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Virtual Binaural Auralisation of Product Sound Quality Importance and Application in Practice

Roland Sottek

HEAD acoustics GmbH, Ebertstr. 30a, 52134 Herzogenrath*, Germany, Roland.Sottek@HEAD-acoustics.de*

The 'Binaural Transfer Path Analysis and Synthesis (BTPA and BTPS)' techniques have been developed for the prediction of sound quality in vehicles not only in terms of numbers and graphs, but also for binaural auralisation. The methodology, based on a combination of test rig measurements and acoustic simulation, has been used successfully by HEAD acoustics in the last several years within numerous consulting projects and it has proven its suitability for efficient sound design engineering and troubleshooting of vehicle noise. BTPA and BTPS enable a prediction of vehicle interior as well as exterior noise and sound quality based on any number of modifications to the transfer paths of the baseline vehicle. As a result, test rig measurements of various components can be used to assess the sound quality impacts of component exchange.

Within the European research project NABUCCO a Noise Synthesis Technology (NST) for stationary sounds has been applied mainly to domestic products. This technology addresses some specific objectives. The most important is the acoustical matching of the component(s) and the product mainframe. One main output of NST is the prediction of the resulting product noise. Modeling is based on comprehensive selection of measurement inputs and/or simple analytical computations.

1. PRODUCT SOUND QUALITY

A typical design criterion for product improvement with respect to sound quality is a reduction of either sound pressure level or loudness. However, sound quality depends on many different parameters: other psycho-acoustic properties (roughness, sharpness, tonality and prominence ratio) as well as time and spectral structures are also important factors. Additionally, human hearing is able to adapt to specific sound patterns [1], regardless of absolute A-weighted sound pressure level or loudness, resulting in the same subjective perceived annoyance at reduced levels: e.g. the annoyance of tire noise with a modulated tonal component will not change significantly if the overall level is reduced by 3 dB.

On the other hand adding noise may even improve sound quality. In figure 1 (left) the impulsiveness of a diesel engine noise is compared with the impulsiveness of the same diesel engine noise superposed by an additional noise signal. In this case impulsiveness (calculated using the Hearing Model described in [2]) could be reduced by a factor of 2.

Similar conclusions can be achieved by applying the "Relative Approach Analysis". This analysis, assuming the adaptiveness of human hearing, identifies only the time and frequency patterns relevant to sound evaluation. This approach is based on aurally-adequate time-frequency distributions using the Hearing Model. The nonlinear relation between sound pressure and subjective perceived loudness is also considered. Slow level variations are not recognized as significant contributions to the sound event. Transient signals like impulses, squeak and rattle events as well as prominent frequency characteristics (e.g. caused by tonal components) produce high output signals. Background noise is suppressed, only noticeable sound events are shown. Figure 1 (right) illustrates the result of this analysis for the diesel signal and the same signal with additional noise. Significant differences occur at frequencies above 2 kHz. According to the "Relative Approach Analysis" the diesel engine noise mixed with additional noise (higher loudness and A-weighted sound pressure level) is rated less noticeable than the diesel engine noise alone.

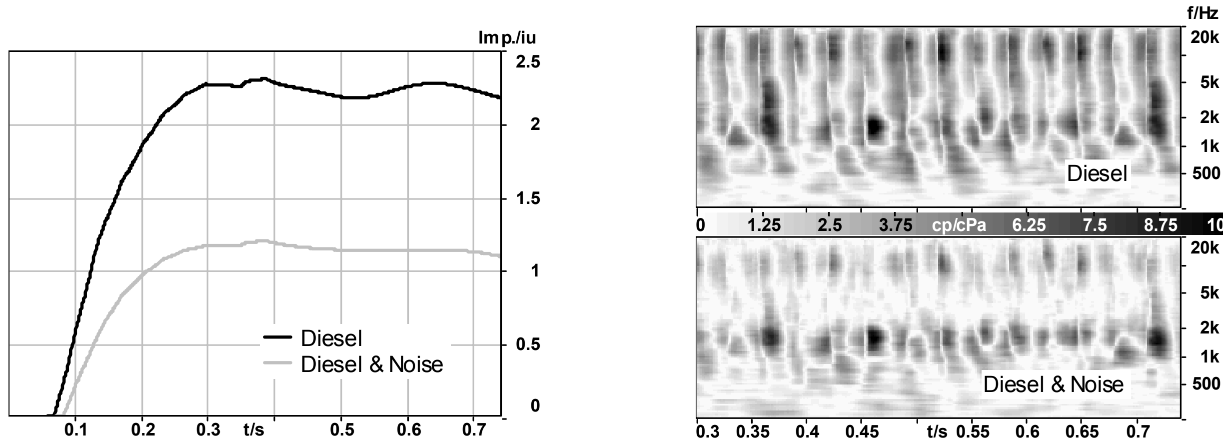

Figure 1. *Impulsiveness based on the Hearing Model according to [2] (left) and detection of significant time and frequency patterns using the "Relative Approach Analysis" (right) of a diesel noise and of the same signal with additional noise*

There are many other application examples with respect to sound quality criteria not only in the automotive area. For example, the sounds of two dish washers with a level difference of about 3 dB(A) have been compared. Subjectively, the dish washer with the higher level has been judged more convenient and smart because of a nearly constant sound. The other one was more annoying due to a kind of splash noise not masked by the operational noise [3].
The given examples demonstrate the manifoldness of sound quality aspects. Generally speaking, sound quality cannot be described by a single number, time signals of the product sounds are needed for auralisation and for the various psycho-acoustic analyses. Therefore the goal of product sound simulation is virtual auralisation. With respect to human hearing as the receiver, it should be a virtual *binaural* auralisation.
The next two sections give an overview of Binaural Transfer Path Analysis and Synthesis as tools for the simulation of vehicle interior and exterior noise. The prediction of acoustic comfort inside a vehicle requires the simulation of the vibrations at the steering and the seats, too [4].
The forth section briefly describes the European research project NABUCCO: the application of Noise Synthesis Technology to domestic products for stationary sounds.

2. SIMULATION OF VEHICLE INTERIOR NOISE

Based on the demands of the automobile industry, Binaural Transfer Path Analysis and Synthesis (BTPA and BTPS) techniques have been developed for the prediction of sound quality in vehicles, not only in terms of numbers and graphs, but also for binaural auralisation.
BTPA is a measurement procedure for characterizing individual vehicle noise paths. The results can be used to create an accurate model for path-related noise heard anywhere inside the vehicle, thus yielding possibilities for troubleshooting and sound design. For structure-borne sound,

transfer functions from the engine mount to both ears are measured reciprocally for each individual noise path. For airborne noise, acoustic transfer functions are determined similarly (figure 2).

The mount transfer characteristics and the car-body inertance (shown in figure 2 as one signal processing block) are determined in situ, without disassembling the engine or other components. The benefits of this approach are:

- acoustic and vibro-acoustic transfer functions of the real system are considered
- no influence on structural characteristics by removing and reinstalling the engine
- reduced measuring time

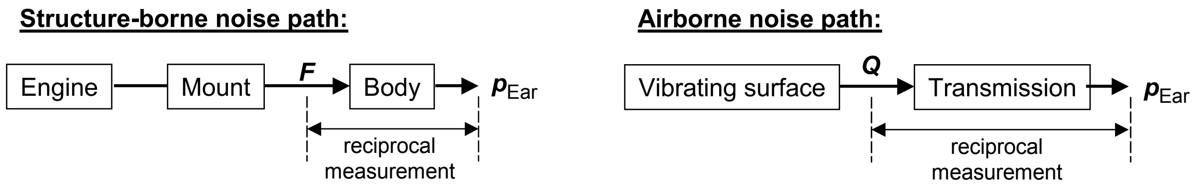

Figure 2. *Transfer functions measured by BTPA*

For the reciprocal measurements a new binaural sound source has been developed [5]. This method provides some essential advantages compared with the direct measurements, such as reduced measuring time and a higher precision. In some cases, it is even the only option, e.g. if an extended vibrating surface has to be divided in sub-areas which cannot be excited to independent vibration. However, applications of the binaural sound source are not a priori restricted to vehicle acoustics; reciprocal transfer-function measurements may also be useful in other disciplines (room acoustics, virtual reality).

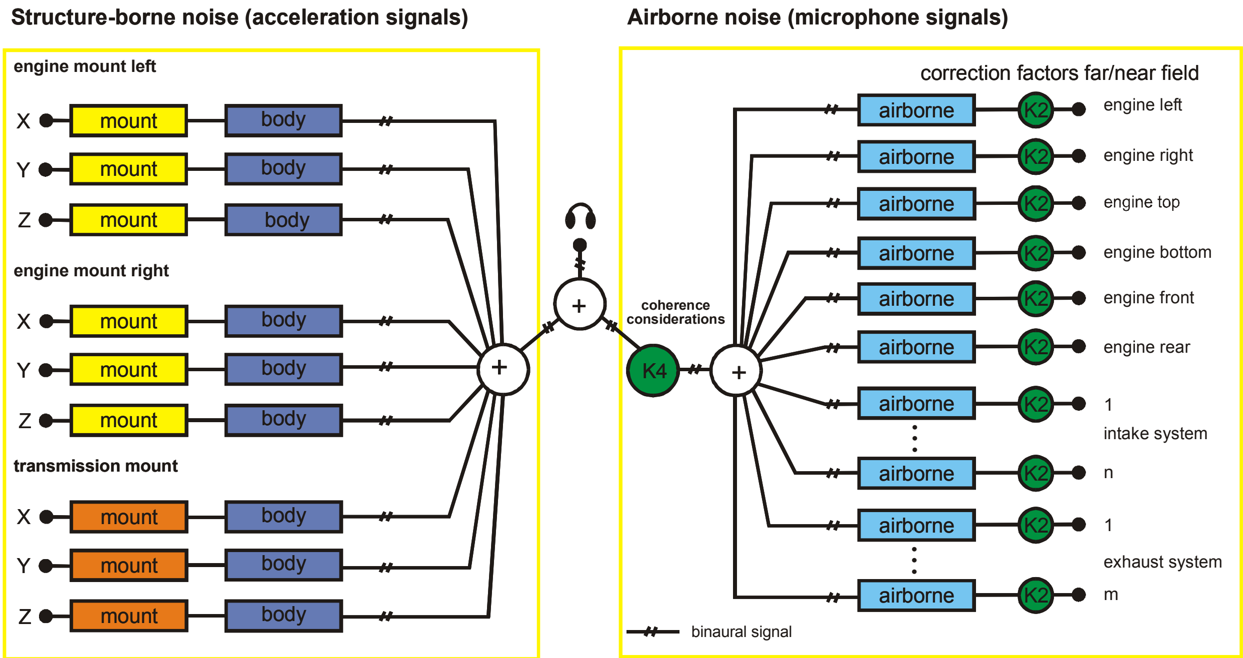

Figure 3. *Binaural synthesis based on airborne and structure-borne sound transfer paths*

BTPS (Binaural Transfer Path Synthesis) is the process of synthesizing interior noise by combining selected noise paths (figure 3). For engine and transmission mounts, vibration signals in all three directions (x, y and z) are considered.
For airborne noise transfer, microphone signals in the nearfield of assumed sound sources are used (around the engine, at the intake and exhaust system). [1] All excitation signals (acceleration and pressure signals) are measured simultaneously.
Each individual path or combination of paths can be listened to independently, in order to assess their respective impact on the overall sound quality. Paths can be modified to simulate countermeasures and their effect on the interior noise. Operating data measured on different sources, such as an engine test rig, may also be put into the model to predict how interior noise is influenced by the different sources.

3. SIMULATION OF VEHICLE EXTERIOR NOISE

The aim of the European research project SVEN (Sound quality of Vehicle Exterior Noise, G6RD-CT-1999-00113) is the development of new methods for the assessment of exterior noise of single vehicles as well as the resulting traffic noise [6]. Whereas the ISO 362 considers only the maximum value of the A-weighted sound pressure level, the new method developed within SVEN enables the calculation of time signals at the ear-canal entrances of a virtual listener or at a microphone located beside the street. This new approach is necessary to apply more advanced analysis methods like psycho-acoustic analyses or to study physiological reactions on traffic noise to evaluate the consequences for the well-being of the population.
Based on near field recordings of the different components (engine, intake, exhaust and tires) a virtual environment around a virtual listener at the roadside has been established: a BTPA/BTPS for the exterior noise of moving sources (Doppler) using time-varying transfer characteristics.

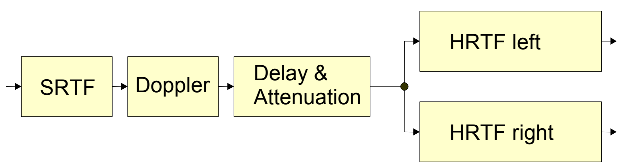

Figure 4. *Simulation model of pass-by noise for one single path [7]*

The set of transfer functions from the sources to both ears is split, as shown in figure 4, into a set of SRTF (source related transfer function), a simulation of the sound propagation according to the distance between vehicle and listener (delay and attenuation), and a set of HRTF (head related transfer function). This approach reduces the measurement effort and allows a more flexible use of the transfer functions for simulations. A SRTF is measured with a microphone at the position of the artificial head, similar to the procedure described in [8]. Current investigations aim at the measurement of SRTF sets at closer distances than 7.5 m to the center of the vehicle,

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[1]Reciprocal airborne transfer functions have not yet been used for synthesis but only for analysis purposes. Currently, the synthesis is based on direct measured transfer functions with reference microphones (pressure reference) in the vicinity of the exciting loudspeakers in the engine compartment or at radiating components. Reciprocal measurements, in contrast, are based on volume velocity reference. Therefore, the two methods reveal different transfer functions. Algorithms to describe the airborne sources using volume velocity are under development.

allowing the determination of transfer functions in smaller anechoic chambers. Excitation measurements can be taken from a test track or from a roller test bench.
The simulation allows the investigation of a variety of questions: Which sound sources in the vehicle, depending on the respective driving situation, determine the noise quality? What influence do the architectural structuring of the road and the traffic flow have?

- The BTPS tool allows to switch on/off or to modify components in order to analyze their influence on the total exterior noise. For example an increase of the low frequency content (below 250 Hz) of the exhaust signal causes a higher ‘boom index’ changing sound quality without a noticeable change in the maximum A-weighted pass-by level.
- Results of subjective tests with traffic noise show e.g. the significant influence of architecture (traffic light vs. roundabout, U-shaped versus L-shaped or open streets, [9]).

4. NOISE SYNTHESIS TECHNOLOGY

Only specific industries, such as automotive and aerospace, have the means and resources to carry out prediction programs of noise reduction. The European research project NABUCCO (Noise ABatment Using Concurrent Component-product Optimisation GRD1-1999-17085) is dedicated to many industries which cannot justify laborious approaches but nevertheless need to reduce product noise in a systematic way. Inspired by the fact that noise of many finalized products is governed by the operation of some key components integrated within an otherwise passive structure a Product NOise Synthesizer (PRONS) for stationary sounds has been developed. Application examples are refrigerators, heat pumps and personal computers. In this group of products noise is transmitted to the surroundings as direct airborne noise, structure-borne noise (via feet, cables etc.) and frequently as fluid-borne noise (via pipes etc.). One goal is to find the best combination of source (e.g. compressor, fan) and main structure. The developed tool allows to predict noise and to define a common interface between the product assembler and the component manufacturer. Figure 5 shows the general setup of the physical system (left) and PRONS equivalent (right): 1. component source strength (CSS: acceleration, sound pressure, fluid and gas pulsations), describing component characteristics; 2. connection transfer functions (CTF), considering coupling between source and main structure; 3. assembly conductivity functions (ACF), corresponding to the various transfer functions to the receiver positions (microphone(s) or artificial head).

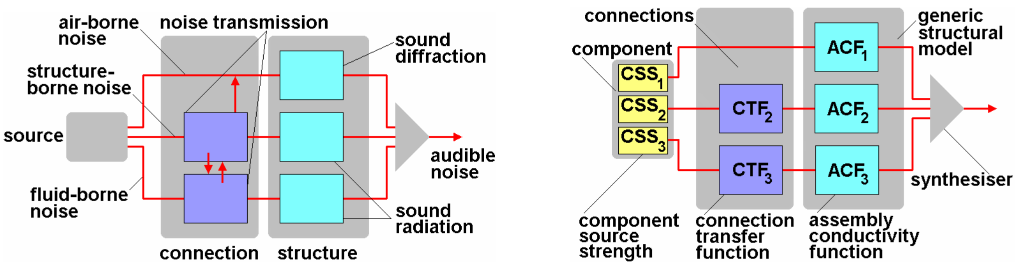

Figure 5. *NST: physical representation (left) and its PRONS equivalent (right)*

The Noise Synthesis Technology is a hybrid approach based on measurements and on numerical calculations. The novel approach helps to identify main transfer paths, the influence of coupling elements and the modification of structural changes on the product sound. Figure 6 shows the

PRONS scheme for a refrigerator. This model includes all three possible noise paths. Airborne noise is conditioned by the excitation of the compressor. It is modeled as a breathing sphere, represented by one monopole and three dipoles, one for each direction. Structure-borne noise arises from the suction and discharge pipe and fluid-borne excitation mainly from the discharge pipe.

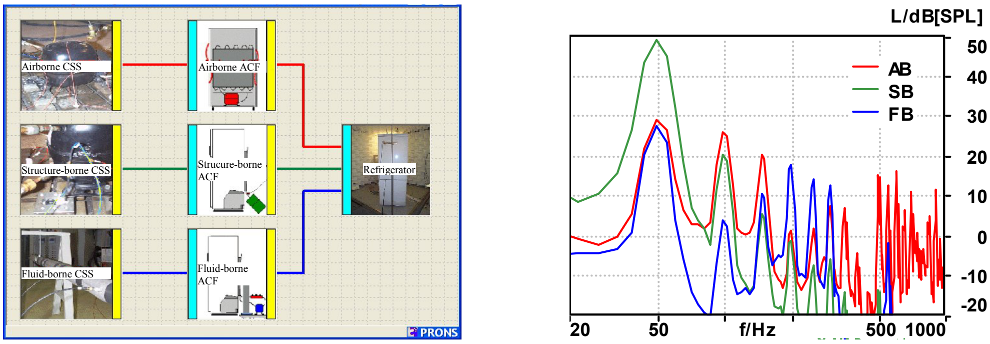

Figure 6. PRONS model of a refrigerator (left) and corresponding predicted spectra (right)

5. CONCLUSION

The assessment of product sound quality requires (binaural) time signals for further aurally-adequate analyses. Binaural Transfer Path Analysis and Synthesis have been proven useful for troubleshooting and sound design in an early development state to predict sound quality of interior and exterior vehicle noise. Data from test rigs can be used for simulation, too. Noise Synthesis Technology for stationary sounds working in frequency domain has been applied to domestic products, finding the best acoustical match of components and product mainframe.

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