SOUND QUALITY OF VEHICLE EXTERIOR NOISE

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1 ABSTRACT

Up to now sound quality approaches have not often been used for the evaluation of the sound emission of cars. The introduced methods do not fit to the complex sound scenarios in urban streets. Within the European project SVEN new approaches are investigated. New methods have been developed for the subjective and objective description of pass-by and traffic noises. The effects of traffic flow on the physiological responses on traffic noise have been studied as well as the influence of the individual vehicle components on the total vehicle exterior noise.

2 INTRODUCTION

Traffic noise is an increasing problem in many parts of the world. Nevertheless sound quality approaches for the evaluation of sound emission are still neglected. The introduced methods are based on the A-weighted sound pressure level under standardized pass-by conditions (ISO 362), which in no way meets the complex sound situation of e.g. urban streets.

Thus, within the European research project SVEN (Sound Quality of Vehicle Exterior Noise) new approaches for investigating such soundscapes are investigated. SVEN follows an interdisciplinary approach, bringing together requirements and ideas from different fields. Several partners cooperate within the framework of the SVEN project: HEAD acoustics (as a provider of hardware and software tools for acoustical measurement and analysis), Bosal (a manufacturer of exhaust systems), Namkey (a manufacturer of intake systems and sound insulation components), Renault (the car manufacturer), Impedance (a traffic noise consultant), Bridgestone/Firestone (a manufacturer of tires), the Institute for applied acoustics at Chalmers University in Gothenborg (working on subjective sound evaluation) and the Institute for occupational and social medicine at the university of Düsseldorf (investigating physiological responses on noise).

Three different points of view are brought together within the scope of the project:

(1) For the citizen, the most important goal is the reduction of noise annoyance in urban living environments. However, more than the reduction of equivalent sound pressure levels or sound exposure levels is required. Sound quality aspects have to be taken into consideration, including additional parameters as time structure or spectral content.

(2) For a car manufacturer the requirements concerning vehicle exterior noise will be different. Up to now, only the requirement given by law (74dB(A) pass-by level in Europe) has been fulfilled. More and more, however, the exterior noise is understood as a message to a potential customer. The car should sound valuable, luxury or pleasant not only for the driver who has already taken his decision, but also to someone listening to the car passing by.

(3) Last, but not least, for the manufacturer of car components, the following question will be the most important one: How does each component contribute to the total exterior noise? Which improvements of which car components result in a significant benefit for the total pass-by sound pattern?

3 SOUND DATABASE

At the beginning a sound database has been built up, consisting of pass-by recordings and traffic noise recordings. Pass-by situations have been recorded for about 20 different cars covering a range of typical car configurations, i.e. different classes, different engine types. Binaural recordings have been performed in parallel to the standardized microphone recordings, see fig.1. Two recordings have been made for each car and driving situation, one with the car approaching from left, the other one with the car approaching from right. The standardized procedures have been extended by additional conditions typical for urban traffic:

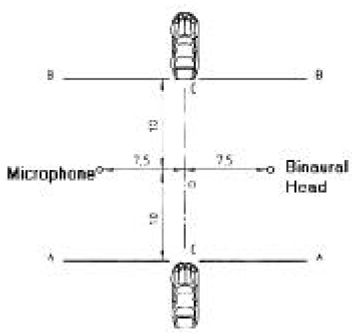

Fig. 1.- Arrangement for pass-by recording

- 50 km/h accelerated (2. and 3. gear)
- 30 km/h, 50 km/h (2. and 3. gear) and
  70 km/h constant speed.
- Coast down, starting at 70 km/h.
- Brake, idle and acceleration
  (typical for "Stop & Go" traffic)

Fig. 2.- Typical arrangement for traffic noise recording

All recordings have been carried out on a test track according to ISO 362. Traffic noise scenarios are much more complex than pass-by noises of a single car. To get a representative collection of traffic noises 20 streets in the city of Paris have been selected for recordings of 10 min. in each street. Fig. 2 shows a typical arrangement. A video recording has been carried out in parallel to enable investigations on audio-visual context.

The database includes recordings in streets with quite different characteristics, considering:

- different shapes:
  - U-shaped (continuously buildings on both sides) with different sizes
  - open-shaped streets (building on one side only) with different sizes
  - streets without buildings
- different traffic flow between 700 and 3000 vehicles/h,
- the influence of traffic flow regulations by traffic lights or roundabouts.

Highways have not been taken into consideration, because the exterior noise is dominated by the tire and wind noise, while in urban environments the other components (engine, exhaust, intake) also contribute significantly.

4 SUBJECTIVE EVALUATION AND PHYSIOLOGICAL RESPONSES

New semantic differentials have been developed for the subjective evaluation of exterior car sounds and traffic noises [3,4]. As a result of extensive listening tests, four main factors have been derived by factor analysis. Each of them covers the following semantic attributes [4]:

1. factor: loudness, expressed by e.g. 'annoying', 'loud', 'unpleasant'.
2. factor: quality, expressed by e.g. 'sporty', 'sharp', 'tonal'.
3. factor: bass, expressed by e.g. 'big', 'booming'.
4. factor: time structure, expressed by e.g. 'impulsive', 'uneven'.

In addition, the influence of the street architecture could be demonstrated: U-shaped streets are judged as less annoying than open-shaped streets, both showing the same A-weighted Leq. In U-shaped streets cars can be heard earlier, thus they seem to be less dangerous. Disturbing time structures are also reduced by reverberation.

In addition, physiological responses on traffic noises have been measured. Significant differences could be obtained due to traffic flow regulations (traffic light vs. roundabout) [3].

5 SYNTHESIS OF VEHICLE EXTERIOR NOISE

For the manufacturer of car components, the following question is the most important one concerning exterior noise: How does each component contribute to the total exterior noise? Which improvements of which car components result in a significant benefit for the total pass-by sound pattern? The contributions of the several components cannot be separated by post-processing from a pass-by recording. To solve this problem, pass-by sounds have to be synthesized from near-field recordings performed with microphones close to the relevant sound sources (engine, intake, exhaust, tires). The recordings can be carried out simultaneously to a normal pass-by recording using an additional mobile multi-channel recorder in the vehicle itself.
Using synthesis techniques, the contributions of the several components can be handled separately, can be mixed, filtered etc. in order to study the influence of each.

The method used in the SVEN project for pass-by sound synthesis [2] is as following: To prepare the simulation the transfer path characteristics for sound emission have been determined for each relevant component and 24 directions in the horizontal plane [1]. A small loudspeaker has been used to excite at each source location with a superposition of a sweep and a pseudo-noise sequence. The binaural transfer functions are calculated from the two microphone signals of the artificial head and the microphone signal at the source location in question, making use of correlation analysis. This “direct measurement of transfer functions” results in enormous measurement efforts, especially if different combinations of relative position and orientation between vehicle and listener are required. The transfer paths from 9 source positions to 24 receiver positions have been measured (9 x 24 = 216 transfer functions). This corresponds to a spatial resolution of the source radiation characteristic between 9° and 21°. For the simulation of pass-by sounds interpolated transfer functions have to be used for intermediate positions, too. The consideration of an additional rotation of the artificial head with a resolution of 10° would increase the measurement efforts by a factor of 36. Obviously, this is not feasible.

Therefore, the following simplified approach has been pursued: The set of transfer functions is split, as shown in figure 3, into a set of SRTF (source related transfer function), a simulation of sound propagation according to the distance between vehicle and listener (delay and attenuation) and a set of HRTF (head related transfer function). This separation that allows to measure SRTF and HRTF independently can be applied if the distance between vehicle and listener is large enough.

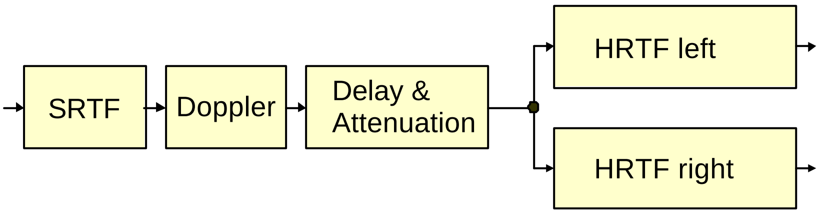

Fig. 3.- Enhanced simulation model of pass-by noise

The SRTF is measured with a microphone at the position of the artificial head, similar to the procedure described in [1]. The calculation uses a minimum phase approach – distance effects are considered in the next signal-processing step. The HRTF sets can be measured for an artificial head or an individual subject in an anechoic chamber. The sound is presented using equalized loudspeakers turning around the test subject (e.g. in the horizontal plane). During the exposure of sound, the microphone signals in the ear-canal are recorded. After a normalization of the direction-dependent spectra with the spectrum of frontal sound incidence, the set of HRTF is calculated as minimum phase filters. The interaural time delay is taken into account in a second step. HRTF sets are available for different artificial heads and human test subjects.

The separation of the signal paths into SRTF and HRTF does not only reduce the measurement efforts drastically. This method is imperative for the room simulation: Reflections are considered using mirror sound sources. The angles of sound incidence of the source and the corresponding mirror source are different as well as the corresponding source radiation characteristic.

To summarize the procedure: For the pass-by simulation itself the following steps have to be performed continuously according to the current position, orientation and speed of the vehicle:

- filtering the near field recordings by the transfer path characteristics (SRTF) of the current direction, given by the current position of the listener from the vehicle's point of view.
- calculation of Doppler effect according to the vehicle speed.
- simulation of sound propagation according to the distance between vehicle and listener (delay, attenuation).
- filtering the result by the HRTF according to the current position of the vehicle from the listener's point of view [5,7].

The procedure results in a binaural pass-by sound of a single component. To achieve a complete pass-by noise, the results of all relevant car components have to be summed up [2].

6 APPLICATION EXAMPLE

In the following an accelerated pass-by of a medium-class vehicle (with petrol engine) in the 2^{nd} gear at 50 km/h is analyzed. The simulation takes into account the relative movement between vehicle and listener (location/direction-dependent transfer functions) and the Doppler effect (figure 2).

In a former simplified simulation [1] the virtual position of the listener had been fixed with respect to the vehicle (i.e. no location-dependent transfer functions and no Doppler effect). Those simulation results have already shown that the tire noise, especially the partial sounds “front wheel out” and “rear wheel in” dominate in the given application example. The influence of the exhaust end pipe and the intake is significant at low frequencies; the engine contributes inconspicuously [1].

These conclusions do not change if we analyze a real pass-by simulation for a virtual listener standing beside the street. But now a comparison between measured and simulated pass-by sound is possible.

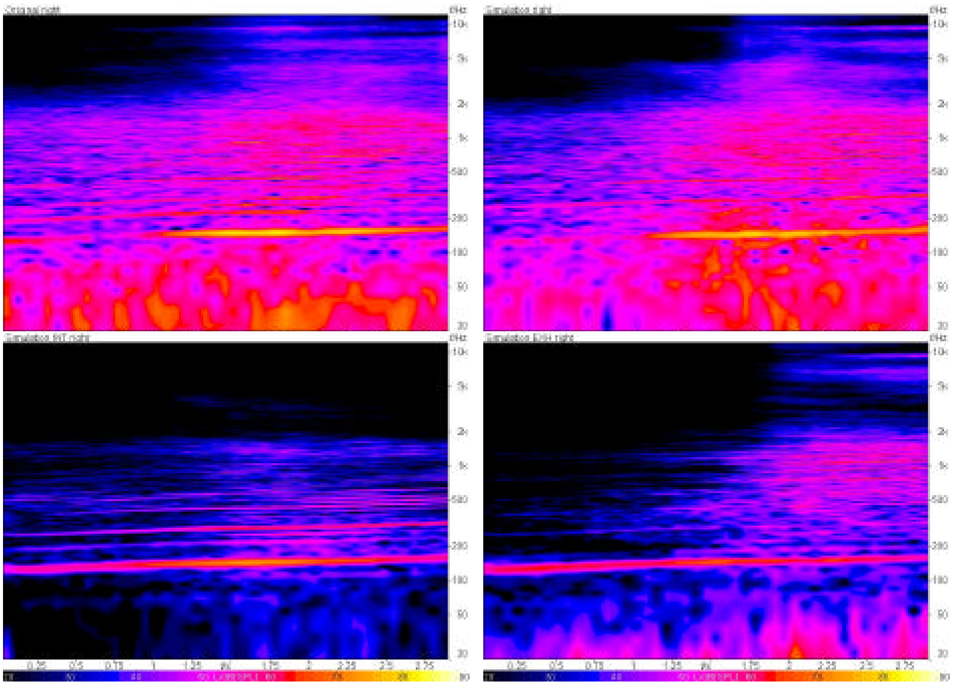

Fig. 4.- Spectrograms of measured and simulated pass-by sounds (upper part) and spectrograms of the contributions of intake and exhaust end pipe (lower part)

Figure 4 shows for the given driving condition a spectrogram of a measured sound (top left-hand picture, right ear of artificial head) and the corresponding simulated sound (top right-hand picture). The aural correspondence is very good, although there can be seen small deviations in the spectrograms at frequencies below 100 Hz due to measurement errors in the original recordings. Differences in the upper frequency range may be caused by the separation into SRTF and HRTF as well as by disturbing noise at the test road.

The simulation model enables the user to auralize and analyze partial sound events, e.g. the contribution of intake and exhaust end pipe (figure 4, lower left- respectively right-hand picture). Subjective tests using these component pass-by sounds show that the “leaving exhaust end pipe” leads to a well-known sound event. This sound is a dominant part of the pass-by sound and can be related clearly to the component.

Additionally, new pass-by sounds can be generated, using filtered contributions of the various sound sources, to simulate modified components. Thus the model can be used for sound analysis and sound design.

7 CONCLUSIONS

It is possible to predict the sound emission of a new power train in the development phase for an already existing vehicle (database of transfer functions is available), based on power train measurements at a test rig. In addition to the set of SRTF, it is necessary to determine adaptation functions to take into account the approximate free-field conditions at the test rig differing from the room-acoustical behavior of the engine compartment. This approach has already been approved for the simulation of binaural interior noise based on engine test rig measurements. Signals not measured at the test rig (e.g. tire noise) are considered as fixed parts and are taken from a noise database to be added to the power train based contributions.

In order to simulate traffic noise scenarios in urban streets some extensions of the method described so far are necessary:

- Consideration of reflections and reverberation, especially in U-shaped streets.
- A random selection of many different vehicles with different driving conditions has to be summed up. The selection is made according to the desired statistical traffic parameters and can include synthesized pass-by sounds as described above as well as binaural pass-by recordings.

Simulation techniques introduce quite new approaches on sound quality of vehicle exterior noise. The approach presented in this paper will be validated within the SVEN project by the investigation of cars with modified components. One additional objective of SVEN is to develop objective descriptors for vehicle exterior noise. This can be done now based on the results of the subjective evaluation.

The existing standards for exterior noise evaluation have to be updated by extended measurement procedures (as described above) as well as new sound-quality descriptors giving a better prediction than A-weighted pass-by levels.

8 ACKNOWLEDGMENT

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