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CAR CABIN EFFECT FOR ACTIVE SOUND DESIGN

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ABSTRACT

A tool for active sound design has been previously proposed to generate sounds that are linked to the dynamics of a vehicle such as throttle and rpm. The tool is flexible and enables the design of sounds without the presence of a physical testing vehicle. The evaluation of the designed sound can be performed individually, or in combination with vehicle noises such as engine, tire-road interaction, and wind. These noises can be recorded and replayed in a fixed scenario or synthesized using a vehicle simulator at new operational conditions. However, the synthesized active sound does not take into account the sound propagation path, which can impact the perceptual aspects of the sound. To improve immersion and accuracy, this paper proposes the inclusion of the car cabin effect in the active sound design toolchain. To achieve this, impulse responses are measured from each car loudspeaker to the driver's ears and convolved with the active sound. The approach is preliminarily evaluated to assess the degree of realism and authenticity considering different speakers' configurations.

Keywords: *NVH simulator, sound synthesis, car cabin impulse response.*

1. INTRODUCTION

Active Sound Design (ASD) is at the same time a creative process to obtain desired vehicle sound attributes and a powerful resource to match NVH and perception targets both for interior and exterior vehicle noise. ASD is based on the creation of sound signature models that are parameterized in function of vehicle state variables. These variables can then evolve in real-time and actuate the sound model that synthesizes the resulting sound within the real dynamic driving environment. The designed sound signatures can be validated directly inside the prototype vehicle or on physical mule vehicles. However, to front-load the ASD activities to the early stages of the vehicle development process, it is desirable to test ASD signatures already on virtual prototypes. To do so a digital framework allowing the synthesis of both the passive and the active vehicle components on NVH simulator should be used (a possible architecture is described in reference [1]. In order for this assessment of the active sound component to be realistic in a virtual environment, it is important to properly account for the car cabin reverberation effect as well as for the characteristics of the car's loudspeakers through which the active sound will be reproduced in operation. The full understanding on the car cabin response and on the influence of the audio reproduction system, moreover, enables what-if games on the virtual prototype where the car cabin characteristics as well as the audio system characteristics can be edited and assessed without the need of physical prototyping. This paper reports on key aspects required to correctly characterize experimentally the car cabin and the audio reproduction system's effect.

2. METHODOLOGY

This section describes the methodology for the active sound design and car cabin impulse responses methodology.

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2.1 Active sound

An increasing number of vehicles are equipped with interior and exterior active sound generation. Apart from the legislative requirement to feature a pedestrian warning (AVAS) aboard electric vehicles, ASD is more and more used either to refine an existing sound - this is mostly the case of ICE-equipped vehicles - or to introduce additional sound features from scratch, as in the case or electrified vehicles. The main objectives of ASD are: give the driver feedback about the current state of the vehicle, increase the driver's involvement, reflect a brand identity, allow masking mechanisms to minimize undesired and potentially annoying noise components. ASD on the one hand therefore incorporates a creative aesthetic process and on the other hand has to fulfill sound quality-influenced targets. To support ASD processes, multiple synthesis methods have been proposed. The most popular methods can be categorized as follows: order-based approaches for tonal components synthesis, pitched playback to create continuous sound synthesis for playback of pitch-shifted sound fragments, frequency modulation synthesis based on addition of harmonics of existing tones to enrich sound, granular synthesis, Shepard synthesis. The interested reader can refer to the overview proposed in reference [2] for more details.

2.2 Car cabin impulse responses

Measurement of impulse responses (IR) is commonly performed to characterize rooms as a linear system. In the car cabin case, the impulse responses represent the electro-acoustic path contribution. The literature on impulse response measurements is vast, but only a few publications are specific for car cabins [3, 4]. Among them, the preferred source excitation is exponential sine sweep (ESS) as compared to maximum length sequence (MLS) since distortions induced by the loudspeaker are spread throughout the period of the IR recovered.

Once the impulse responses have been estimated, the sound synthesis can be performed as shown in Fig. 1. In the simulator, the driver's stimuli (e.g. throttle) are used as input in Testlab Sound Designer (TL SD) through Can Bus communication. A sound is then generated using one of the methods discussed previously. Then the synthesized sound stereo signal (left and right channels) are convolved with impulse responses for a set of speakers. In this illustrative example, the two front speakers are employed.

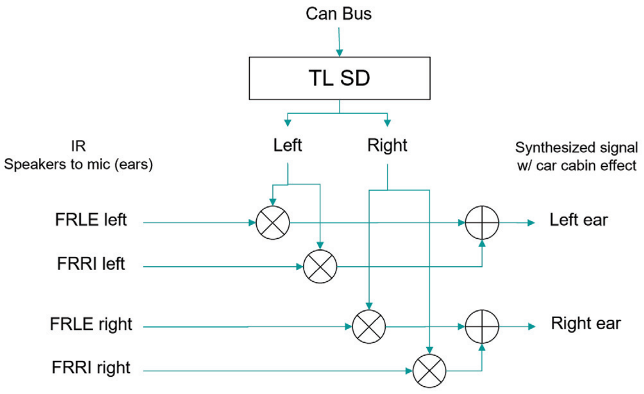

Figure 1. Digital signal processing diagram for the input sound, generated in Testlab Sound Designer (TL SD), and the convolution operation.

3. MEASUREMENT SETUP

Measurements have been performed on a commercial available fully electric SUV cabin in a large engineering hall. Fig. 2 shows a picture of the right microphone in the driver seat headrest.

Figure 2. Left and right 1/2" microphone in the driver seat headrest at ear level; Left side is occluded in the picture.

The instrumentation is shown in Fig. 3 and is as follows: Simcenter SCADAS Mobile with a 8-channel voltage/ICP input module and digital to analog module output module as the acquisition system. Two ICP 1/2" microphone (G.R.A.S.) located in the drivers' headrest. The amplifier is the 6-channel pre-amp Alpine amplifier (PDP-

E800DSP) which is used instead of the original equipment manufacture (OEM) amplifier. Four OEM sound system mid-range 6” loudspeakers located at the doors were used as sound sources. The loudspeakers are labeled as follows: left front door (FRLE), right front door (FRRI), left rear door (RELE), and right rear door (RERI). The infotainment system also includes a central tweeter, a central loudspeaker, and two subwoofers underneath the front seats. Those are not employed in this preliminary investigation.

In addition to the OEM loudspeaker, a monopolar source (Simcenter Mid-High-frequency volume velocity source Q-MHF) is also employed and placed at the same loudspeaker location. The use of the Q-MHF (valid from 100 Hz to 10 kHz) is done to simulate the impulse response at the speaker location. There are three reasons for this. Firstly, in some cases, the speaker wires may not be easily accessible for fast measurement. Secondly, the original loudspeakers may not be suitable for impulse response measurement due to large sound distortions. Thirdly, the collected database of impulse responses using the same source can be used for eventual comparison between different vehicles can be performed in a fair manner.

Fig. 3 shows a schematic of the measurement procedure. The source signal is generated using Simcenter Testlab. The loudspeakers are excited using an ESS excitation from 20 Hz to 20 kHz at a 40960 Hz sample rate. The signal is converted to analog and sent to the amplifier and from there to the loudspeakers. The amplifier allows all the loudspeakers to be connected simultaneously. However, in this measurement, the speakers are excited separately. The signals from the two microphones near the headrest are recorded and digitally converted.

The driver’s seat was occupied by a person to account for the driver’s presence in the vehicle. The human model is static throughout the measurement. However, small head movements are unavoidable and can cause variability in the recorded signal. The speaker levels were set to avoid distortions.

3.1 Post-processing

The frequency response functions (FRF) were estimated by performing 50 averages. The averaging lowers the noise level proportionally with a square root of a number of averages, thus improving the measurement signal-to-noise ratio. In addition to this, the averaging minimizes the variation caused by small head movement during measurements.

The sweep duration was determined from initial measurements with Q-MHF where it is found that the impulse is relatively short with direct sound close to the early reflection. The impulse response has short reverberation (0.05 s) and the onset time is around 0.003 s. Therefore, the impulse responses were truncated at 0.05 s.

4. RESULTS

This Section shows the results for the frequency response and impulse response estimation.

Fig. 4 shows a comparison of FRFs of the left receiver between Q-MHF Q-source and the original car loudspeaker. The analyzed frequency band is chosen for a region where both measurements have equally good coherence.

The OEM loudspeaker has lower energy at low frequencies as compared to the Q-MHF while at higher frequencies (above 900 Hz), the opposite is observed. The cause of more dips for both speakers is due to reflections. The dip below 900 Hz is matching fairly well, especially at 400 Hz. Nonetheless, care should be taken when using the Q-MHF for such application as the response may differ from the OEM loudspeakers both in overall level and frequency. The remaining of this section uses OEM loudspeakers.

Fig. 5 shows the autopower of the left and right ears for excitation on the left front speaker and the background noise at the left ear. It can be noticed that the signal-to-noise ratio is acceptable for the analyzed range.

Between 7 kHz and 8 kHz, a higher energy is observed in the left ear which can be due to reflections from the door panels and the reduction in energy at the right ear can be due to the head and torso occluding effect. At low frequencies, the car cabin effect is similar between the two signals.

Fig. 6 shows the impulse response at left and right for excitation on the left front speaker. It can be noticed that the time of arrival of the direct wave occurs at an earlier time in the left speaker and at a higher level. The car cabin is well insulated producing a short reverberation time.

Finally, the sounds have been evaluated with and without the IR in TL SD. The impulse responses can be implemented in an offline or real-time manner. In the real-time case, the impulse response ought to be a low-tap finite impulse response (FIR) filter for an efficient implementation in terms of computational cost and for deployment in the vehicle. The truncation of the IR to a

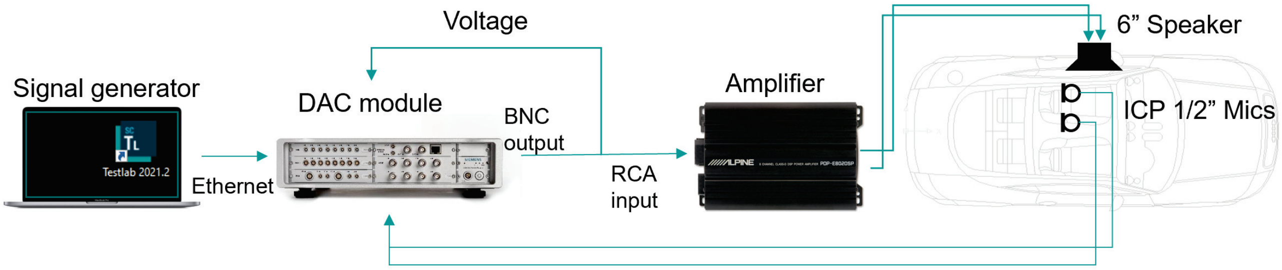

Figure 3. Schematic of the signal toolchain for the measurement of the car loudspeaker's impulse responses.

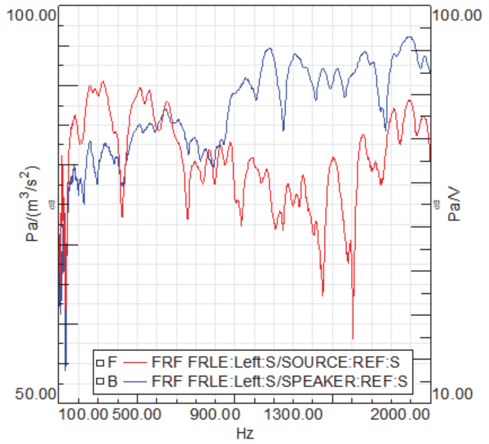

Figure 4. Comparison of FRF of left ears for excitation on the left front speaker between Q-MHF (in red) and original car loudspeaker (in blue).

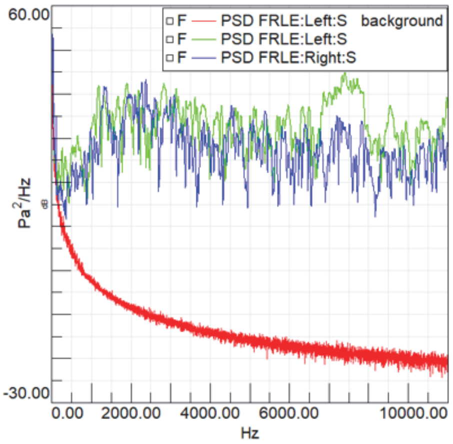

Figure 5. Autopowers of left and right ears for excitation on the left front speaker; background noise is shown as reference.

low tap filter at a higher sample rate can cause the tail of the response to be lost. A solution for this problem is to downsample the impulse response at the expense of reducing the Nyquist frequency and losing accuracy at high frequencies. The implication of a low-tap IR implementation is the subject of future research. In preliminary listening experiments, a clear difference is noticeable between a scenario with and without the IRs. However, a formal listening test is required to quantify the benefit of the proposed implementation.

5. CONCLUSION

This paper investigated the use of measured impulse response in the synthesized active sound tool-chain. A measurement setup has been proposed to estimate the impulse responses from the car loudspeaker to the driver's ears. In addition to the car loudspeakers, an alternative setup using a monopolar source has been proposed. Results showed that the loudspeaker's response differs from the monopolar source mainly at frequencies above 900 Hz and this can have a major influence in the sound evaluation. Therefore, care should be taken when using the monopolar source for such an application. Finally, the generated impulse responses have been implemented in the Sound Designer tool-chain and preliminary sound evaluation shows a noticeable improvement in the realism of the sound synthesis as compared to no impulse responses. The method has the potential to improve the development of active sound design by virtually changing the car loudspeaker setups.

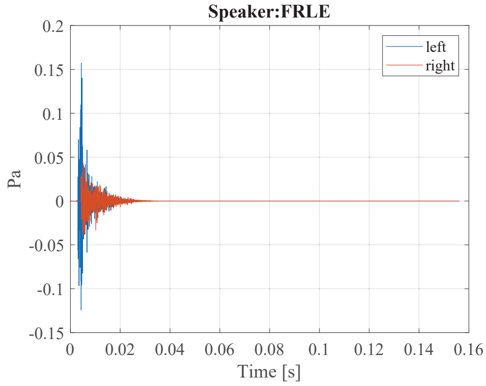

Figure 6. Impulse response at left and right for excitation on the left front speaker.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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