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Experimental analysis of spatial properties of the sound field inside a car employing a spherical microphone array

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ABSTRACT

A 32-capsules spherical microphone array was employed for analyzing the spatial properties of the sound field inside a car. Both the background noise and the sound generated by the car's sound system were spatially analyzed, by superposing false-color sound pressure level maps over a panoramic 360x180 degrees image, obtained with a parabolic-mirror camera. The analysis of the noise field revealed the parts of the car body where more noise is leaking in, providing guidance for better soundproofing. The analysis of the impulse responses generated by the loudspeakers did show useful information on the reflection patterns, providing guidance for adding absorbent material in selected locations and for optimizing position and orientation of loudspeakers.

1. INTRODUCTION

The experimental evaluation of the sound field inside a car is usually performed employing microphone systems having very limited capability of detecting the direction-of-arrival of wavefronts, both when measuring the background noise or the sound generated by means of the car's sound system. Of course, omnidirectional microphones do not allow getting any information on the direction-of-arrival. Some attempts have been made employing binaural microphones, but this revealed to be useful only for subsequent binaural listening tests, it is very difficult to analyze a binaural recording for obtaining information about the spatial properties of the sound field. Also low-order microphone arrays have been employed inside cars (i.e., Soundfield microphones), but their spatial resolution revealed to be insufficient for the goal of detecting the origin of the wavefronts in such a reactive environment. Recently, high-order spherical microphone arrays have been developed [1], which revealed successful both for music and speech recording, and for analyzing the spatial properties of the sound field inside concert halls and theatres (or outdoors).

In this paper, the authors did attempt to employ a 32-capsules spherical microphone array (Eigenmike[1])

Figure 1: The 32 capsules spherical array (Eigenmike).

as a probe for detecting the spatial information and they did develop special software tools for deriving false-color maps which allow for visualizing graphically the spatial distribution of the sound energy arriving from every direction. The authors did previously develop a novel "virtual microphone" methodology [1], which allows listening to the sound arriving from a very narrow cone around a selected direction: by moving the virtual microphone marker over the color map, it is possible to analyze the sound coming from "hot spots".
This method was first applied for analyzing the background noise recorded while the car was running at constant speed on the road. A time-averaged static color map was created in this case, and the subsequent analysis made it possible to detect several "weak points" in the car's body, where external noise penetrated inside the cabin.

Even more interesting results have been obtained analyzing the sound generated by the loudspeakers installed as part of the car's sound system.
By feeding every loudspeaker separately with an exponential sine sweep (ESS) signal [2], it was possible to measure the impulse response of each of them. In this case, a time-sliding analysis was performed, creating a video which shows a continuously-changing color map, showing first the "red spot" caused by the direct sound generated by the loudspeaker, followed by the distribution of reflections over the internal surfaces of the cabin.
The analysis of these reflection patterns made it possible to insulate some disturbing reflections, causing comb filtering and spatial blur of the stereo image.
Noise and loudspeaker measure, were performed on a space wagon shown in Figure 2.

Figure 2: the car subject to measures.

2. MEASUREMENTS

2.1. Measurement System description

The experimentation described in this paper was realized using the Eigenmike microphone array produced by MH acoustics [3]. As shown in Figure 1, the Eigenmike is a sphere of aluminum (the radius is 42 mm) with 32 high quality capsules placed on its surface; microphones, pre-amplifiers and A/D converters are packed inside the sphere and all the signals are delivered to the audio interface through a digital CAT-6 cable, employing the A-net protocol. The audio interface is an EMIB Firewire interface; being based on the TCAT DICE II chip, it works with any OS (Windows, OSX and Linux through FFADO). It provides to the user two analogue headphones outputs, one ADAT output and the word clock ports for syncing with external hardware. The preamplifier's gain control is operated through MIDI control.

Figure 3: Measurement system.

[1] Eigenmike is a registered trademark of mh acoustic LLC

The 32 capsules of the Eigenmike were virtualized into 32 4th order cardioids to analyze the background noise and in 64 7th order cardioids to perform the IR analysis. The choice of high order cardioids microphones was due to the requirement of high directivity without lateral or rear lobes in the polar pattern as noticeable in hypercardioids or shotguns microphones.

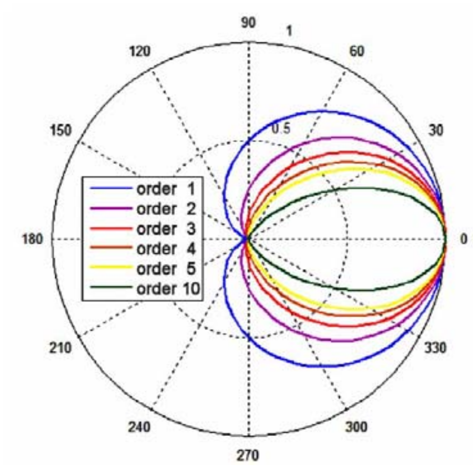

Figure 4: Polar plot of virtual cardioids microphones of various orders

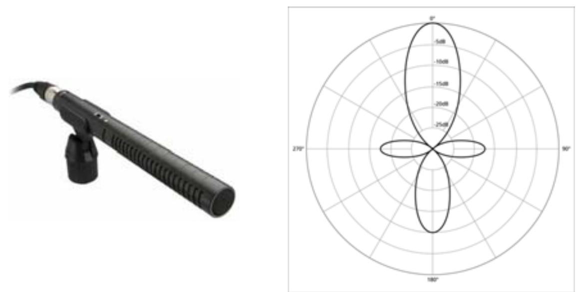

Figure 5: Shotgun microphone

2.2. Background noise measurement

The background noise was recorded placing the Eigenmike on the front passenger seat by mean of a rod. The array was positioned as shown in figure 6.

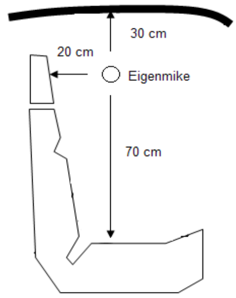

Figure 6: Eigenmike placement

Background noise field was captured driving the car in different trunks of roads at different speeds and using different gears as reported in Table 1.

	Speed	Gear	Road type
Test 1	50 Km/h	2	State highway
Test 2	50 Km/h	3	State highway
Test 3	90 Km/h	3	Ring road
Test 4	90 Km/h	4	Ring road
Test 5	110 Km/h	5	Highway

Table 1: Background noise measurements

A full and octave band analysis was performed. The results are reported in dB_{spl} using the equation (1).

$$dB_{spl} = 10\log_{10}\left(\frac{p_{rms}^{2}}{p_{ref}^{2}}\right) \quad (1)$$

The octave band analysis took into account the range from 125 Hz to 8 kHz. This is of course narrower than the Eigenmike real microphones frequency responses and it is imposed by the virtualization methodology. In particular, the virtualization methodology is based on filtering the real capsules signals with proper filters that have been synthesized starting from measurements of the IR of the Eigenmike in anechoic room. Due to technical problems these measures are valid in the bands from 125 Hz to 8 kHz. Finer anechoic room measurements have been already scheduled by the authors to extend these boundaries.

The figures below display the false-color maps of the SPL background noise recorded inside the car cabin. It is possible to distinguish the noise coming from the floor and the car frame (Figure 7 and Figure 8), by the windows (Figure 9) and the leakage from the front right door (Figure 10).

Figure 7: cabin noise @ 50 km/h, gear 2, 125 Hz

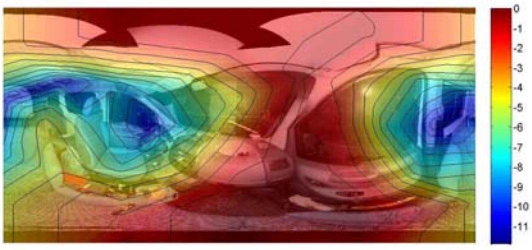

Figure 8: cabin noise @ 90 km/h, gear 3, 125 Hz

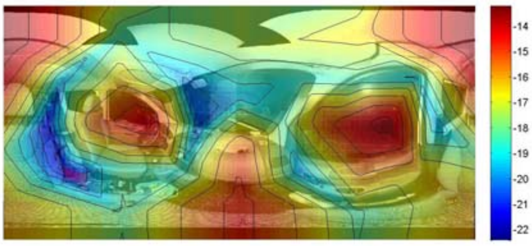

Figure 9: cabin noise @ 90 km/h, gear 4, 500 Hz

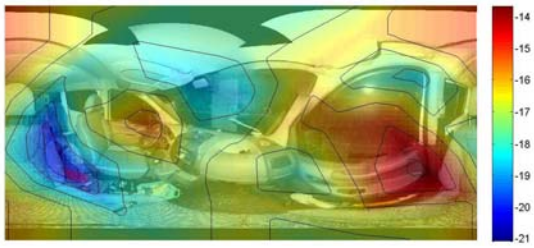

Figure 10: cabin noise @ 110 km/h, gear 5, 500 Hz

Figure 11 shows the SPL octave band spectrum recorded inside the cabin at 90 km/h. Similar spectrums come from the other speed analysis.

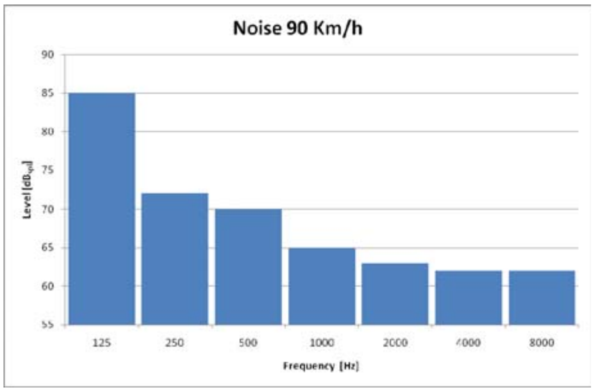

Figure 11: SPL octave band spectrum of the noise inside the car cabin.

2.3. Sound system measurement

The Eigenmike was placed on the driver seat in this case. It was positioned as in figure 6. The 6 loudspeakers installed inside the car was measured by means of the exponential sine sweep method [2] and they were so distributed:

- 2 front woofers (inside the car doors)
- 2 front tweeters (near the windshield)
- 2 rear woofers (inside the car walls)

Loudspeakers were feeded one at a time with a 10 seconds long ESS: the range of swept frequencies was 20 Hz – 20 kHz if woofer, 1 kHz – 20 kHz if tweeter. Every ESS was recorded by each of the 32 capsules of the Eigenmike therefore the measurement of a single loudspeaker did consist in a 32 multitrack recording that provided 32 impulse responses after the deconvolutions. In order to obtain information about the way the wavefront did move, it was performed the same analysis as in the noise case but employing 64 virtual 7th order cardioids to obtain more detailed false-color maps. As in the background noise case, anechoic measurement imposed frequency limits.

2.3.1. Sound system maps

Figure 7 shows a panoramic image of the car's cockpit used as background for the SPL maps.

Figure 12: panoramic image of car's cabin

The following figures show the color maps obtained after processing the impulse responses. The circle with a cross inside represents the loudspeaker that was feeded.

Figure 13 shows the color map of the impulse responses processed with an octave band filter at 2000 Hz. It could be noticed how front left area, where tweeter is installed, presents higher values of SPL. Reflections on the windshield are evident too as the energy spreads along it.

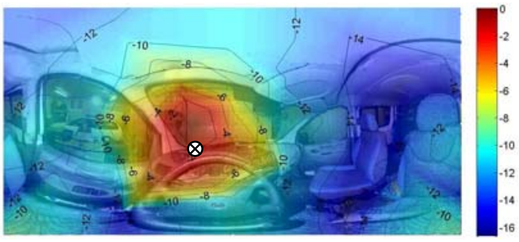

Figure 13: Front Left Tweeter @ 2000 Hz

When front right woofer was feeded, reflections on the left front window could be noticed (Figure 14). Impulse responses were processed with an octave band filter at 4000 Hz in this case.

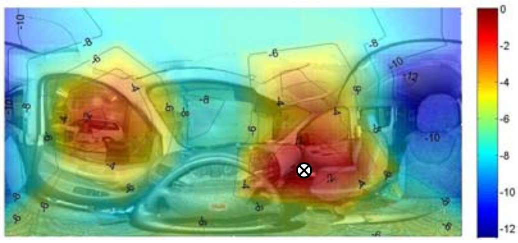

Figure 14: Front Right Woofer @ 4000 Hz

As expected, lower frequencies generated less directive patterns and waves reflect on the roof (Figure 15).

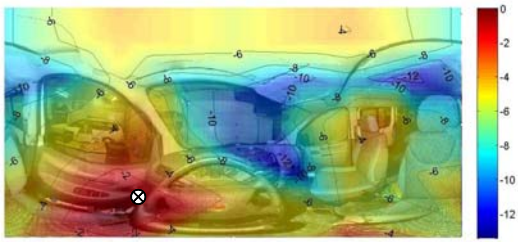

Figure 15: Front Left Woofer @ 125 Hz

The following pictures (16, 17, 18 and 19) show other maps where can be distinguished the waves coming from direct source and the primary reflections.

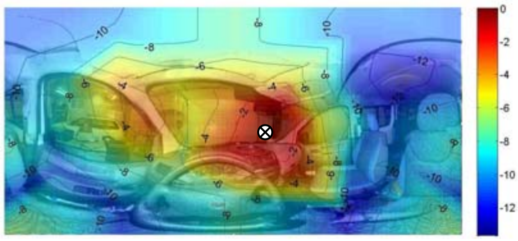

Figure 16: Front Right Tweeter @ 2000 Hz

Figure 17: Rear Left Woofer @4000 Hz

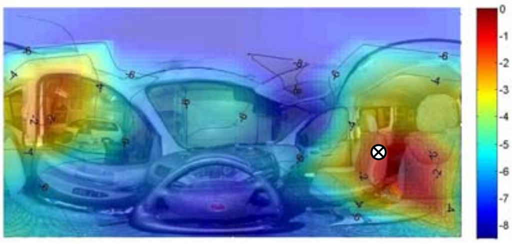

Figure 18: Rear Right Woofer @2000 Hz

Figure 19: Rear Left Woofer linear band

Beyond the time averaged analysis performed before, a time-sliding analysis was performed. The IR was sliced in 64 samples pieces (with 50% overlap). Joining the SPL false-color maps from each slice, a video was obtained. Figure 20, 21 and 22 displays 3 subsequent frames of the propagating field emitted from the front left tweeter.

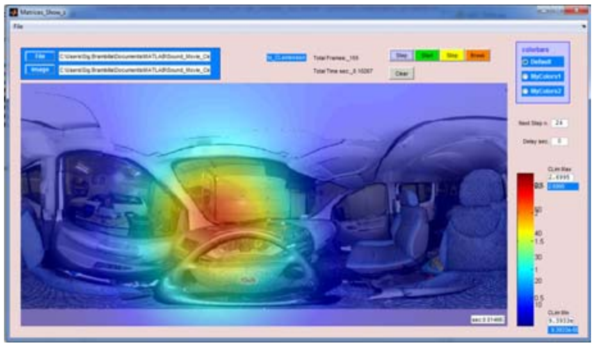

Figure 20: SPL video frame of front left tweeter @4000 Hz, t = 14.6 ms

Figure 21: SPL video frame of front left tweeter @4000 Hz, t = 15.3 ms

Figure 22: SPL video frame of front left tweeter @4000 Hz, t = 17.3 ms

In figure 23 and 24 is reported the SPL octave spectrum of the recorded and averaged IRs.

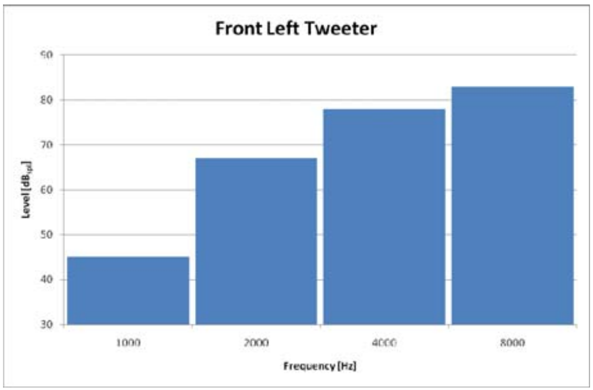

Figure 23: octave bands SPL for front left tweeter

Figure 24: octave bands SPL for rear right woofer

3. DEVELOPED SOFTWARE

The software developed was written in Matlab[1]. It allowed calculating the false-color maps and overlying them with the 360x180 degrees panoramic image. To obtain the continuous false-color map, it was necessary to interpolate the 32/64 discrete values of SPL by a 2D linear algorithm. The border values were not available because of the capsule arrangement on the Eigenmike, so the authors solved the problem as exposed below.

3.1. Boundary condition handling

It was important, in order to have correct results, to compute in the right way the values on the boundaries of the image. The solution was to think about the image for what it represents: an unwrapped version of a spherical object, as if it was a map of the world (Figure 25). It was therefore necessary to surround the original point values with “mirrored” versions of themselves (Figure 26), then interpolate and keep only the data over the original image range.

Figure 25: World Map

ᗡ	Ɔ	ᗡ	Ɔ	ᗡ	Ɔ
ꓭ	∀	ꓭ	∀	ꓭ	∀
A	B	**A**	**B**	A	B
C	D	**C**	**D**	C	D
ᗡ	Ɔ	ᗡ	Ɔ	ᗡ	Ɔ
ꓭ	∀	ꓭ	∀	ꓭ	∀

Figure 26: interpolation map. The original map (top) is rounded with mirrored versions (bottom)

[1] Matlab is a registered trademark of The MathWorks[2], Inc.
[2] The MathWorks is a registered trademark of The MathWorks, Inc.

4. CONCLUSIONS

The use of Eigenmike coupled with virtual microphones methodology allowed to inspect the sound field inside a car's cabin with higher spatial resolution compared with low-order microphone arrays. The false-color maps obtained during noise measurements provided consistent results with these hypotheses: low frequencies components of noise are mainly due to chassis vibrations; at high frequencies the doors/windows leakage become noticeable. Analysis of the IRs provided useful information about the way the wave field moves inside the car. False-color maps always revealed the source of the stimulus and its primary reflections, the video created by the time-depended analysis provided an intuitive way to inspect the paths of the wave field too.

4.1. Future developments

It could be possible to use the signal recorded by the microphone array for feeding a roughly-spherical loudspeaker array, inside which it could be possible to perform listening tests. In this way it could be possible to overcome the limitations currently posed by the binaural technology which was employed till now for subjective assessment of both the "background noise quality" and the "sound system quality".

Finer anechoic measurements of the Eigenmike will be done; in this way it will be extended the frequencies range where virtual microphones methodology works.

To rise the order of the virtual microphones, a stand able to rotate the Eigenmike around its polar axis will be built. In this way it will be possible to repeat multiple IR measurements of a speaker rotating the array. This will simulate the presence of a higher number of capsules allowing higher virtual orders and spatial resolution.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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[2] A. Farina, *Simultaneous measurement of impulse response and distortion with a swept-sine technique*, 108th AES Convention, Paris 18-22 February 2000

[3] http://www.mhacoustics.com