Investigation of an auditory thresholds for early reflections in car-cabins

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ABSTRACT

A current challenge that NVH engineers are asked to face is to optimize the passengers' acoustic experience in vehicle cabins. The combined use of sound source localization techniques and auralization tools can help in tackling such issue. Data from the source localization step, i.e. sources and early reflections, can be auralized in order to assess the acoustic quality of the cabin. The remaining question is to understand how many reflections are effectively needed for providing a realistic listening experience. By varying the order of early reflections included in the auralization step, a different auditory impression is perceived by humans. At a certain point, increasing the number of individual reflections doesn't change the auditory impression and the rest of reverberations can be replaced by a constant reverberation tail. This paper aims at defining the optimal number of reflections that is necessary to use for in-vehicle sound auralization purposes. A ray tracing model of a car cabin is used for generating the data set containing the sound samples auralized by changing the number of reflection orders. Results from subjective tests are presented to show the correlation between auditory impression in the cabin and the optimal number of reflections used in the auralization.

Keywords: car-cabins, reverberation, auralization I-INCE Classification of Subjects Numbers: 61.6, 25.4

1. INTRODUCTION

Auditory thresholds for early reflections in concert halls and rooms have been previously investigated using real sound sources (1) (2) (3) or using auralization for simulating direct and reflected sources (4) (5). Additionally, some authors focused on minimum audible difference in direct to reverberant energy ratio (6) (7). However, no previous work is known to the authors focusing on similar problem for automotive applications. Car cabins are characterized by peculiar acoustic environment, where reverberation time is short and reflections appear close to each other in time. Different, compared to concert halls or rooms, forward and backward masking (8) can cause different perception of early reflections.

In this paper we investigate two problems. First, how including or excluding individual reflections in auralization affect human perception (threshold for inclusion a reflection). Car interior is a mixture of various absorbing materials (e.g. well dumped seats, doors and reflective windows), where we can expect single strong reflections from windshield or windows, and many weak reflections from trimmed parts. Hence, only a few early reflections might be necessary to include in auralization to achieve the "natural" sound, while the rest of reverberations can be replaced by a constant

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reverberation tail. The second problem under investigation is the level of early reflections at which we can perceive change in auralized sound (threshold for inclusion of an early reflection). This threshold leads to very useful information of required dynamic range of sound source localization techniques for car cabins applications. Previous studies show threshold dependence as a function of angle of incidence, time delay and sound source type (9) (10) (6) (11) (12). Therefore, results vary from almost -30 dB (reflection to direct relative level) for broadband noise, lateral reflection and long delay time (3), to -5 dB for speech, reflection from the same direction and short time delay (5). Also dependence of the threshold level and reverberant environment was reported (3). In this work we will measure threshold of individual reflections for short delay times, broad band noise simulating car cabin wind noise and different directions (detailed description in sec. 2)

2. METHOD

2.1 Stimulus generation

Using a ray tracing technique impulse responses of a premium sedan car cabin were generated. Calculations were carried out in LMS Virtual.Lab software. In order to simulate wind noise, monopole source was placed at the position of the left mirror. 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 auralization. Receiver was placed in the center of a driver's head. A model of the car with marked ray paths and the corresponding energetic impulse response are presented in Figure 2.

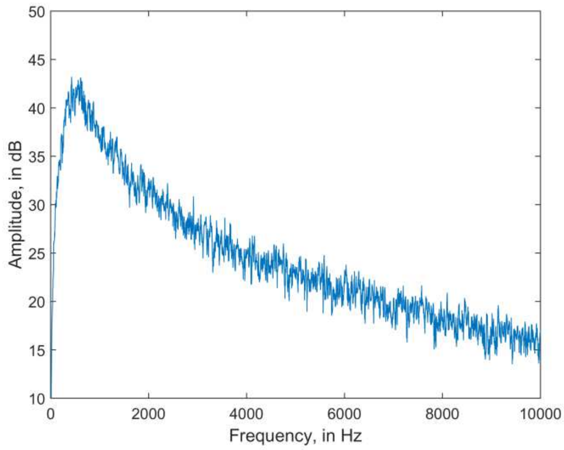

Figure 1 Spectrum of wind noise signal used in auralization

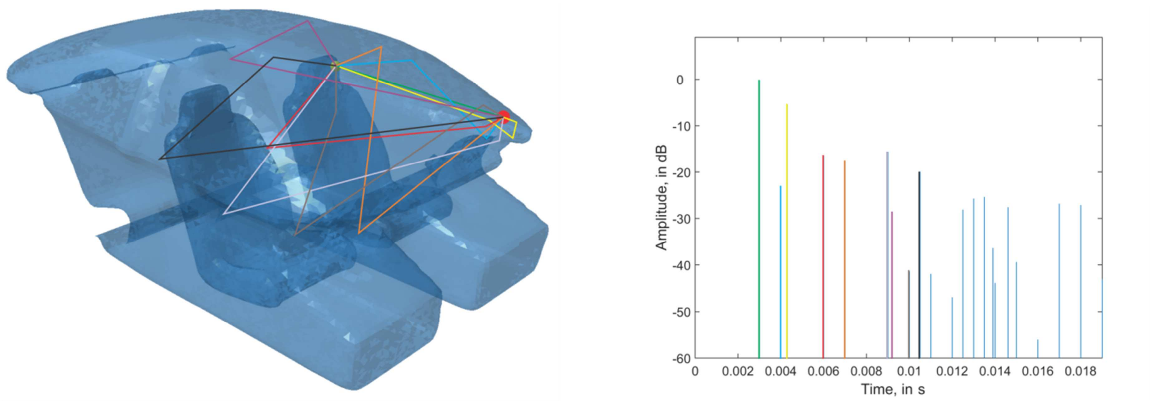

Figure 2 The model of a car used in ray tracing simulations (left) and first 20ms of the corresponding impulse response (right)

The ray tracing model was used not only to generate impulse response or a car 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 (12) for detailed description of HRTF database used).

2.2 Experiment

Two listening experiments were carried out. The aim of the first experiment was to determine the threshold for inclusion of a reflection (early or late). The second experiment was focused on the level of early reflections at which humans can perceive change in auralized sound. Ten listeners without known hearing problems (all male, ages 22–31) participated in both experiments. All stimuli were presented to subjects via headphones (Sennheiser HD-600 with an external sound card) within a quiet office room, where the noise floor was below 20 dBA. The level of stimuli was calibrated using a head and torso simulator in order to present them with a level comparable to the one generated by wind in car cabins – 40 dBA.

In the first experiment, sounds, which were presented in pairs, consisted in a reference reverberant sound (spatialized, with all reflections) and a modified sound. The modifications consist in excluding individual or multiple reflections from the impulse response. Finally, listeners were asked to identify whether two stimuli heard in succession are different or not. The test consisted of 50 pairs and reference and signals were presented in random order, with an interstimulus interval of 500 ms. Due to high number of reflections in echogram, performing full factorial experiment is practically impossible. Therefore, preliminary investigations took place, where authors selected, according to them, the most relevant reflections or group of reflections to be removed in stimuli for the experiment. Reflections from one to eight (those appearing within first 10ms, see Figure 2) were removed separately at a time. Most of sound samples consist of two or three removed early reflections. The purpose was to investigate the influence of each early reflection separately and a group of early reflections on auditory perception. The latter, gives as information about possible interactions between early reflections. Last part of stimuli was focused on a late reverberation. Thus, we removed some of reflections appearing after 10ms. Detailed description of which reflections were removed from sounds and corresponding results are listed in Table 1.

The second experiment was carried out in a similar way. However, the way how stimuli were modified is different. Here, we are interested in the level of early reflections at which humans can perceive change in auralized sound. Therefore, a set of stimuli were prepared where the level of individual reflections was changed, while other reflections remain the same. The level of analyzed reflection was changed in 1dB step from -18dB to -8dB (reflection to direct relative level). Due to time constrains of a listening experiment and preliminary investigations, only the first five reflections were taken into consideration. To sum up, 55 pairs, consisted of modified sound and the reference, were presented to listeners. Like in previous experiment reference and signals were presented in random order, with a time gap of 500ms and listeners were asked to identify whether two stimuli heard in succession are different or not.

3. RESULTS AND DISCUSSION

In both experiments, thresholds were calculated analogously. Each modified sound gets 1 point when a listener identifies it as different from the reference. Points for all stimuli for all participants are summed together and divided by the number of participants. In this way, results are presented on a scale from 0 to 1, where 0 means none of participants was able to recognize a difference, and 1 means all participants perceived the stimulus as a different from the reference. The threshold is a point where at least half of participants identified a difference (results higher or equal 0.5).

3.1 Threshold for inclusion of a reflection (first experiment)

Table 1 presents results of the experiment with a description of which reflections were removed from stimuli. According to predictions, reflection number two was selected to be the most significant. Lack of this reflection independently or together with other reflections is audible by all listeners who participated in the experiment. The reason is straightforward: the level of this reflection is approximately only 5 dB lower than the true source which is in compliance with results achieved in sec. 3.2. Additionally, reflection number two appears only 1,3ms after the true source. That short repetition of a “dry” sound coming from almost the same direction as the source causes strong interference pattern. This leads to a perceptual effect called tone coloration (9) (11). Figure 3shows two spectra of the sound with all reflections (left) and sound without first five reflections (right). Strong comb filter can be noticed when all reflections are present. Removing early reflections makes the spectrum more “flat”, therefore reduce tone coloration. Further removing of reflections doesn’t affect a change in spectrum and becomes unnoticeable for listeners. Different spectrum presented in left part of Figure 3 in respect to the “dry” sound (Figure 1) are caused by a convolution with HTRF filters.

Table 1 List of sound samples used in the experiment with numbers of removed reflections and corresponding results

Sample no.	Reflections removed	Score	Sample no.	Reflections removed	Score
1	1,2	1	26	1,8	0,3
2	2,3,4,5	1	27	3,7	0,3
3	2,3,4	1	28	5	0,3
4	2,3	1	29	1,3	0,2
5	2,4	1	30	1,7	0,2
6	2,5	1	31	1	0,2
7	2,6	1	32	3,6	0,2
8	2,8	1	33	3	0,2
9	2	1	34	4,6	0,2
10	3,5	1	35	4	0,2
11	2,7	0,9	36	5,6,7	0,2
12	3,4,5	0,8	37	5,6	0,2
13	2,4,5	0,7	38	6,7,8	0,2
14	4,9	0,7	39	6	0,2
15	4,5,6	0,6	40	7	0,2
16	4,5	0,6	41	8	0,2
17	5,6,7,8	0,6	42	13,14,15,16	0,2
18	5,7	0,6	43	4,8	0,1
19	1,3,4,6,7,8,9	0,5	44	6,7,8,9,10,11	0,1
20	3,4	0,5	45	6,8	0,1
21	4,5,6,7	0,5	46	7,8	0,1
22	4,7	0,4	47	13,15,18,21,23,24,25	0,1
23	5,8	0,4	48	1,6	0
24	1,4	0,3	49	6,7	0
25	1,5	0,3	50	9,10,11,12	0

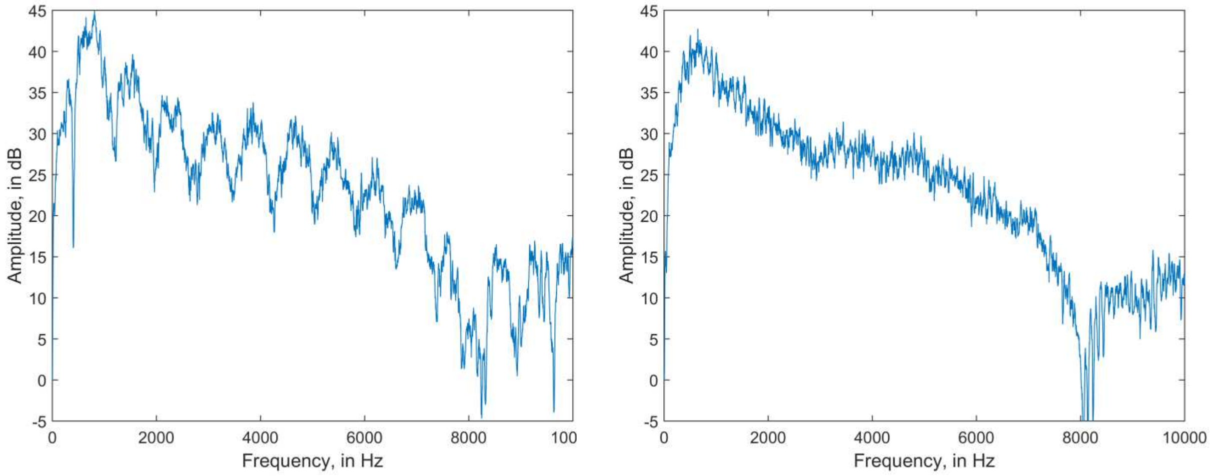

Figure 3 Spectrum of the sound with all reflections (left) and sound without first five reflections (right)

Table 2 shows levels of first eight reflections with corresponding directions of arrival (azimuth and elevation angle). Also the indications of significance are given, where “yes” and “no” mean reflection is significant or not, “yes/no” means reflection is significant only when other reflections are removed at the same time (see Table 1). We can notice that absence of reflections 3, 4, 5, 8 are perceived only when more than one early reflection is removed. Those reflections are too weak to cause individually strong interference pattern like reflection number 2. However, when removed collectively they can create different spectral masking effects and reduce the total level of a signal.

Removing reflections from the late reverberation (after 10ms) does not affect perception of a sound. As can be seen from Table 1, stimuli no 42, 44, 47 and 50, where removed high number of reflections, were impossible to distinguish from the reference stimulus. It leads to a conclusion, that reflections from late reverberations do not need to be treated individually. It is sufficient for an auralization to replace exact calculation of a late reverberation from ray tracing with an universal reverberation tail, calculated stochastically.

Table 2 Levels of first eight reflections with corresponding directions of arrival and an indications of significance

Reflections	1	2	3	4	5	6	7	8
Level, in dB	-23	-5	-16	-17	-15	-28	-41	-20
Azimuth, in deg	340	345	90	280	75	215	45	80
Elevation, in deg	10	10	-40	0	-20	20	10	0
Significance	no	yes	yes/no	yes/no	yes/no	no	no	yes/no

3.2 Threshold for a single reflection with a full impulse response (second experiment)

Figure 4 shows results of the second experiment. Reflections 2,3 and 5 have lower threshold (around -14 dB, reflection to direct relative level) than reflections 1 and 4 (around -10 dB). Reflection no 1 appears almost together from almost the same direction with very strong reflection no 2, thus higher threshold can be explained by masking effect caused by reflection no 2. Reflections 3 and 4 have almost the same levels, but they have different thresholds of perception. The reason lies in direction of arrival. Reflection no 3 is lateral, causing higher energy in the right ear than a direct sound or reflection no 2 as well as different spectral content due to HRTF.

Listeners in this experiment were consistent. Influence of results were listeners did not perceive a difference of a stimulus with a level higher than beforehand marked as a perceived is statistically non-significant.

To conclude, it is possible to reproduce a sound in car-cabins by reducing number of reflections included in auralization. Considering wind noise source, optimal number of reflections used in the auralization is defined by the level of individual reflection as well as the direction of arrival. For reflections appearing from a similar direction as a direct sound, important are those with a level higher than -10dB relative to a direct sound. Listeners are more sensitive for lateral reflections, where the threshold is approximate -14dB relative to a direct sound.

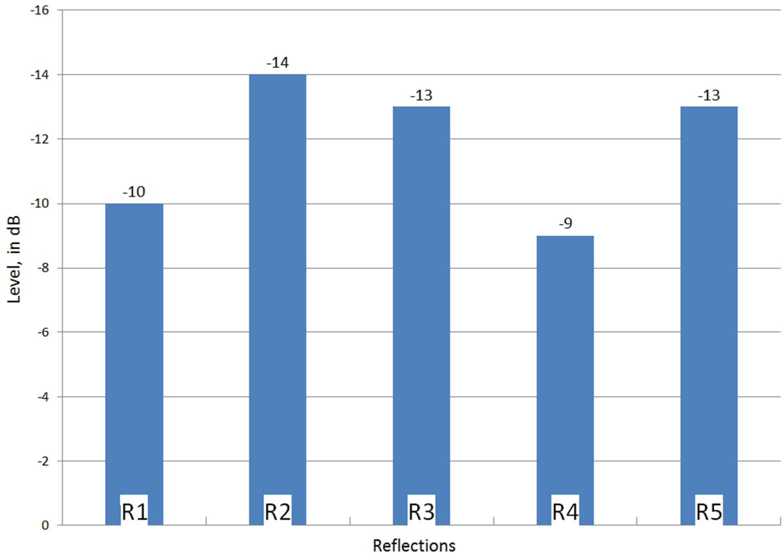

Figure 4 Thresholds for single reflection with a full impulse response

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