Sound source localization accuracy in car-cabins: a human perception perspective

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Abstract
The aim of this paper is to present a human-oriented approach to define the minimum accuracy required for source localization techniques when used in car interiors in combination with auralization strategies. A ray-tracing model of a car cabin is used as data provider. By assigning a random distribution of the source positions around the ideal one, the associated reflections are then consequently estimated from a ray-tracing model of the cavity. Source and reflections signals are convolved with corresponding Head Related Transfer Functions (HRTFs) for generating data aimed at filling a data base for subjective evaluation. A listening experiment was conducted in order to understand the influence of both source localization accuracy and different reverberant environments (due to reflections) on human perception. A Minimum Audible Angle MAA is also proposed as a parameter to assess the Just Noticeable Difference (JND) for sound source localization measurements inside a car.

1 Introduction

Optimizing the passengers' acoustic experience in vehicle cabin is becoming the most important task in the NVH field. However, any improvement to the cabin acoustic response starts from the identification of the source locations entering the cabin. Among the different sound source localization techniques, acoustic beamforming has gained relevance in car interior applications, mainly because it guarantees a good balance between localization accuracy and contained testing time. Moreover, interior beamforming can provide information related to the main source position as well to the early reflections. For these reasons, a trend in the recent years is to exploit data collected in a beamforming test also for auralization purposes. Despite this is an interesting approach, the fidelity of auralization strongly depends on the accuracy of localized sources and reflections. This issue has been faced in the past addressing energetic aspects only [1]. This paper aims at identifying the accuracy required for a sound source localization technique as acoustic beamforming in identifying the position of sound sources in car cabins from a human-centered point of view, i.e. when the source location are to be used for auralization purposes. This is done in the paper by associating localization accuracy to the Minimum Audible Angle (MMA), the angle formed at the center of the head by lines projecting to two sources of sound whose positions are just noticeably different [2].

A sound source localized in a position that differs from its true location may affect perception of the environment during a sound reproduction. In free field, this difference is caused only by the change in direction of arrival of the localized source. For sinusoidal signals presented on the horizontal plane, spatial resolution is highest for sounds coming from the median plane (directly in front of the listener) with about 1° MAA, and it deteriorates markedly when stimuli are moved to the side – e.g., the MAA is about 7°for sounds originating at 75° to the side [3, 4]. MAA depends not only on direction, but also type of a signal and a frequency content. The lowest values of MAA in the horizontal plane are around 750Hz (MAA=1°), and the worst around 2kHz (MAA=3°) [3].

Those differences have their origin in spatial cues which are provided to both ears. The sound reaching the farther ear is delayed in time and is less intense than that reaching the nearer ear. There are thus two possible cues as to the location of the sound source: an interaural time difference (ITD) and an interaural level difference (ILD) [4]. In sound propagation in reverberant environment, such as car cabins, the first event is the direct sound (the "first wave-front"). This is followed by a set of sparse early reflections for the next 20 ms or so (depending upon the size of the car), and then by dense late reflections that form a decaying "tail.". Different position of a sound source affects then different energy of reflections and distribution over time. Thus, coming back to our original problem, inaccurate localization of source in a car cabin does not only leads to a wrong direction of arrival, but different reverberation pattern as well. This might cause other perceptual effects like tone coloration or image shift [5]. Therefore in this paper we investigate perceptual effects of different source positions focusing on any perceptual differences, not only direction of arrival. In section 2 we describe the experiment methodology. Results are presented in section 3.

2 Method

2.1 Stimulus generation

Investigations of MAA were based on a simulated scenario. A car mock-up model was created in LMS Virtual.Lab software in order to generate impulse responses. A ray tracing technique was employed for calculations. Simulated wind noise source was used for the experiment. The dry sound was obtained by filtering a white noise to achieve the same noise spectrum as measured in wind tunnel during previous measurements. Figure 1 reports the wind noise spectrum used for later auralization.

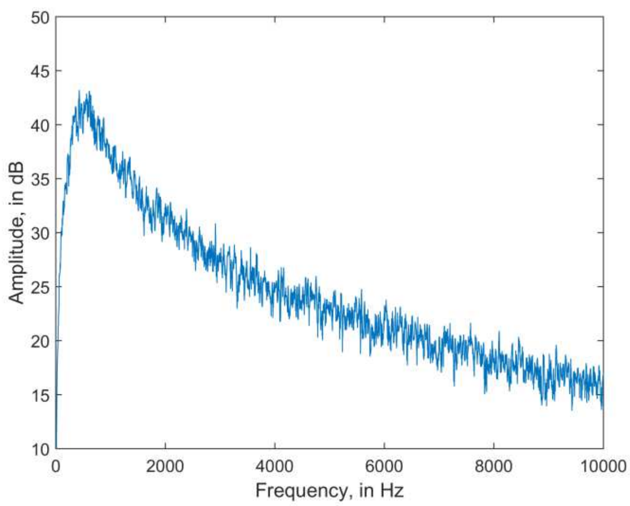

Figure 1: Spectrum of wind noise signal used in auralization

The receiver was placed in the position of a driver's center of the head. Sources were distributed evenly on the windshield with 2° angle step within the range of 40° from the left to the right with respect to the driver's center of the head (Figure 2 and Figure 3). All sounds were distributed either on the horizontal plane (Figure 3) or the median plane (Figure 2).

The ray tracing model was used not only to generate impulse response or the simplified car mockup but also to obtain direction of arrival of each reflection, which is a great advantage of ray tracing over other numerical methods. The reverberant stimuli were generated by additional processing of the dry stimuli.

Each reflection was spatialized by convolution with HRTF filter pair, corresponding to the angle of incidence calculated by ray tracing (see [6] for detailed description of HRTF database used).

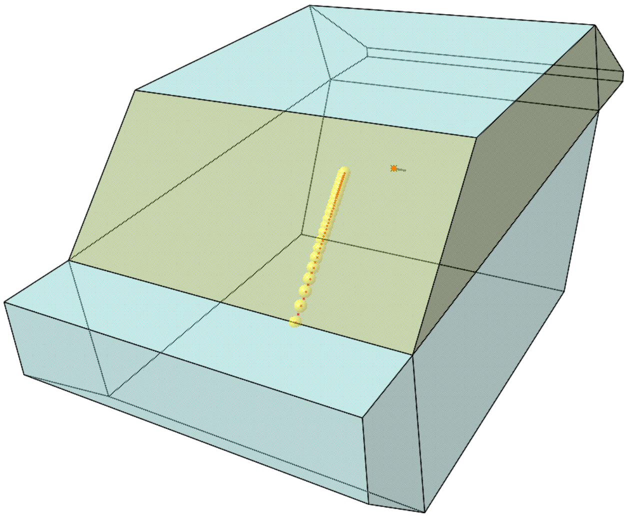

Figure 2: A car mockup model used for generating impulse responses with marked sources in the median plane

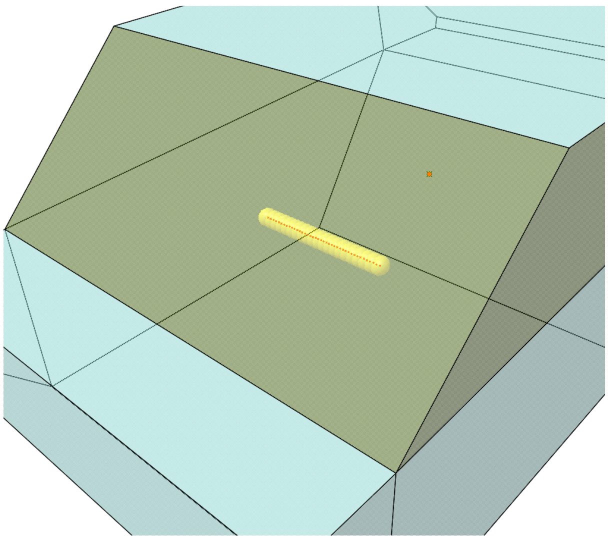

Figure 3: A close-up of a car mockup model used for generating impulse responses with marked sources in the horizontal plane

2.2 Experiment

In order to determine the MAA for the azimuth and elevation a listening experiment was carried out. Eleven listeners without known hearing problems (two females and nine males, ages 22–35) participated in the experiment. All stimuli were presented to subjects via headphones (Sennheiser HD-580) in a quiet office room, where the noise floor was below 20 dBA. In the experiment, sounds were presented in pairs. Each pair consisted of a reference sound and a tested sound. The reference sound was a sound appearing in forward direction (0° elevation and 0° azimuth angle). Tested sounds varied in median and horizontal plane within the range of 40° from the left to the right. Tested sounds were presented in decreasing angle order, e.g. from 6° to 4. If a listener perceived a difference three consecutive times, another test sound which is closer to the reference was presented. At first sounds appeared in different azimuth angle in the vertical plane were investigated. Then, sounds varied in median plane with constant 0° azimuthal angle were presented. The order of appearance of the reference sound and the sound under investigation was randomized. Finally, listeners were asked to identify whether two stimuli heard in succession are different or not.

3 Results and discussion

Figure 5 presents results achieved from the listening experiment. MAA for the median plane was found to be equal 6° for upper position, and 4 ° for lower position of the source. For the horizontal plane, MAA is different for left and right source positions, that is 2° and 4° respectively. Listeners responses are presented in Figure 4

Due to the fact that localization in the vertical direction vary with azimuth, an additional test was carried out. After estimation of MAA in the horizontal plane, sound samples were generated for 4 ° azimuth and different elevation angles. Results are presented in Figure 5Figure 5 (left). In all tests, listeners responses varied within 2° only, what is equal to the experiment accuracy.

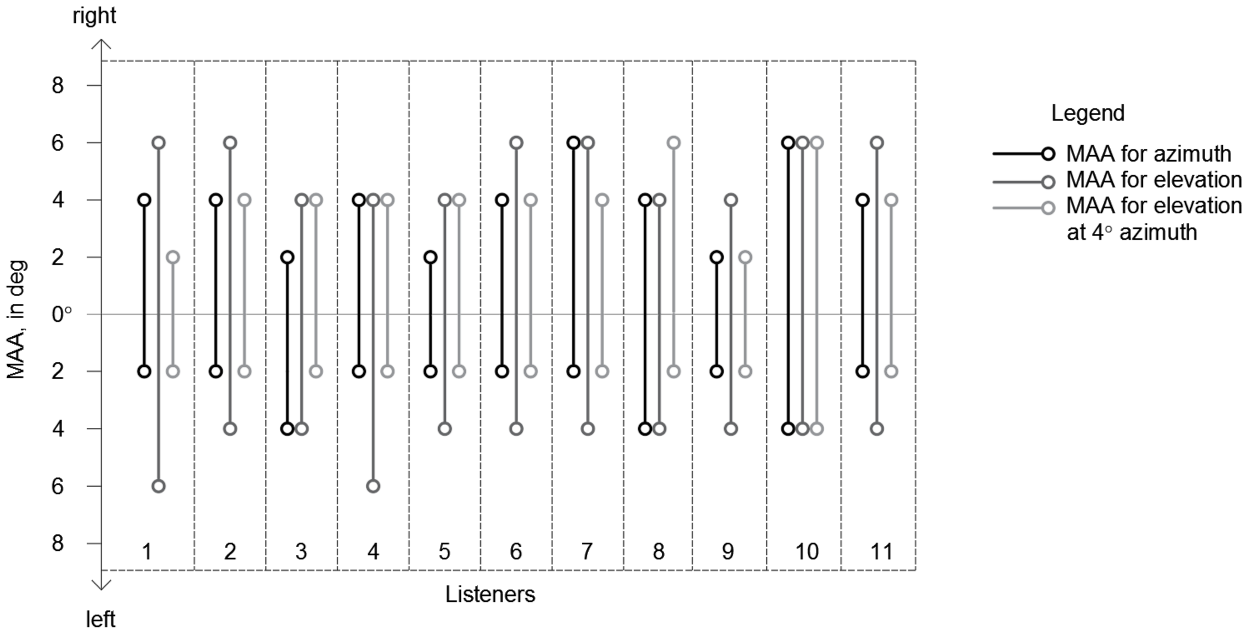

Figure 4: Results of MAA for the horizontal plane, median plane and vertical plane at 4 ° for each listener

In general, we need to remember that achieved results should not be directly associated with localization of a sound. Perceived difference between two sounds appearing from different direction only in free field conditions corresponds to different location of the source. In this paper we investigated sounds inside a car cabin, where besides direct sound, multiple reflection occurs. Listeners were asked to assess the difference between two sounds, not a perceived direction of arrival. Nevertheless, achieved values of MAA are similar to those known from the free field conditions. For MAA in median plane in car cabins is the same as for the white noise in free field. In the horizontal plane, on the contrary MAA is slightly worse than in the free field. Inconsistency of left and right MAA in horizontal plane and up and down for 4° azimuth vertical plane was also reported. Possible differences listed above might be due to following reasons:

1) Experiment accuracy is equal to 2°. The accuracy is limited to a resolution of the HRTF data base used. Moreover, 2° corresponds to a very small change of a source displacement: 1.5cm,
2) Even though in reverberant environments according to the precedence effect [7] sound source is perceived from the direction of the first wave front, in car cabins early reflections appear very
3) close to each other in time. This leads to other perceptual effects like tone coloration or image shift [5, 8]. For some displacements distributions of early reflections may provide different audible effect, not directly correlated with sound localization,

4) Position of the source inside a car. For some sources positions, especially those close to boundaries, even small displacement may lead to perceptual difference. This case can be noticed in every estimated MAA. Moving source on the horizontal plane towards left is more likely to perceive than the same displacement towards right (Figure 5 right). Source moving towards left is closer to the car's left door, and therefore reflection from this obstacle arrives faster than when the source is displaced towards right,
5) Source frequency content. In this experiment we used a wind noise signal, which is similar to Brown noise centered at 500 Hz. For more broadband signals, due to higher content of useful ILD and ITD source displacements might be perceived even more accurately. There is also possibility that for some signals even more significant changes of a source position might stay unnoticed.

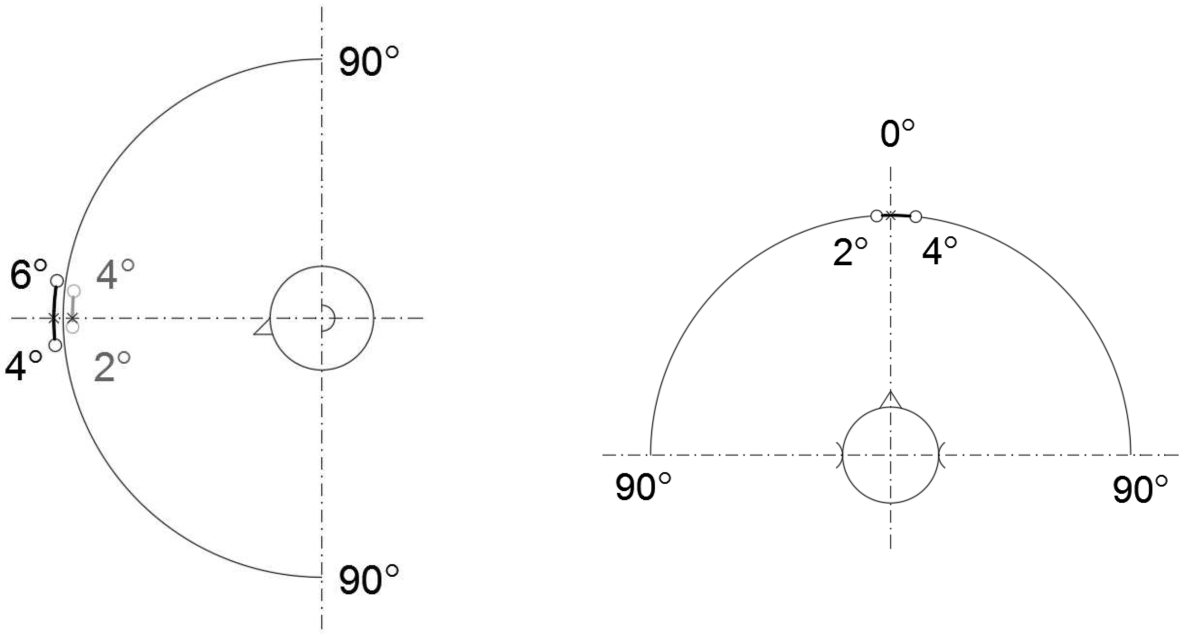

Figure 5: MAA for the horizontal direction (right) and for the vertical direction (left). For MAA on the median plane (left) results are marked with black line and with grey line for 4° azimuth

MAA for known source-receiver distance can be represented in cm. For the investigated car cabin mockup 2° corresponds to approximately 1.5 cm. To summarize, differences caused by source displacements larger than 3 cm were clearly heard by all participants. In some cases, e.g. displacements in the horizontal plane towards let were perceived with the change as small as 1.5 cm. Those results are in compliance with similar work known to the authors [9], where small displacements of a source in car cabins were investigated based on binaural records.

4 Conclusions

In this paper we investigated a human-oriented approach to sound sources localization accuracy in car cabins. A data set of simulated sources evenly distributed on the windshield with 2° angle resolution within the range of 40° from the left to the right with respect to the receiver's position were used in the experiment. The receiver was placed at the center of a driver's head. Minimum Audible Angles were derived from a listening experiments for two vertical planes and the horizontal plane. MAA for the horizontal plane varies from 2° towards left to 4° towards right with respect to the head orientation. For the vertical plane at 0° azimuth (median plane) MAA are approximately 2° worse than in the horizontal plane. MAA for vertical plane is 2° better when a source is moved slightly towards MMA for the horizontal plane. The investigation performed suggests that listeners certainly can perceive a difference when a source is localized farther than 3 cm with respect to its true location. In some cases, changes as small as 1.5 cm can be perceived as well. These values can be interpreted as the accuracy required for a source localization technique if its results are aimed to be exploited for auralization purposes.

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