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Comparison of 2D and 3D scanning solutions for sound visualization

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ABSTRACT

The efficient identification of the areas that produce significant acoustic excitation is one of the main challenges of most noise and vibration problems. The introduction of novel scanning techniques such as Scan & Paint enables to acquire an extensive amount of information in a fast and efficient manner whilst preserving the simplicity of a single probe solution. Acoustic variations throughout space can be determined by combining the signals acquired with tracking information. The direct visualization of the resulting sound pressure, acoustic particle velocity or sound intensity fields can be achieved in a matter of minutes, obtaining a detailed description of the sound spatial distribution. There are currently two main techniques suitable for performing such analysis, either using a PU probe or a 3D sound intensity probe. This paper aims to provide an overview of the two techniques along with experimental evidence to thoroughly investigate their advantages and limitations. It is shown that the colormaps of normal sound intensity can be very useful, especially when the main sound sources are captured within the measured surface. On the other hand, the visualization of the sound intensity vector field can provide key insight on how sound interacts in complex measuring environments.

Keywords: Sound visualization, source detection, Scan & Paint, Scan & Paint 3D
I-INCE Classification of Subject Number: 41

1. INTRODUCTION

Sound visualization is a key approach to identifying sound sources, studying sound fields and quantifying noise [1, 2]. Measurement techniques to achieve sound visualization can be generally categorized into three types: step-by-step, simultaneous and scanning techniques. In terms of measurement time, flexibility and total cost of equipment, which are the main features for measurement evaluation, the scanning measurement technique has been implied to outperform the other two [3].

Scan and Paint is a scanning technique based on the acquisition of sound pressure and particle velocity by manually moving an intensity probe (containing a pressure and a particle velocity sensor, the latter also known as Microflown sensor) across a sound field whilst filming the event with a camera [4, 5]. It is then possible to visualize sound variations across the space in terms of sound pressure, particle velocity or sound intensity. The visualization of vector fields has changed the approach to examining many acoustic problems, greatly simplifying research methods [6]. It enables fast noise source quantification and convenient sound propagation investigation [7]. In recent years, the

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Scan and Paint technique using the 1D PU and 3D intensity probes has been introduced for in-situ sound visualization in 2D and 3D. The two approaches are realized by Scan&Paint 2D (S&P2D) and Scan&Paint 3D (S&P3D) techniques, respectively. For S&P2D, the recording from a continuous scanning trajectory is split into multiple segments. The segmented recording signals are linked to the grid cells on the scanning surface, and then calculated to deliver the colormap on the picture captured by the camera [3]. While for S&P3D, a 3D stereo camera is used to extract the instantaneous positions of the 3D probe in the 3D space. Therefore, the grid cells are three-dimensional, and the calculated results for all grid cells are presented over a 3D sketch of the tested object. Hence a visual representation of the sound distribution is obtained around the object [7].

Both techniques can be applied to calculate the sound field and hence for sound visualization. However, due to different contained equipment, the two techniques share common advantages, but also have their specific features. This work aims at comparing the two techniques in terms of their advantages and limitations. The fundamentals and procedures of measuring and post processing are first introduced. Subsequently, the inherent comparison is made. Finally, experiments with a three-way loudspeaker and a car are conducted to further compare the potential applications of the two techniques.

2. SCAN AND PAINT FUNDAMENTALS

The key procedures of the Scan and Paint technique are the probe tracking and spatial discretization. The probe can be easily tracked by setting up a camera, whereas the recorded information from the camera, and the microphone and Microflown sensors needs to be spatially discretized for sound visualization [7]. As the spatial discretization in 3D is nothing but an extension to a higher dimension, the fundamentals of spatial discretization in 2D will be explained in the follow content.

For 2D spatial discretization, the 2D spatial scanning space is discretized into grid cells $\Omega_h^{m,n}$. The continuous scanning trajectory is then discretized and allocated to the grid cells. With the associated time slots according to the trajectory discretization, the recording is segmented. The segmented signals correspond to the grid cells, and thus the calculated results of the grid cells can illustrate the sound energy distribution. The discretization procedure can be found in Figure 1 [3]. The scanning starts from $\Omega_h^{1,1}$ and ends at $\Omega_h^{1,4}$. The scanning trajectory is then discretized into eight parts, so is the recording. Note that one grid cell can have multiple associated sections of the original recording if the probe crosses the same volume multiple times. A detailed description of the mathematical derivation of an analogous method for 2D spatial discretization can be found in [2]. For 3D spatial discretization, the only difference is that the grid cell is not 2D but a 3D cube cell. After the grid cell is defined, the following procedure is the same as the 2D case.

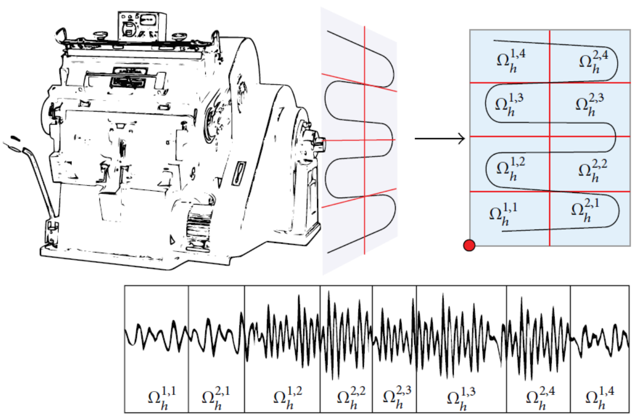


Figure 1. 2D spatial discretization and signal segmentation.

3. SCANNING AND POST-PROCESSING PROCEDURES

The working principles of the S&P2D and S&P3D techniques are quite similar. The differences lie in the camera and probe, which lead to different scanning procedures. Figure 2 illustrates the equipment contained in the S&P2D and S&P3D systems.

Figure 2. S&P2D and S&P3D systems.

3.1 S&P2D

In the post-processing stage, the probe position is extracted by applying automatic colour detection to each frame of the video. The recorded signals are then split into multiple segments using a spatial discretisation algorithm, assigning a spatial position depending on the tracking information. Therefore, each segment of the signal is linked to a discrete location of the measurement plane. Next, spectral variations across the space are computed by analysing the signal segments. The results are finally combined with a background picture of the measured environment to obtain a visual representation which allows us to “see” the sound pressure, particle velocity or sound intensity distribution in 2D. This procedure can be found in Figure 3.

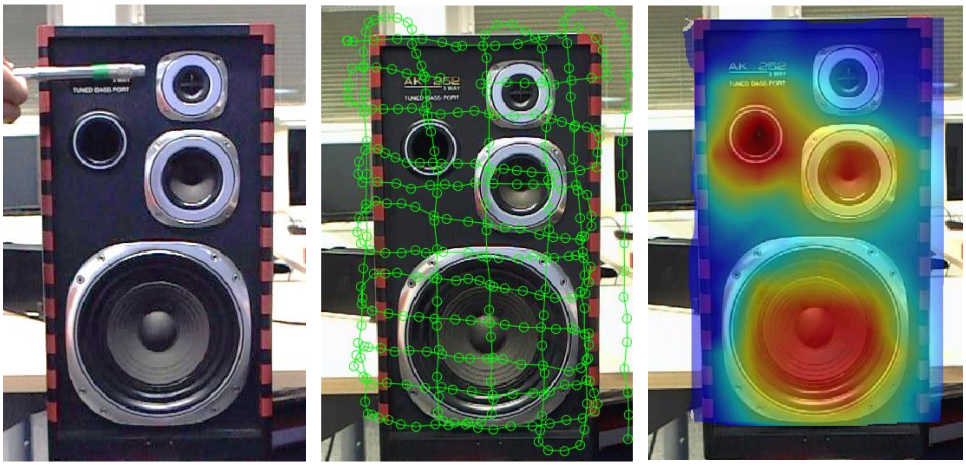


Figure 3. Scanning and post processing of S&P2D.

3.2 S&P3D

For S&P3D, a stereo camera is used as a tracking system. It measures six degrees of freedom, i.e. the position in three directions and the orientation in three angular coordinates. The camera is equipped with an infrared (IR) pass filter in front of the lens and a ring of IR LEDs around the lens to periodically illuminate the measurement space with IR light. An uneven spherical structure with embedded retro-reflective markers is attached to the probe handle in order to track translation and rotation movements of the probe. The IR light reflections are detected by the stereo camera, and the tracking system translates them to exact 3D coordinates along with the probe orientation. The spatial resolution of the system depends upon the camera view angle, the measurement distance and the amount of reference markers as well as their size. As reported in [9], a tracking error lower than 0.5 mm in position and 1 degree in orientation can be achieved using a grid of 7 mm diameter markers in a range of 2.5 m distance from the tracking system. Compared to S&P2D, the tracking can be done in real time and the tracked trajectories are indicated by the coloured curves in the middle picture in Figure 4. Following the spatial discretization introduced above, the velocity or intensity in each grid cell is calculated and represented over the 3D model of the measured object.

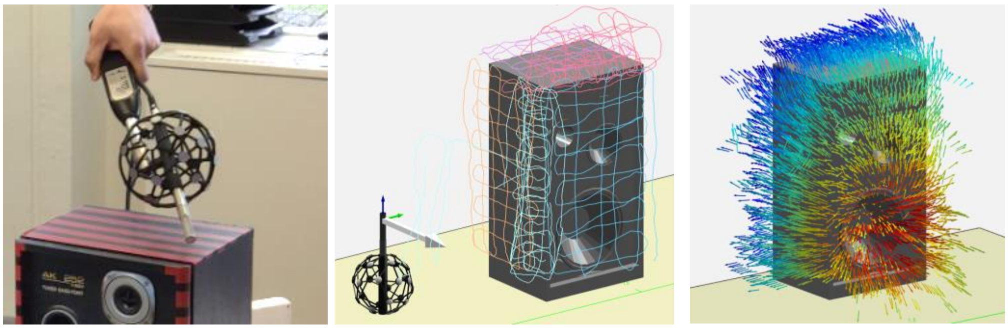


Figure 4. Scanning and post processing of S&P3D.

3.3 Inherent features

The sensors and scanning procedures lead to different features and applications of the two techniques. The inherent similarities and differences are summarized in Table 1. The major differences of the two systems are the probe and camera. S&P2D contains a microphone and a Microflown sensor to measure pressure p and normal velocity u, while S&P3D containing a microphone and three orthogonal Microflown sensors to measure p and three orthogonal velocities u_x, u_y, u_z. Therefore, S&P2D measures normal intensity, whereas S&P3D measures 3D intensity. To avoid any visual errors caused by the camera projection using in S&P2D, the camera should be placed where its view is perpendicular to the measurement surface [12]. By moving the PU probe across the surface, the sound field can be two-dimensionally mapped on this surface. While for S&P3D, a 3D probe is able to capture pressure and three orthogonal velocities, allowing a 3D representation of the measured sound field. An S&P3D operator is free to place the probe in whatever position and orientation within the scope of the stereo camera. Thus S&P3D is operator independent, whereas S&P2D is more operator demanding. The scanning trajectory is obtained by post processing for S&P2D and in real time for S&P3D. In this sense S&P3D is faster. However, considering the setup and calculation time, S&P2D is less time consuming.

Table 1. Inherent features of S&P2D and S&P3D.

	Similarity		**Difference**					
	Sound field	Physical quantity	Probe	Camera	Dimension	Trajectory	Setup	Operator
S&P2D	Stationary	p, u, I, P	p+u	Web	2D	Post processing	5min	Dependent
S&P3D			$p+u_x+u_y+u_z$	Stereo	3D	Real time	10min	Independent

With incorporating Scan and Paint technique, S&P2D and S&P3D are designed for time-stationary sound fields. Sound intensity can be obtained by integrating p and u, and sound power is also available given the surface area the probe scans. Therefore, S&P2D and S&P3D can both provide the calculation of *p*, *u*, *I* and *P*.

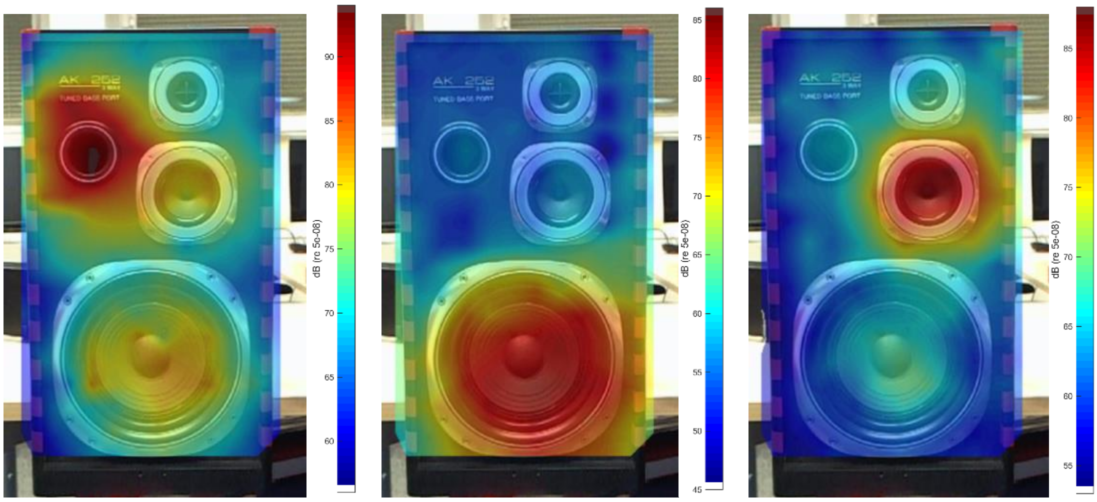
4. EXPERIMENTAL EVALUATION

The fundamentals of the two techniques, and the inherent comparison have been introduced in the last section. In this section, two experiments are provided to further investigate the advantages and limitations of the two techniques in terms of practical measurements.

4.1 Simple case – Loudspeaker

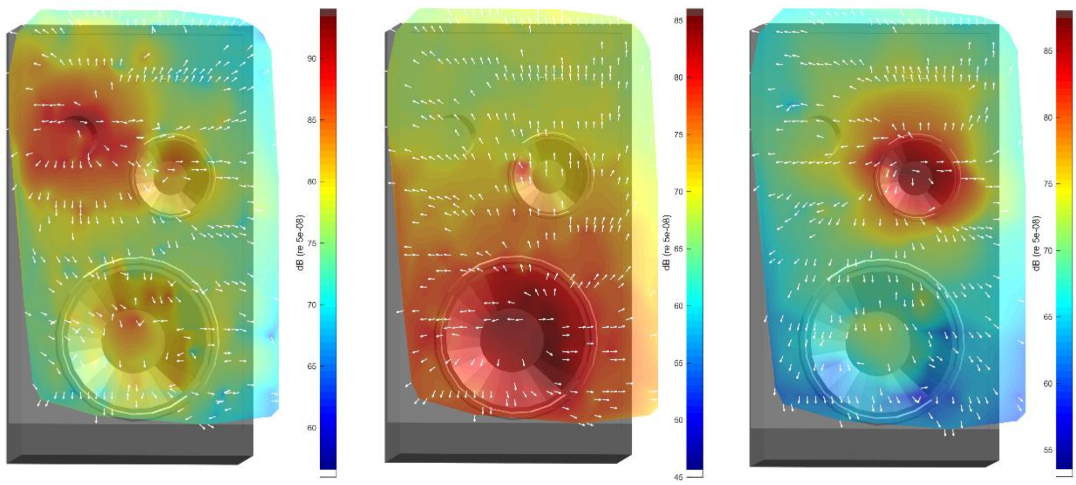
4.1.1 Source localization in 2D

A three-way loudspeaker playing white noise was measured with S&P2D and S&P3D in an office environment. The loudspeaker was marked with red tapes to indicate the scanning trajectories for both systems for the sake of later comparison. Both systems are able to fast localize sound sources in a broad frequency range in a matter of minutes. The particle velocity colormaps measured with S&P2D and S&P3D are illustrated in Figure 5 and Figure 6 in three 1/3 octave bands, with center frequencies of 80 Hz, 630 Hz and 6300 Hz.



a) f = 80 Hz *b) f = 630 Hz* *c) f = 6300 Hz*

Figure 5. Particle velocity colormaps measured with S&P2D (in 1/3 octave bands).



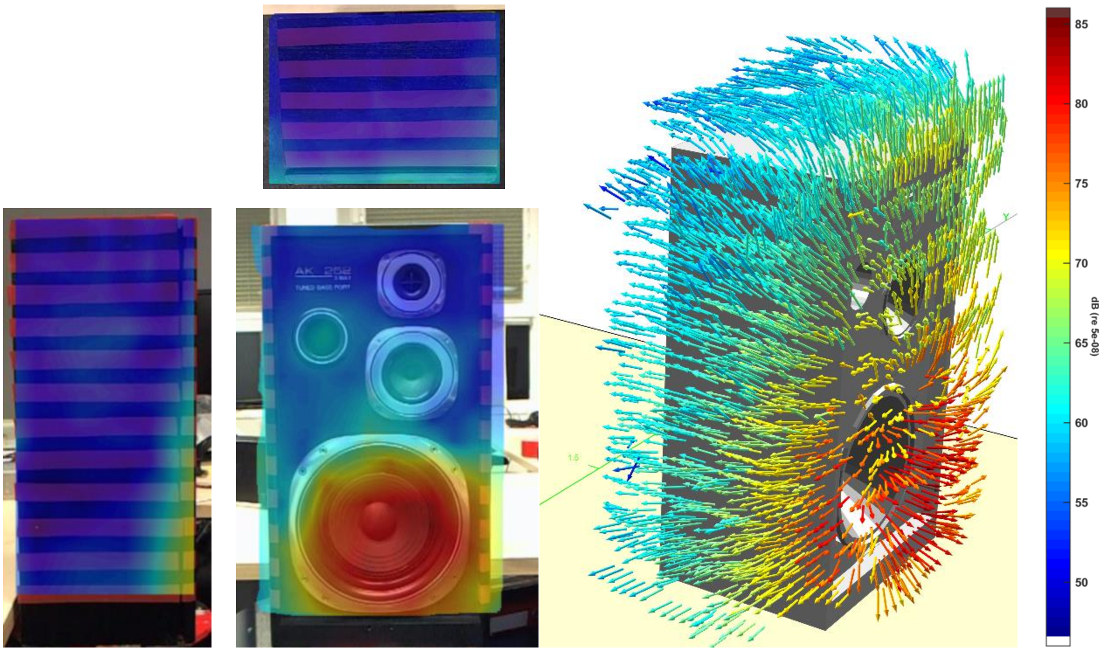
a) f = 80 Hz *b) f = 630 Hz* *c) f = 6300 Hz*

Figure 6. Colormaps of particle velocity distribution measured with S&P3D (in 1/3 octave bands).

From the colormaps in Figure 5, the bass reflex, woofer and mid-high driver are well localized in different octave bands, respectively. S&P3D identifies the same sound sources, as indicated by the colormaps in Figure 5 and Figure 6. The S&P3D results also show the directions of the particle velocity, represented by the white arrows. Another observation is that for the same 1/3 octave band, the level range of S&P2D and S&P3D is the same. Nevertheless, the level difference between the source area and the rest area measured by S&P2D is larger than by S&P3D. The sound propagates from the source to the rest area of the loudspeaker surface, as illustrated by the white arrows Figure 6. This propagation is mostly parallel to the loudspeaker surface, and thus can be captured by the 3D sensors but not the 1D PU sensor, the latter of which only captures the normal velocity from the loudspeaker surface.

4.1.2 Source localization in 3D

For sound source localization on a flat surface of an object, S&P2D and S&P3D share quite similar performance, except that S&P3D allows the visualization of the direction of the calculated physical quantity. It is necessary to visualize the object in 3D because the visualization allows the investigation of how sound radiates from the source, propagates in the media and interacts with obstacles. As the PU probe in S&P2D only captures the normal particle velocity, it has limitation to illustrate spatial sound radiation. The 3D views of the particle velocity distribution measured by S&P2D and S&P3D can be found in Figure 7. By S&P2D, the 3D view can only be represented by setting the camera in three positions with the camera view perpendicular to the three surfaces of the loudspeaker. Figure 7a) indicates that the sound radiated from the woofer to the part on the side surface that is close to the edge, and a little amount to the top surface. Whereas in Figure 7b), a comprehensive 3D view of the sound radiation around the loudspeaker is presented in one stereo camera view. The diffraction over the edges is also clearly visualized.

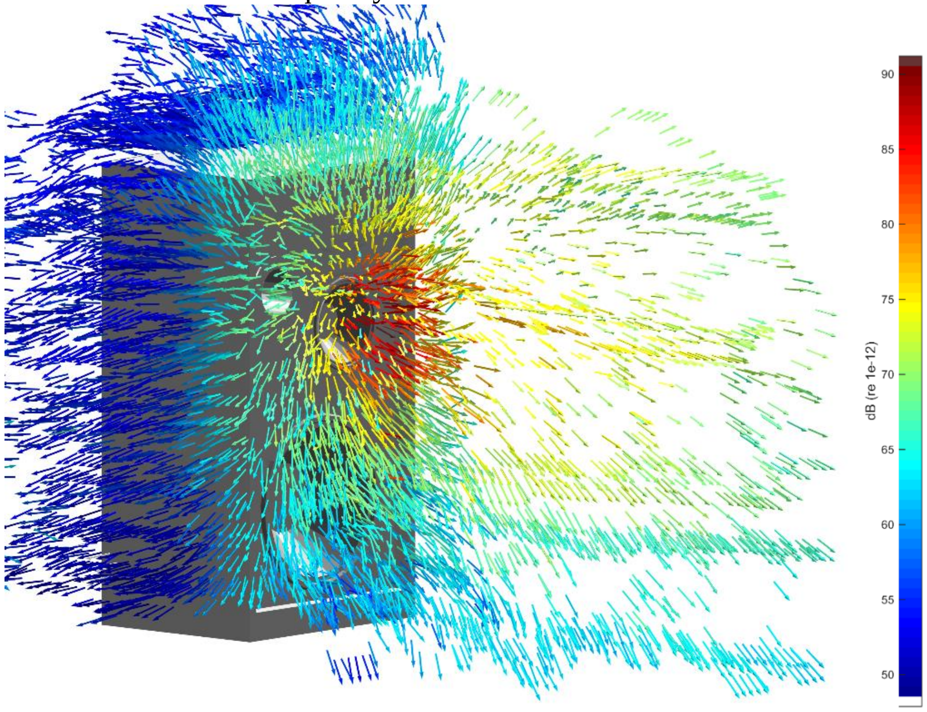


a) S&P2D *b) S&P3D*

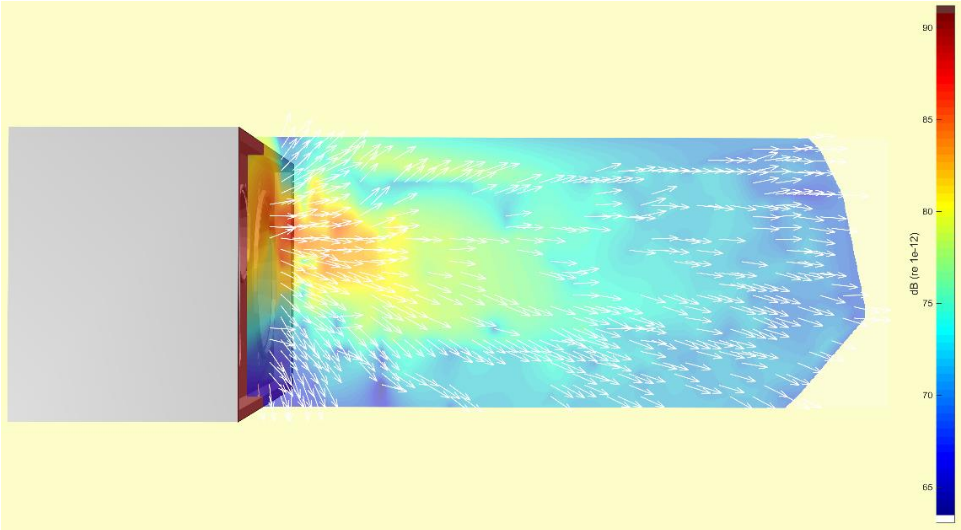
Figure 7. Particle velocity distribution in the 1/3 octave band with the center frequency of 630 Hz.

4.1.3 Sound field visualization

The visualization of sound field enables characterizing sound sources and how sound propagates and interacts with the environment. It requires measurements both in the near and far fields to obtain a holistic spatial representation of the sound field. The PU probe only captures the normal velocity, enabling it to be applied in the near field where the sound mostly propagates perpendicularly to the source surface. However, for the sound visualization in the far field, S&P2D has its inherent limitation. In this case, the 3D Microflown sensors contained in S&P3D help overcome the constraint of far field due to its capability of 3D data acquisition. The sound field visualization of the loudspeaker in 3D and top view can be seen in Figure 8. The 3D view shows not only how the sound diffracts over the edges, but also the directivity of the mid-high driver. Figure 8b) provides a clear view of the highly directional propagation pattern of the driver in the 1/3 octave band with the center frequency of 8000 Hz.



a) 3D view



b) Top view

Figure 8. Sound intensity field visualization using S&P3D in the 1/3 octave band with the center frequency of 8000 Hz.

4.2 Complex case - Car interior

4.2.1 Source localization

The dashboard area and the driver's head area in a car were performed with S&P2D and S&P3D with the car idling at 3000 rpm. Similar as the loudspeaker case, source localization and sound field visualization are of interest in this case. This experiment case is more complex because the sources can be spatially located, and the complicated structure causes more sound interactions. The A-weighted power spectrum of the active intensity in 1/3 octave bands is shown in Figure 9. Three harmonics from the engine can be found in the frequency ranges indicated by the red rectangulars.

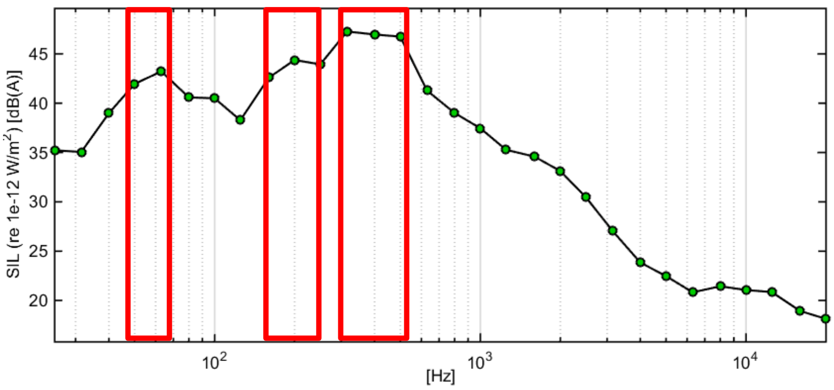
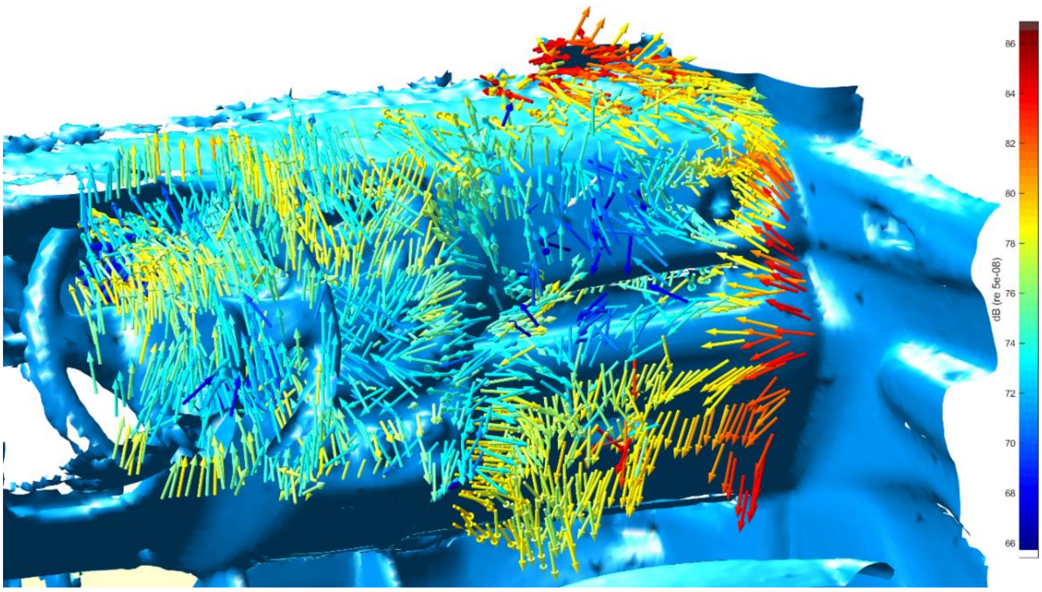


Figure 9. A-weighted power spectrum of the active intensity in 1/3 octave bands with the car idling at 3000 rpm.

The particle velocity distribution of the dashboard is shown in Figure 10 in the frequency range of 44-70 Hz, where the fundamental frequency of the engine noise is. The result of S&P2D in Figure 10a) shows that the sound sources are located below the right side of the dashboard, and the ventilations on the right side. Whereas in Figure 10b), the velocity arrows indicate that the sound mainly comes from the gap between the right top of the dashboard and the windshield, and between the dashboard and right door. As the top surface of the dashboard is not perpendicular to the camera's view, this area was not scanned while using S&P2D and thus the sound from the right corner is not covered.

Figure 10b) clearly indicates that the sound radiates from between the dashboard and right door. It can be the engine noise emitted from the gap between the dashboard and right door, or from the vibration of the door. There are two major differences in the detected sound sources in Figure 10. First, different sound sources are localized. S&P2D partly detected the sound from the gap between the dashboard and right door. However, it is not clear whether the sound is from the floor or the gap. Besides, from the 3D result we can notice that the ventilation on the right is not the main sound source in this frequency range. Although S&P2D achieved to detect the sound source on the right bottom, it missed another main sound source and detected secondary sources as the main sources instead. Also we can see in Figure 10b) that the sound is radiated into the right ventilation, but not outwards. Second, S&P2D detected lower levels of the sound sources. This is because S&P2D only captures the normal velocity, whereas for S&P3D the net velocity is calculated from the three orthogonal Microflown sensors.

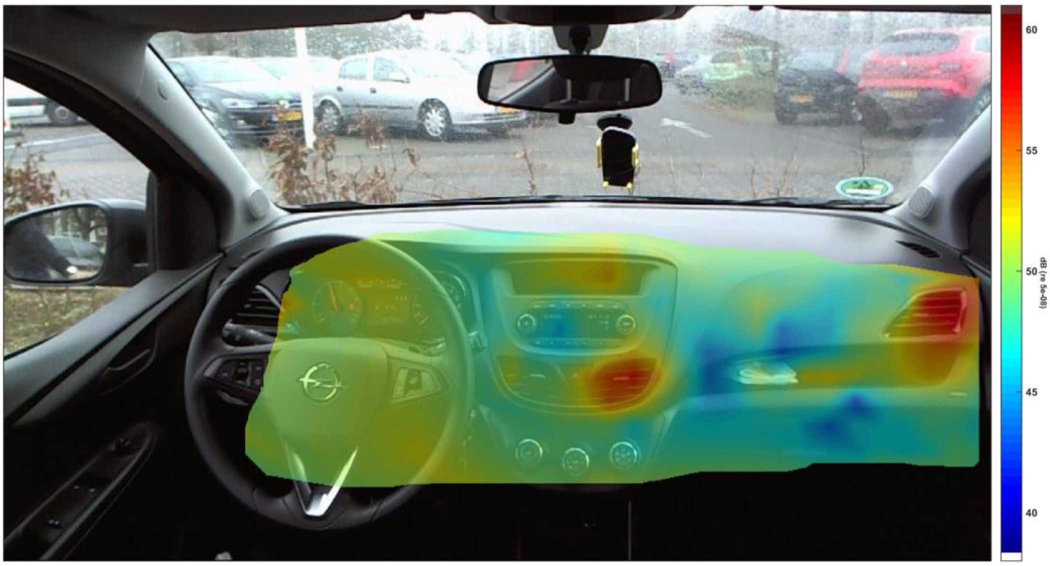
a) S&P2D



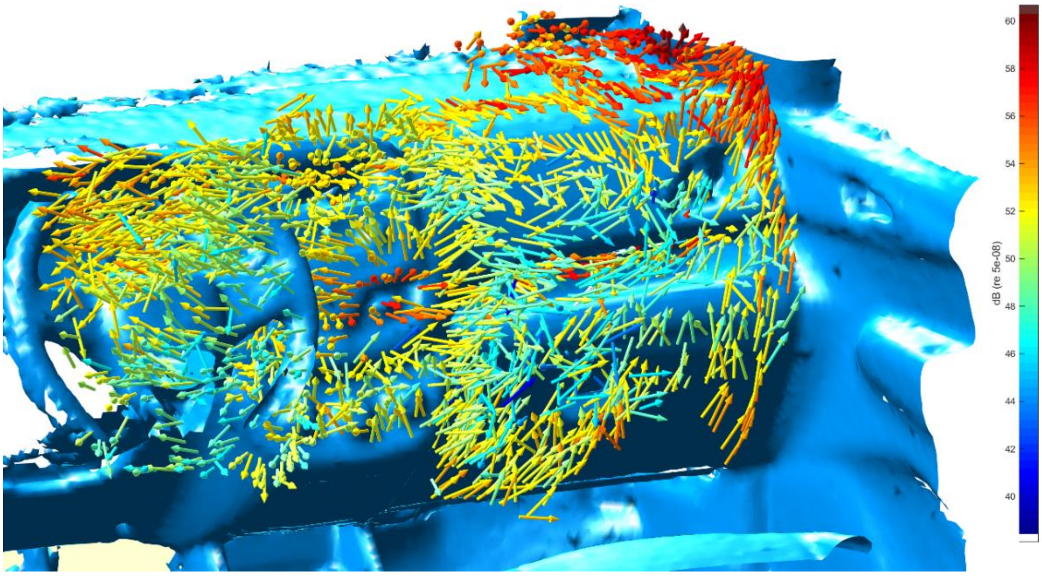
b) S&P3D

Figure 10. Particle velocity distribution in 44-70 Hz.

In the frequency range of 355-447 Hz, the ventilations on the right side and the right ventilation in the middle are localized as the main sound sources using S&P2D (Figure 11a)). Figure 11b) indicates similar results, except for the source between the top surface of the dashboard and windshield, which is the same as in Figure 10. Moreover, both figures impliesthe cavities in the middle and on the right can be regarded as secondary main sound sources.



a) S&P2D



b) S&P3D

Figure 11. Particle velocity distribution in 355-447 Hz.

4.2.2 Sound field visualization

Same as the loudspeaker case, the sound field visualization in the car is presented. White noise was played by the audio system in the car with the engine off. The A-weighted power spectrum of the measured active intensity is shown in

Figure 12. The resonances of the car cavity can be seen from 300-400 Hz. Two resonances (indicated by red circles in Figure 12) are selected to further visualize the modes of the car cavity on the driver's side. In the frequency ranges of 844-1031 Hz and 1312-1359 Hz, the audio system excited the car cavity resonances, which can be visualized in Figure 13. This helps understand the sound field generated by the audio system, and the design of the structure and audio system to provide the driver better acoustic perception.

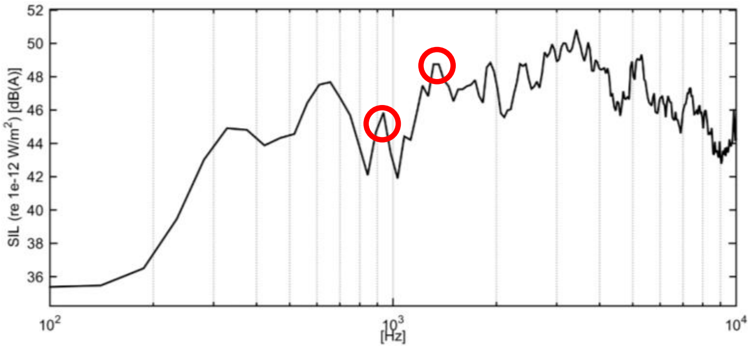
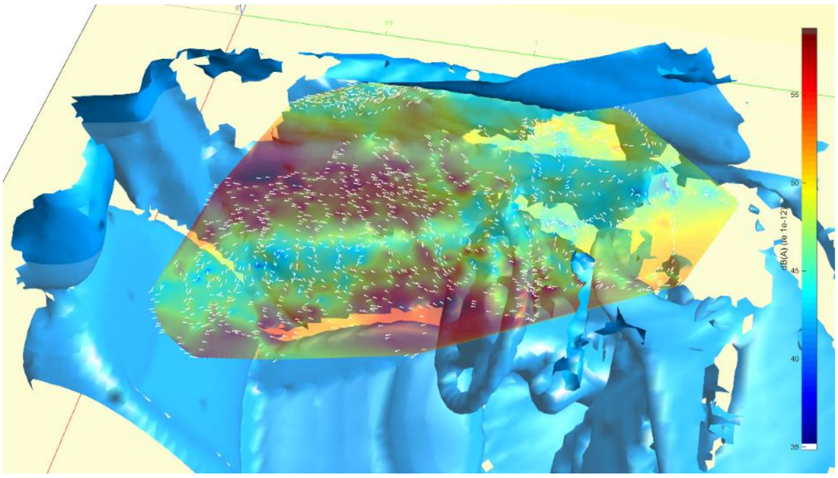
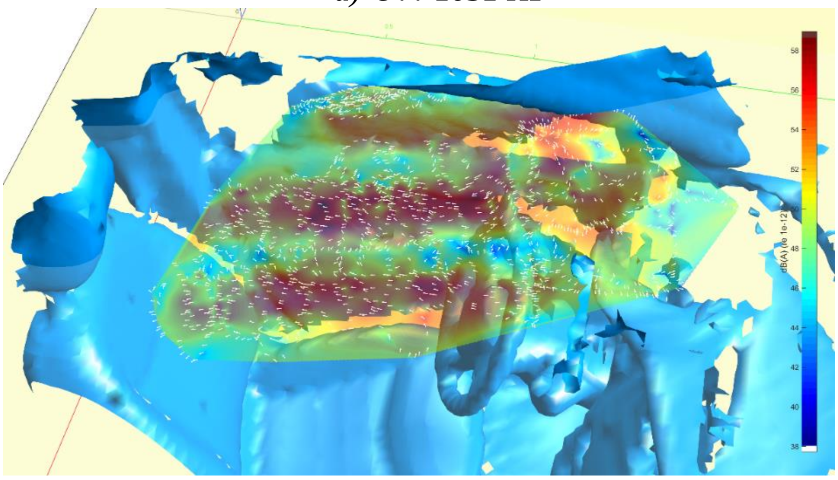


Figure 12. A-weighted power spectrum of the active intensity. The red circles indicate two resonances, which are visualized in Figure 13.



a) 844-1031 Hz



b) 1312-1359 Hz

Figure 13. Sound intensity distribution on the driver's side. It shows the resonances excited by the audio system in the two frequency ranges.

5. CONCLUSIONS

This paper investigated the S&P2D and S&P3D techniques and provided a comprehensive comparison between the two techniques in terms of their advantages and limitations. The inherent features were compared, and the applications on sound source localization and sound field visualization were studied. The two techniques are both advantageous for fast in-situ source localization, which serves for acoustic troubleshooting. On the one hand, it was demonstrated that for more complex sources and measurement environments, S&P3D outperforms S&P2D in sound field visualization. On the other hand, S&P2D is more competitive in the respect of cost and measurement efficiency.

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