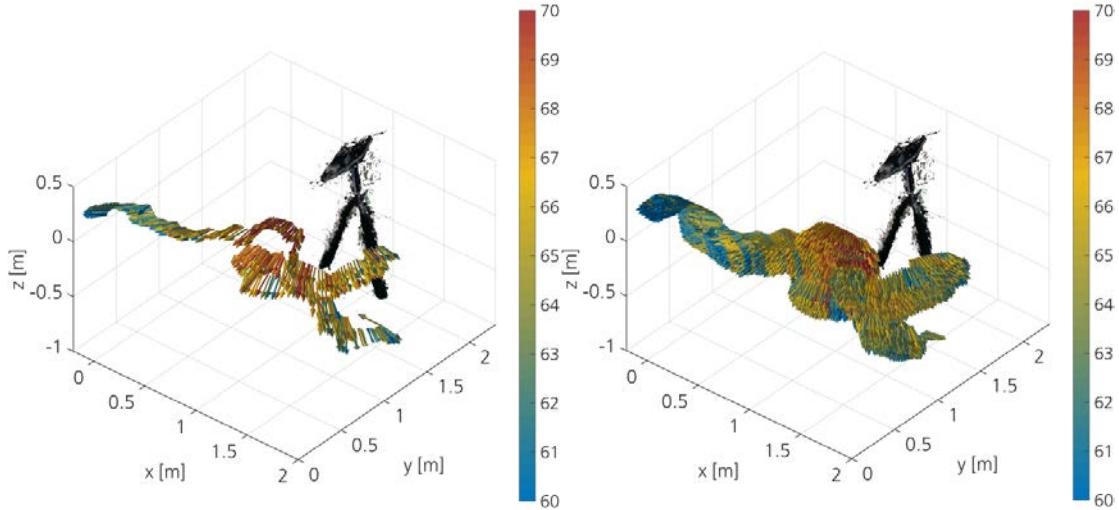
$$I_{i,j}(\omega) = -\frac{1}{\rho_0 \Delta x} \text{Im}\{C_{i,j}(\omega)\},$$

where  $\rho_0$  is the density of air,  $\omega$  is the angular frequency and  $\Delta x$  is the spacing between the microphone intensity pairs.

This procedure results in a three-dimensional central finite difference scheme using the eight microphones at the cube corners to determine the particle velocity vector. The equidistant pattern with two layers of microphones allows the calculation of the intensity vector at  $7 \times 7 = 49$  positions.

## 5. MEASUREMENT RESULTS

In *Figure 11* the sound intensity at a 1/3<sup>rd</sup> octave band with a center frequency of 500 Hz is displayed measured with the *pu*-probe (left) and the MEMS array (right). The arrows indicating the intensity direction are all normalized to one. The direction of the arrows indicating the measured sound intensity, the amplitude of the sound intensity is indicated by the color bar.



*Figure 11: Sound intensity at 1/3rd octave of 500 Hz; [left] pu-probe, [right] MEMS array.*

As expected the sound measured sound intensity is directed away from the source and decreases with increasing distance from the sound source. The MEMS array calculated the sound intensity from 49 intensity probes, therefore the sound field is scanned with a higher spatial resolution than with the single *pu*-probe. The results confirm the feasibility of measuring the sound intensity distribution with the presented system components.

## 6. CONCLUSIONS

In this paper, an optical tracking system was combined with two sound intensity measurement systems in order to develop a handheld system for in-flight cabin noise measurements. The optical tracking system was a RealSense D415 by Intel providing with software by GfAI the three-dimensional environment and the time-dependent camera position and orientation.

For the determination of the sound intensity a commercial available *pu*-probe (the acoustic vector sensor by Microflown) was tested and the in-house development of a MEMS microphone array. The test and calibration of the MEMS microphones were presented. The MEMS microphones were arranged in an equidistant two layer array to calculate the sound intensity via finite differences.

The results confirm the feasibility of measuring the sound field with the presented systems. The accuracy of the systems has to be tested in the coming steps.

## **7. ACKNOWLEDGEMENTS**

The beamforming software SAGAS was used for the analysis in this paper. This software was developed by DLR Institute for Aerodynamics and Flow Technology in Göttingen, Germany. We acknowledge gratefully Florian Phillip (DLR) for his implementation of the software.

We would like thank the GfA in Berlin, Germany for design, development, testing and implementation of the tracking software.

The authors would also like to thank the Federal Ministry of Economics and Technology (BMWi) for the financial support of “InScan” as part of the aerospace research program (LuFO V).

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