ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

Presentation of the Transfer Path Analysis of the Car's Interior Sound via Headphones

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Abstract
This treatise addresses the simulation of the interior sound of a car. The car's sound is the sum of numerous sound components which originate from different sources that employ various transfer paths to reach the passenger cabin. The sound components are synthesized one at a time in the time domain. By assembling them, the simulation of the car's overall sound is obtained. The simulation is presented via headphones and judged subjectively. This makes a gauge of the sound components' influence on the car's overall sound possible. In addition, a new method to synchronise serial measurements of the engine's sound components is developed. The method preserves the relative phase enabling the superposition of serial measurements without phase artefacts. To demonstrate how a modification of the car's structure would affect the subjective perception of the car's sound, stiffer engine mountings and a thinner windscreen are used as examples. To validate the simulation, the car's run up sound is recorded and compared with the simulation in a physical as well as psychoacoustic manner.

INTRODUCTION

Agile driving dynamics, the comfort of low vibrations and the car's sound quality establish the subjective perception of the driving experience. In order that the interior sound may create a harmonious unity with the overall impression of the vehicle, a desirable sound design is obtained by modifying the vehicle's structure. To this purpose, a tool is necessary that imparts data about the nature and composition of the internal sound and reliably predicts how a production revision affects the auditory perception of the car's sound. Its distinctive feature is the representation of the relevant sound components as discrete signals in the time domain. This is accomplished by identifying the sounds' sources, measuring them and combining them with the associated transfer functions. The sum of these acquired signals provides a simulation

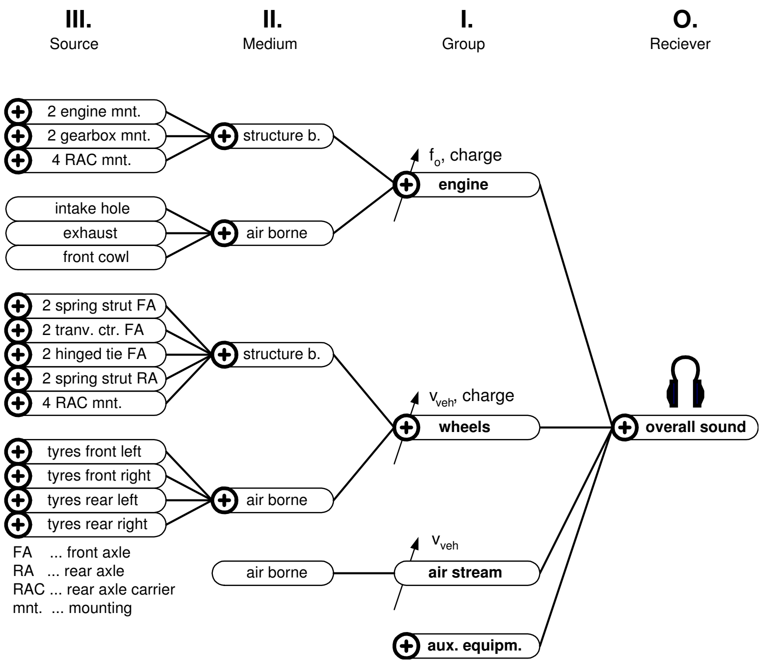

Figure 1: The components' signals are synthesized for the acceleration at full throttle. Adding them together yields a simulation of the vehicle' overall interior sound.

of the vehicle's internal sound, for example at the driver's ears (fig. 1). In the simulation, it is possible to amplify or attenuate single sound components. The strength of the developed procedure lies in that the simulation is presented via headphones and the sound's sensory perception becomes accessible. This makes it possible to investigate how a single sound component affects the subjectively perceived sound quality of the vehicle.

OVERALL SOUND

The car's interior sound originates from the three major groups of excitations: engine, wheels and air-stream. These groups can be subdivided according to medium, transfer path, source and direction. The synthesis assumes a LTI-system that is free from feedback so that a variation of the transfer functions does not influence the excitation. It is based on data retrieved from one reference vehicle. The experimental setup determines the frequency range of validity. The lower limit of 35 Hz stems from the accelerometers. The upper limit depends on the application. With regards to structure borne sound a resonance of the component test rig limits the simulation at 800 Hz. Concerning air borne sound of the engine and the wheels, the loudspeakers' uniform directivity lasts till 3000 Hz and 3600 Hz respectively [3]. Nevertheless, the air-stream's air borne sound is valid in the complete area of hearing. The frequency domain from 35 Hz to 3000 covers 2/3 of the critical band rate scale. The vehicle's sound is

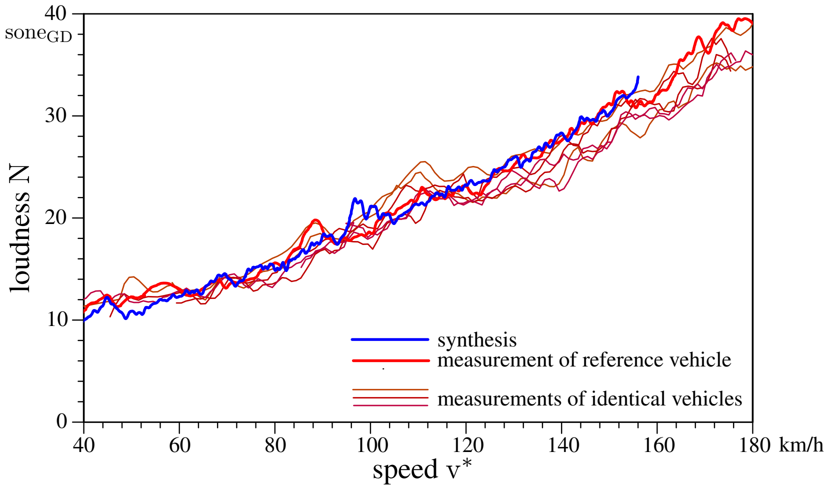

Figure 2: Loudness of the car's overall interior sound as function of speed.

dominated by low frequencies. A glance at the specific loudness in fig. 3 shows that about 85% of the loudness impression is formed in this area. Actually, the synthesis would have to be validated with a 3000 Hz low pass filtered recording. However, when listening to such a low pass filtered recording, it sounds a bit dull due to the missing sharpness. In order to restore a familiar auditory impression some high frequency noise must be added. This is accomplished by high pass filtering recordings of the engine's and wheel's sounds and adding them to the synthesis. Except for the sharpness, this hardly affects the sound's subjective perception.

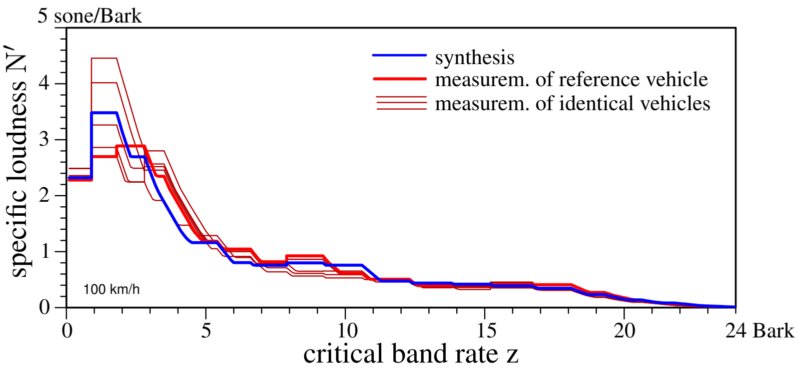

Figure 3: Specific loudness of the car's overall interior sound at 100 km/h. The loudness pattern of the synthesis is well within the band produced by identical vehicles' measurements.

The synthesis of the engine's noise involves convolution. The advantage is a high fidelity in reference to the phase relationship and the signal's temporal structure. The disadvantage is that the synthesis is bound to one driving cycle, in this case the uniform acceleration with full throttle in the 4th gear. All in all, 84 sound components are synthesized offline and saved in a data bank. For the simulation they are amplified, summed up and presented via headphones. During the simulation, the subject can change the amplification of any sound component arbitrarily and instantly hear and judge the resulting overall noise.

To validate the synthetic overall interior sound, a dummy head microphone was placed in several almost identical vehicles on the co-pilot's position. The driver accelerated the car with full throttle, and the interior sound was recorded. After that, the recording was analyzed with a loudness meter compliant to the DIN 45631. The calculated total loudness varies from recording to recording by 19% in average over all speeds (fig. 2). In average, the total loudness of the synthesis fits to the total loudness of the reference vehicle with an accuracy of 7%. Fig. 3 displays the calculated specific loudness. Analogously the synthesis' curve is imbedded in a band of measurements of identical vehicles. The specific loudnesses of the recordings differ from each other by 41% in average, and that of the synthesis by 17% in average. By and large two vehicles from the same series may differ more from one another in terms of loudness than the synthesis from its reference vehicle. This means, that the loudness of the overall simulation is sufficiently exact.

ENGINE'S SOUND

For the engine's sound, 24 structure borne and 3 air borne sound components were synthesized. To obtain the engine's sound components, their excitation signals were recorded in the time domain and convoluted with the associated impulse responses [2]. Should the number of transfer paths exceed the number of simultaneously available measuring channels, it is appropriate to split up the excitation signals into several serial measurements. Even if the driving cycle can be reproduced excellently, minimal differences of the rotational speed's time functions show up. When signals belonging to different measurements are merged, these differences cause beats among the harmonic engine orders thus adulterating the auditory sensation. Therefore a procedure is developed, which enables the synchronisation of measurements. This is achieved by declaring one combustion cycle or one revolution of the cam shaft as 2π, regarding the acoustic signals as functions of the cam shaft angle and warping all the measurements in such a way, that the time function of the cam shaft angle time of the reference measurement is impressed upon them (fig. 4). Due to digital inaccuracies, an irregular frequency modulation occurs during the process of rescanning. Its frequency deviation $2\Delta f_{\mathrm{dis}}$ depends on the sampling rate of the phase sensor f_{ph} and its spikes per rotation rate κ. By choosing a sufficiently high sampling rate for the phase sensor, the frequency deviation can be reduced to the extent that it is too small to be discerned by the auditory system [4]. No irregular frequency deviation is perceived for any harmonic order of the rotational speed f_o, if the following is observed:

$$f_{\mathrm{ph}} \leq \frac{2\kappa f_o}{0.007} \tag{1}$$

This does not necessarily affect the sampling rate of the general recording f_s. The synchronisation establishes the correct phase relationship among the harmonic engine orders of different measurements: an interference of the simulation, be it reinforcing or extinguishing, reflects an interference of reality. Through this, it is possible to correctly superimpose sound components from different measurements in the time domain.

In order to validate, the engine's sound was recorded on a roller dynamometer and then compared with the synthesis. Despite careful provisions to minimize the wheels' noise, like using slicks and encapsulating the wheels, a residue of the wheels' noise remains in the measurement. Since the simulation only takes the most dominant components into account, sound pressure level and loudness of the synthesis are lower than those of the measurement. In the frequency range between 35 and 800 Hz, the spectrum of the synthesis lies up to 4 dB lower than that of the measurement. Using a loudness meter, the total and specific loudness of engine's sound are calculated. At the critical band rate from 1 to 7 Bark, the calculated specific loudness of the engine's sound synthesis lies up to 20% lower than that of the measurement. In fig. 5 the calculated total loudness of the engine's sound is displayed as a function of the rotational speed. In average, the synthesis is about 14% lower than that of the measurement.

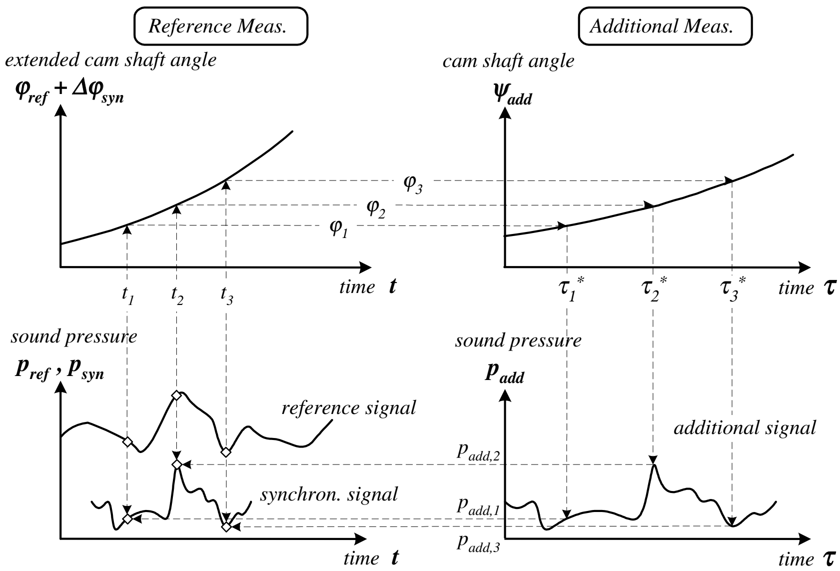

Figure 4: Synchronisation Procedure. The signal of the reference measurement p_ref is known at the times t_1, t_2, t_3. At these moments, the reference cam shaft has the extended angles φ_1, φ_2, φ_3. In the additional measurement, those points in time τ_1^*, τ_2^*, τ_3^* are identified, at which the additional cam shaft angle ψ_add reaches the values φ_1, φ_2, φ_3. At these points in time $\tau_1^*, \tau_2^*, \tau_3^*$ the additional measurement is rescanned. Then the synchronized signal is superimposed over the reference signal.

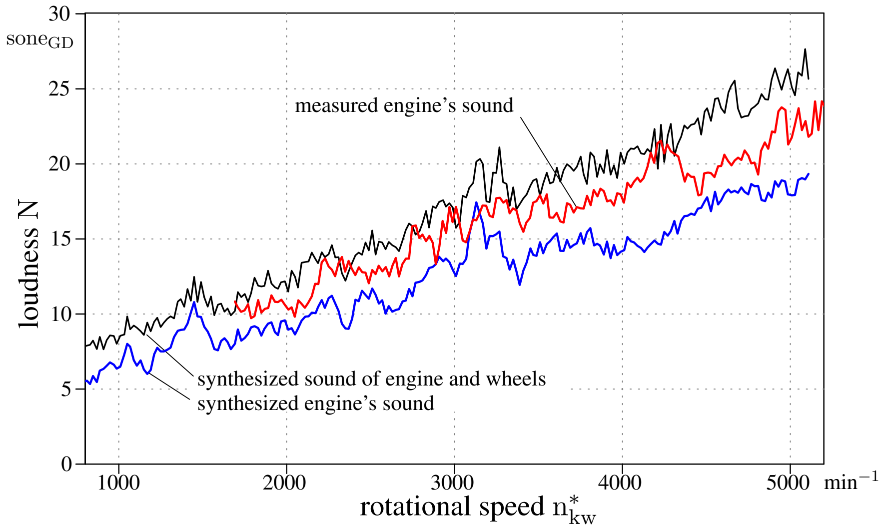

Figure 5: Loudness of the engine's sound as function of the rotational speed. The measurement of the engine's noise (red) contains a residue of the slicks' tyre noise. It is 14% louder than the synthesis of the engine's sound (blue), but 11% less loud than the combined engine and wheel noise synthesis for profiled tyres (black).

WHEELS' SOUND

With reguards to the wheels' sound, 36 structure borne and 20 air borne sound components were synthesized. The synthesis of the wheels' sound and the air-stream's sound is based on auto power spectra measured on a reference vehicle [1]. For this purpose two methods have been developed, which operate with a substitute excitation and a temporally variable filter. These filters are derived from speed dependant auto power spectra. The filter coefficients are exchanged in dependence of an arbitrarily chosen speed time function. In the "Synthesis with filtered white noise" white noise serves as substitute excitation. This method produces a sound with identical long term spectrum in respect to the target sound. The wheels' sound contains spectral patterns that are formed by the harmonic orders of a variable fundamental frequency, i.e. the wheel's rotational speed. With appropriate care, the method retrieves amplitude and frequency information of these patterns and reproduces them in the simulation.

The "synthesis with a complex tone" serves to reproduce sounds that are exclusively composed of harmonic orders with random phase. The procedure generates a complex harmonic tone, which contains the frequency information, and sends it through a filter, that contains the amplitude information.

For the validation, the sound during the coast down of the vehicle with turned off engine was recorded. In this experiment, the wheels' sound and the air-stream's sound occur at the same time and cannot be separated. For fair comparison, the air-stream sound synthesis was added to the wheels' sound synthesis. Concerning the combined wheels' and air-stream's sound spectrum, the measurements on practically identical vehicles span out a band that is up to 12 dB wide. The synthesis is imbedded in this band and surpasses the measurement of the reference vehicle by 9 dB. The calculated total loudness of the wheels' and air-stream's sound displays similar results. The synthesis is 9% louder than the reference vehicle's measurement; whereas the total loudnesses of identical vehicles' measurements differ up to 14% from each other. Finally, sound pairs containing measurement and synthesis were presented to normal hearing subjects via headphones in a 2AFC-test. The subjects judged[1] the synthesis as "louder", "with greater pitch strength" (88%), "deeper" (88%), "darker" (77%) and "less restless" (54%) than the measurement.

AIR-STREAM'S SOUND

To synthesize the air-stream's sound, the "synthesis with filtered white noise" was employed. With no surface microphones available, the measurement of sound in an air current of 30 m/sec is difficult. Therefore only the sound arriving at the right and left ear of the driver was synthesized. For the purpose of validation, the vehicle was placed in the acoustic wind channel where the air-stream's sound was recorded with a dummy head microphone. The simulation is compared with the recording. The spectrum of the synthesis reproduces the spectrum of the measurement with an accuracy of ± 2 dB. The total loudness and the sharpness of the sounds were calculated using psychoacoustic models [4]. In respect to the total loudness, the synthesis reproduces the measurement with $\pm 4\%$ accuracy, and in respect to sharpness with $\pm 2\%$ accuracy. The calculated specific loudness of measurement and synthesis are identical within the range of temporal fluctuations. Finally, the two sounds were compared with each other in a 2AFC test. Concerning the categories[2] "loudness" (47%), "sharpness" (49%) and "spatial impression" the subjects could not distinguish the synthesis from the measurement.

DESIGN MODIFICATIONS

A modification of the vehicle's structure changes its transfer characteristics, its overall interior sound and thus the subjective perception. Using the simulation, the change of the auditory perception can be forecasted. The modified transfer characteristics are obtained by measurement on a component test rig or from another physical model. Then the modified transfer characteristics are integrated into the simulation. The simulation yields the changed sound components and the resulting overall interior sound. The reliability of this simulation is demonstrated with two examples. In the first example, the influence of the engine mounting on the engine's sound is examined. For this purpose "more rigid", "standard" and "softer" engine mountings were manufactured and measured on a component test rig. The model forecasts, using this measurement, that installing the "more rigid" mountings would make the engine's sound louder by 55%. In an experiment on the roller dynamometer it actually became louder by 30%.

[1]Translation from German: "lauter", "tonhafter", "dunkler" & "weniger unruhig".
[2]Translation from German: "Lautheit", "Schrillheit" & "Raumwirkung".

Furthermore, the model forecast that installing the soft mountings would hardly change the total loudness of the engine's sound. This was also confirmed by an experiment on the roller dynamometer.

The second example examines how reducing the thickness of the windscreen by 20% influences the air current's noise. The model predicted that the air current's noise would become louder by 5% and sharper by 3%. The air current's interior noise was recorded in the acoustic air channel with a standard windscreen and with the thinner windscreen installed in the vehicle. The evaluation of the recordings using psychoacoustic models [4] underlined the prediction: with the thinner windscreen the air current's noise in the interior got louder by 7% and sharper by 5%. Finally, the presentation to subjects via earphones confirmed that the air current's noise with thin windscreen was really perceived as louder and sharper.

CONCLUSION

The sound component signals of a car were synthesized, assembled to form the overall interior sound and presented via earphones. The engine's sound, the wheels' sound and the air-stream's sound were recorded on test rigs and compared with the simulation. In terms of physics as well as psychoacoustics, the simulation agrees well with the recordings, i.e. the difference between synthesis and reference measurement is smaller than the scatter of the vehicles' series. For a design review, the simulation enables to cut down time and cost intensive trials and thereby accelerate and economize the development process. Two examples impressively demonstrate that the combination of synthesis and its presentation enables a forecast on how a design review would affect the vehicle's sound and the subjective auditory perception.

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