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VALIDATION OF CAR SOUND MODELS

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Abstract
The evaluation of car interior sounds in the laboratory may substantially differ from real life judgments of sound quality in the car. The main reason for this effect is the dynamic behavioural interaction of the driver with the process of sound generation, e.g. by accelerating the car, which does not occur in the laboratory. The driver, thus, gets an auditory feedback of his or her activity what may give a much more realistic impression of sound quality as compared to laboratory data. On the other hand, different from the laboratory, it is not easy for the experimenter to control for all sorts of disturbing environmental effects in the car. To overcome this problem the authors developed a reliable method for the modelling of interior car sounds. Basically the method consists of a highly versatile synthesis device for online sound generation being controlled by various steering parameters (e.g. rpm, speed, etc.). The paper will present the method and will give evidence for the validity of the approach.

INTRODUCTION

The perception of a car interior sounds when heard in the car environment significantly differs from judgments of the same sounds as presented in the laboratory. The reason for this phenomenon is the very fact that the driver is not a passive listener to the sound but rather interacts with the process of sound generation, e.g. when accelerating the car or even – to a lesser degree - when cruising. In this case the sound has the function of a feedback to his or her own actions, i.e. sound perception is not solely determined by acoustical features but to a great extend by the consequences the subjects feels when responding to it [1]. The driver, thus, gets a much more realistic and more comprehensive impression of sound quality as compared to the laboratory situation. On the other hand, different from the laboratory, it is not easy for the experimenter to control for all sorts of disturbing environmental effects in the car. To overcome this problem the authors developed a reliable method for the modelling and validation of interior car sounds. Figure 1 shows a general scheme of the method.

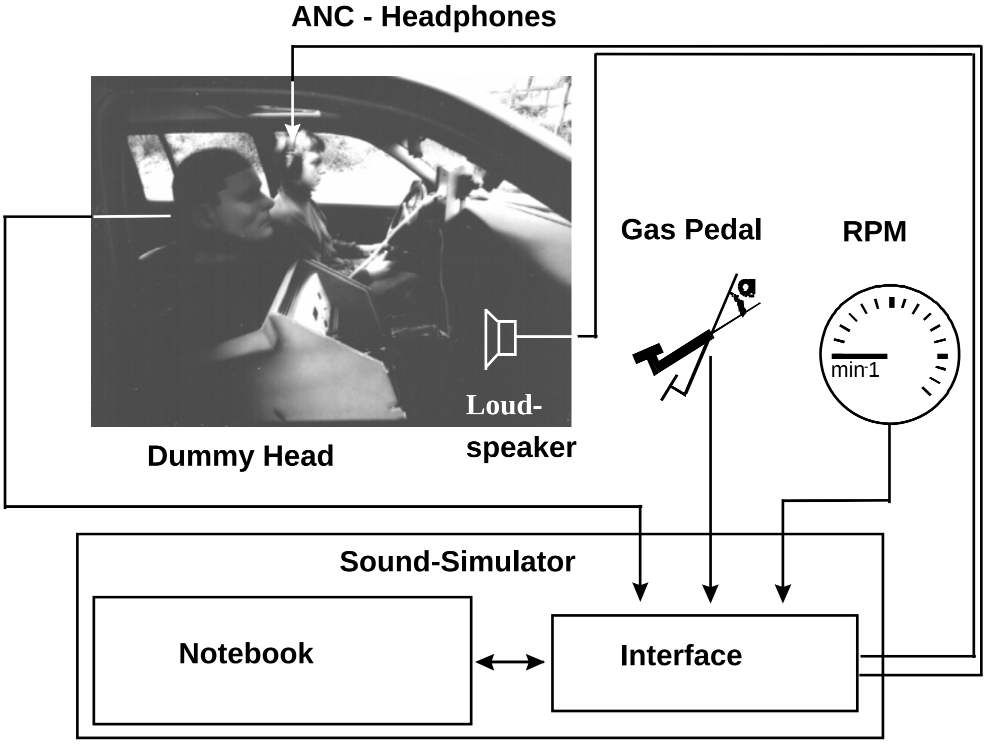

Figure 1: Sound generation in the car

The simulator has two options to generate the sound:

1. The sound is picked up by a microphone (e.g. a dummy head or a head set microphone, etc.) and processed by the simulator using filtering and/or additive synthesis of desired spectral components. The output is presented via headphone. ANC-headphones are preferably used in order to improve the SNR relative to the environmental noise.
2. In case that only additive synthesis is needed the sound is presented by headphones or by a loudspeaker. No microphone input is necessary in this case.

Applying the second options it could be demonstrated that the addition of feedback sound while driving significantly increased the driver’s perception of power without affecting his/her perception of pleasantness. This effect, however, strongly depends on the spectral characteristics of the feedback sound [1]. Even slight deviations from this constraint may jeopardize any positive perceptual effect. Therefore it is mandatory for the synthesis procedure that the resulting sound scenario perfectly meets the natural acoustics of the car under study. The purpose of the present study is to demonstrate that this goal can be achieved by a combination of additive sinusoidal synthesis of selected engine orders combined with a synthesis of broadband car environmental noise generated by inverse FFT. As a criterion of perfect matching an index of determination above $r^2 = 0.95$ between most representative acoustical criteria of the original and the synthesized car sound is adopted (corresponding to a percentage of common variance of > 95%). As a first step these criteria are defined by factor analysis of a battery of acoustical measures. As a next step the synthesis of a representative sample of car interior sounds is performed and the correspondence between the original and the synthesized sounds can be determined.

CRITERIA FOR SYNTHESIS VALIDATION

The interior sounds of six different cars were measured on the dynamometer. The microphone was positioned corresponding to the left ear of the driver. Table 1 shows some technical data describing the measurement conditions.

Table 1

car no.	engine	acceleration	gear	RPM range
1	4-cyl. gasoline - inline	slow	2nd	764-6495
2	6-cyl. gasoline - inline	slow	2nd	766-5995
3	6-cyl. diesel - inline	slow	2nd	695-4499
4	6-cyl. gasoline - inline	slow	2nd	1971-6226
5	6-cyl. gasoline - inline	slow	3rd	794-6445
6	12-cyl. gasoline – V12	slow	2nd	817-5630

The subsequent measures were applied to the six sounds. All analysis using SASSWin V.1.96 were done dependent upon RPM with a resolution setting of 60 RPM.

- A-level (DIN/IEC 651)
- Loudness (ISO532B)
- Sharpness [2]
- Roughness[2]
- Speech Intelligibility - SVI [3]
- Levels of engine orders 0,5 – 16, order steps of 0,5

For each car a matrix of N=37 variables was gained. The six matrices were combined to one common matrix for all six cars and submitted to principal component analysis with VARIMAX rotation (SPSS13.0). As a result a five-factorial solution was gained representing 77,5 % of the entire variance. The following six measures (Table 2) were selected from the resulting component matrix having maximal correlations to the extracted factors. Note that this selection is entirely statistical. Based on other criteria, e.g. vibroacoustical expertise or correlation to perceptual factors (pitch, tonality, etc.) other measures may have been taken. For the purpose of the present study, however,

Table 2			
factor	explained variance (%)	selected measure	correlation with factor
1	24,7	engine order 2 engine order 15	0,63 0,92
2	20,6	engine order 9	0,87
3	13,9	speech intelligibility - SVI	0,84
4	11,5	engine order 6	0,81
5	6,8	engine order 4	0,72

the chosen six measures are optimal in a sense of describing most representatively the common acoustical space of the six cars. In case that a sufficiently high correlation can be obtained between the original and the synthesized sounds relative to the adopted metrics the procedure can be considered as validated in respect to the common acoustical space.

SYNTHESIS

The control parameters for the synthesis are the profiles of the five engine orders in combination with the respective background sound spectra. Steering of the synthesis is performed by an externally fed in signal (e.g. a tacho signal). Synthesis is done with SASSWin V.1.96. RPM resolution is set to a value of 60. Figure 1 shows two engine order profiles for comparison (car no.1 and 6).

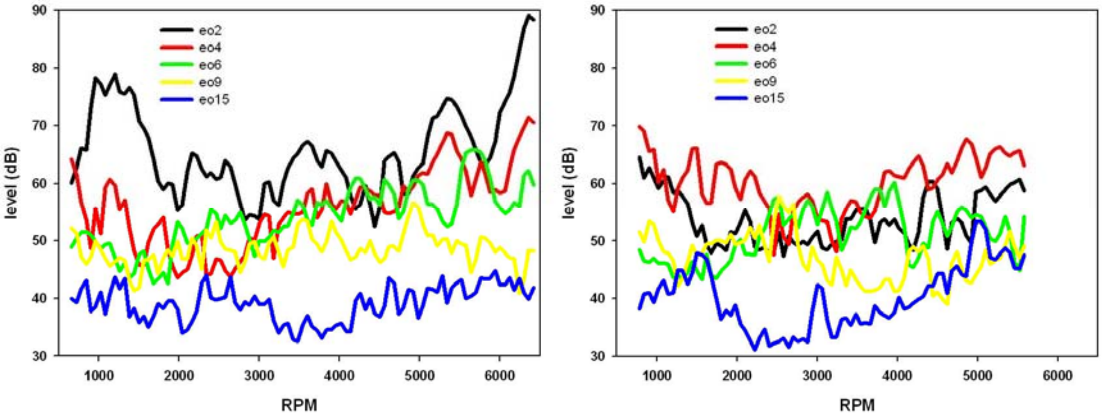

Figure 2 – Engine order profiles of car no.1 and 6

The phases of all engine order are treated randomly. Alternatively the phases can be set to some predefined values. In any case minimum phase is to be avoided as it may lead to an unwanted superposition of amplitudes.

Concurrent to the engine order synthesis the background noise is synthesized dependent upon the RPM, too. Prior to synthesis the background noise is automatically extracted by SASSWin and allocated to RPM (or other steering parameters, e.g. speed). Figure 2 shows three background noise spectra of car no.1 and 6 at 1000, 3000 and 5000 RPM.

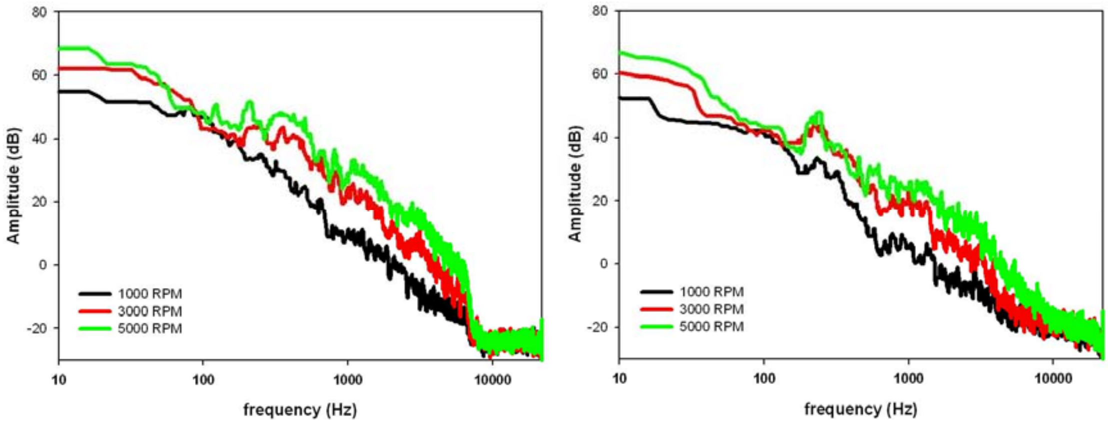

Figure 3 – Examples of background noise spectra of car no.1 and 6

For both set of control parameters (engine order profile, background noise spectra) various constraints, e.g. level constraints, can be defined (what is omitted in this case as it would lead to unwanted bias effects in the synthesis). Synthesis is done online by feeding the external steering signal into the synthesizer. Figure 3 summarizes the procedure.

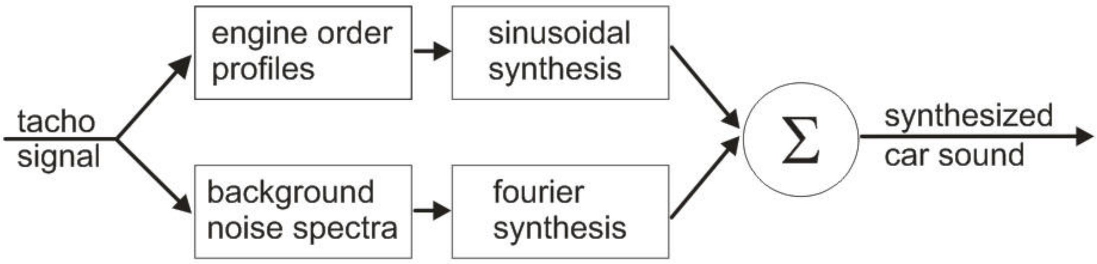

Figure 4 – Scheme of the synthesis

VALIDATION

Figure 5 shows a comparison of the order and the speech intelligibility profiles of the original and the synthesized sound for car no.1. The result obtained for the other five cars are quite comparable. The mean correlation between the original versus synthesized profiles for all six measures and all six cars is r = 0.995. The coefficient of determination is $r^2 = 0.99$, i.e. 99% of acoustical variance are in common.

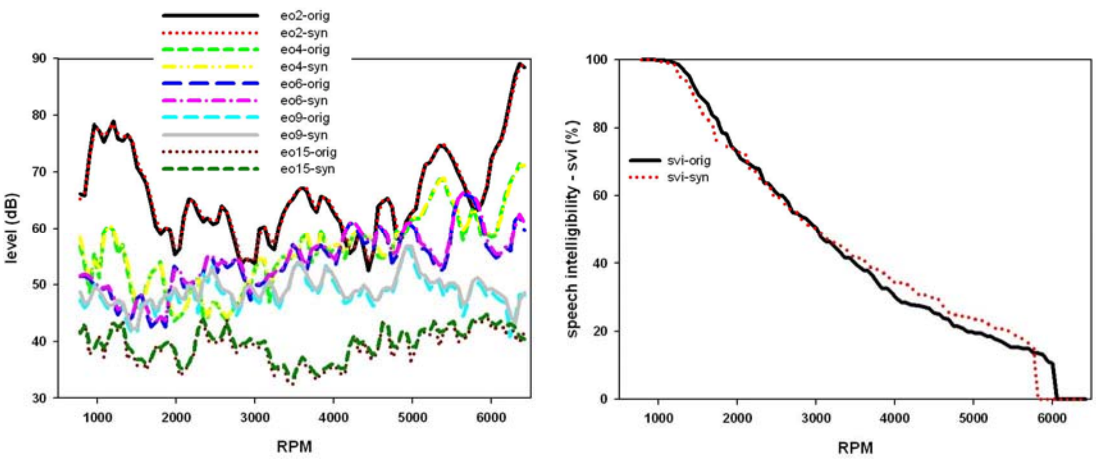

Figure 5 - Engine order profiles and speech intelligibility of the original and synthesized sound of car no.1

CONCLUSION

One of the most crucial factors for the perception of car sound quality is the close linkage between the behaviour of the driver and the process of sound generation in the car. In order to analyze this effect systematically by sound simulation it is mandatory for the applied method to be capable to generate sound models not only online while driving but to do so in a quite natural way. The described method does fulfil these criteria. By online synthesis of six different interior sounds and comparison of these sounds to the originals this capability could be demonstrated. Both sets of sounds proved to have 99% of their acoustical variance in common, i.e. they are identical with just a small amount of residual variance left. As the method is able to synthesize both major acoustical sources in the car – sinusoidal and random components – a broad variety of sound scenarios can be generated. Furthermore, as the synthesis is based on analysis of natural sounds and technical constraints a closed linkage to physical processes is guaranteed.

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