Prediction of Sound and Vibration in a Virtual Automobile

Klaus Genuit, HEAD acoustics GmbH, Herzogenrath, Germany
Wade R. Bray, HEAD acoustics, Inc., Brighton, Michigan

Ability to both feel and hear the results of engineering decisions via a "virtual car" – simultaneous engineering – can significantly shorten vehicle development time. Sound quality and discrete vibration at the driver's position may be predicted and 'driven' before the first prototype is built. Although sound quality cannot yet be predicted in an unknown chassis, the sound and vibration behavior resulting from a new engine, never previously installed in a given vehicle, may be predicted, heard binaurally and felt in an interactive 'drivable' simulation based on transfer path analysis. Such a simulation, which includes the binaural sound information and discrete vibration of steering wheel and seat, can also include wind and tire noise to determine if certain engine contributions in sound quality and vibration may be masked. The method involves use of two technologies in conjunction: binaural transfer path analysis (with vibration transfer path analysis) and a real-time interactive multichannel acoustic and vibration simulation system. From transfer path data the simulation environment permits interactive control from throttle position of relevant vehicle behavior including load, gear ratios, vehicle mass, etc., providing running acoustic and vibration simulation. The user can change chassis impedances, etc., and 'drive' the resulting behavior.

Binaural Transfer Path Analysis was developed to predict the interior noise of vehicles in response to modifications at input signals of the engine or at individual transfer paths. This tool considers airborne noise contributions up to 12 kHz and structure-borne noise contributions up to 2 kHz. A clear distinction between these two principal origins is essential for investigations of vehicle interior noise.

The approach presented here enables the user not only to calculate resulting parameter data, but also to listen binaurally to the noise situation in an aurally-equivalent way. Consequently, it can be used for an efficient solution to Sound Quality and Sound Design tasks in the automotive industry. The reduction of effort required for investigations is ensured by combining the transfer path measurements on vehicles and acoustical measurements of engines with a simulation tool. The simulation yields binaural sound samples for each transfer path under investigation and for their combinations. The samples can be used in listening sessions and permit subjective judgement of the effect on sound patterns caused by modifications. Further, the simulation results and, if desired, other vehicle data may be brought into an interactive, real-time 'drivable' multichannel acoustic and vibration simulation environment. Masking effects due to other causes, such as wind and road noise, may be realistically assessed under virtual operating conditions in a representative sound field. All measurements at the vehicle are carried out without requiring removal of the engine or other components that influence their structural behavior.

An application example shows clearly how the cause of an annoying portion of interior noise can be determined precisely, permitting target-oriented modifications. Within the scope of the research project, designated AQUSTA (Improvement of the Structural Acoustic Quality of Transportation Vehicles Using Simulation Techniques of Binaural Analysis),[1] several approaches have been developed, tried and tested towards achieving an aurally-equivalent, binaural simulation of noise in the interior of a vehicle due to the wind and engine.[2-5] The model presented is based on measurements made with a complete vehicle or with an engine on a dedicated test rig. It includes the relevant transmission paths of the airborne and structure-borne sound components to the ears of a person sitting in the driver's seat.

Based on paper number 2001-01-1474 © 2001 Society of Automotive Engineers, Inc. Presented at the 2001 SAE Noise & Vibration Conference & Exposition, Traverse City, MI, April/May 2001.

Model Description

The complete binaural acoustic response recorded in a vehicle with an artificial head representing the driver's head can be mathematically defined as the sum of several mechanical and acoustical sources propagating waves which impinge upon the head. The objective of the "hybrid model" was to include a representation of equivalent mechanical and acoustical forces as well as structure-borne and airborne transfer paths.[2]

This model for prediction of interior sound with respect to the engine is based on vibration signals (triaxial) at the engine side and several (4 or more) microphone signals close to different surfaces of the engine. The vibrations are transmitted through the engine mounts into the chassis. Depending on engine stiffness and chassis inertance, the force can be calculated which is transmitted into the chassis and creates the structure-borne-related sound. Complex superposition with the airborne transmitted sound produces the total sound simulation inside the vehicle with respect to the engine (see Figure 1).

Simulation Methodology

The "hybrid model" was created with experimental data in order to obtain realistic binaural responses covering the wide frequency range of human hearing. Then, methodology and hypotheses had to be developed for the modification of source terms and transfer paths with new data based on other experiments or from numerical or analytical simulation of modified components.

Structure-borne Transfer Paths. For determining the structure-borne transfer paths, a new method was developed which enables the user to measure the effective relevant structure-borne transfer characteristic in a fully assembled situation. It is not necessary to remove the engine from the car, so this new method is very time- and cost-saving. The effective relevant transfer characteristic of the engine mounts is based on a measurement of the triaxial acceleration measurements at engine and chassis sides and is calculated in combination with the inertance of the chassis.

The aim of the methodology is to predict changes in vehicle interior sound when transfer paths or acoustic and vibrational characteristics of the engine (including intake and exhaust system) are modified. Application is desired both for the reduction of annoying noise components and for the realization of particular sound characteristics (e.g., sporty, sedan, etc.). This may also include the determination of the effectiveness of measures with respect to interior acoustics.

A suitable process should allow the determination of qualitative differences in the acoustic situation. For practical reasons it is necessary to carry out all measurements on a complete vehicle. For simulation purposes, the data are combined with measurements at engine test rigs using standard microphone and accelerometer configurations.

Based on these aims, a methodology was developed that in-

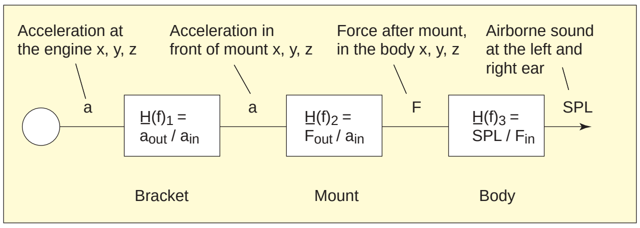

Figure 1. Transfer path from acceleration at an engine mount (engine side) to airborne sound.

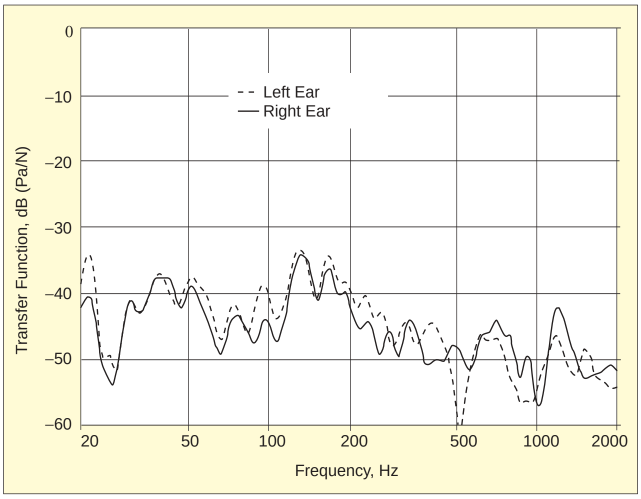

Figure 2. Example of structure-borne transfer function (smoothed spectrum) to left and right ear.

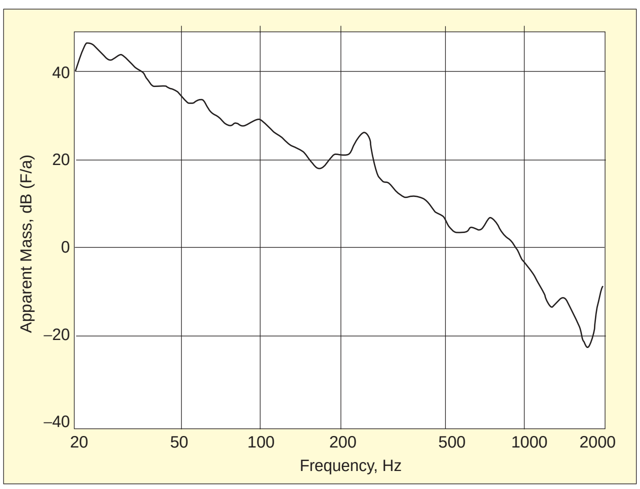

Figure 3. Example of apparent mass for a car-body in z-direction.

cludes the following steps:

1. Determination of mount transfer characteristics.
2. Measurements of structure-borne noise transfer paths from engine mounts to driver's ears.
3. Measurements of car-body impedances at engine mount locations.
4. Measurements of airborne noise transfer paths from engine compartment and exhaust system to driver's ears.
5. Measurement of binaural acoustic and vibration situation at driver/passenger seat(s) during operation using a baseline configuration.

During all measurements the engine remains installed in the vehicle. Although this may pose difficulties with respect to structural excitation, this procedure includes some important advantages:

- Structural characteristics are valid for the complete system (the absence of an engine can only be partly replaced by adding weights to simulate structural behavior).
- No influence on structural characteristics due to removing and reinstalling the engine.

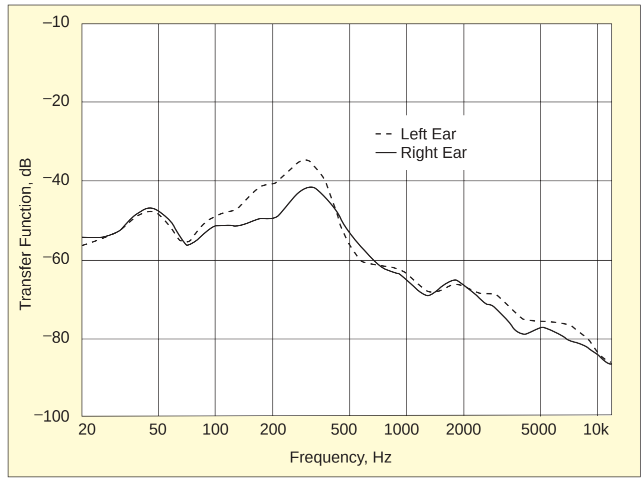

Figure 4. Example of an airborne noise transfer function (smoothed spectrum).

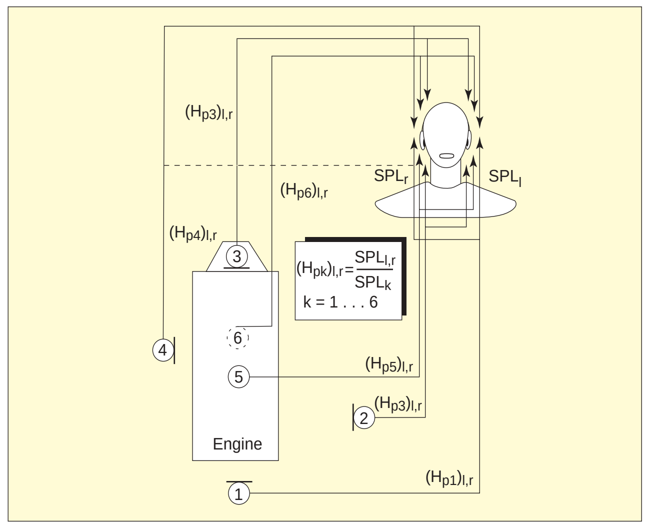

Figure 5. Measurement of airborne noise transfer paths.

- Less time is required.

Triaxial impact excitation is applied to all engine mounts on the car-body side. Additional excitation is applied to exhaust system mounts. Triaxial accelerations in parallel at all mount locations (a_j) and the sound pressure level at the artificial head ($SPL_{l,r}$) are measured time-synchronously. Based on these data, transfer functions can be calculated up to 2 kHz. Samples of such transfer functions are shown in Figure 2.

The acquisition of accelerations at the impact excitation location allows for additional determination of *car-body inertance* input as shown in Figure 3. The corresponding measurements require experience in order to obtain reliable results. An impact test device is used for practical reasons. Electrodynamic shakers offer advantages with respect to energy input especially at low frequencies but require more space for their application.

For measurements of *airborne noise transfer paths* (an example is shown in Figure 4), a special reference sound source is used that achieves high levels at low frequencies and is dimensionally small. Airborne excitation is performed in the engine compartment (and at particular exhaust system positions) with a suitable signal up to 12 kHz. A microphone arrangement similar to the engine test rig configuration (Figure 5) is used and the artificial head is positioned in the interior of the vehicle. The measurements are repeated for several locations in the engine compartment. The average transfer functions from each microphone to the artificial head are then determined.

The following binaural acoustic measurements at several operational conditions (i.e., run-up at full and/or partial load) comprise the acquisition of baseline interior vehicle sound.

Additionally, they allow determination of *mount transfer characteristics* up to 2 kHz if the following prerequisites are valid:

- Mount stiffnesses are low.
- The stiffness of the car-body is high.
- The system can be seen as a minimal-phase one.
- Dynamic characteristics are considered linear in the frequency range of interest for acoustical purposes.

In this situation, both the amplitudes and stiffnesses can be calculated based on measurement of accelerations on the engine side, accelerations on the body side and impedances of the car body. The corresponding phase values are determined by using the Hilbert transform. An example result is shown in Figure 6. This simplified approach to transfer function determination, compared to measurements on mount test rigs, has proven sufficient for the described objectives.

In a further step, the *binaural simulation of a baseline situation* may be used for verification. The procedure is shown in Figure 7 for the simulation of engine noise. The triaxial accelerations at all engine mounts on the engine side are combined with mount transfer characteristics, car-body inertance and structure-borne transfer paths to comprise the interior noise caused by structure-borne excitation.

In parallel, the measured acoustic data at the engine are combined with the airborne transfer paths and the coherence. It must be considered that the interior sound is independent of the number of measuring microphones. Therefore, the mixture of a single airborne noise signal into a summarized overall signal requires a correction factor dependent on coherence. This factor is applied to the binaural simulation K4.

The following assumptions must be made:

- The current version of the Binaural Transfer Path Analysis procedure considers the noise contributions of engine and intake/exhaust-system. This implies that a prediction of sound pressure level is only possible for these main causes of interior vehicle noise.
- For sound quality and sound design tasks, it is important to simulate characteristic signal patterns. Several configurations may be compared subjectively.
- The "Binaural Hybrid Model" may be fine-tuned as a preprocess for further simulations. The latter use exactly the same procedure as described above, but the input data are changed. Transfer paths may be modified virtually and engines with different airborne and structure-borne excitations may be 'installed' virtually by using corresponding test rig data. Additionally, the influence of various mount transfer characteristics on the interior noise may be simulated.

In summary, the Binaural Hybrid Model makes it possible: to determine and auralize binaurally the influence on the interior noise of modifications at components; to determine those structural characteristics of transfer elements (mounts, car body, etc.) which must be modified in order to achieve a particular (designed) interior noise; and to investigate the effects of various engines (and/or exhaust/intake systems) on interior noise.

Aerodynamic Noise Simulation

Aerodynamic noise becomes dominant for interior sound above a certain speed, the limit of which depends on the type of vehicle and environmental conditions. In the laboratory, the aerodynamic noise of a vehicle can be investigated in a wind tunnel under definable conditions. Under the experimentally verified hypothesis that different panels are incoherent sources for aerodynamic external noise, a masking procedure was applied on the test vehicle in order to estimate transfer paths of different panels. Using the procedure shown in Figure 7, binaural recordings at the driver or codriver position in the interior of the vehicle can be used for estimating noise transfer paths of different panels.

In a complex aerodynamic noise situation with transmission through all panels as shown in Figure 8a, the binaural sound signal P_{orig} is recorded. The masking procedure then is applied to each individual panel from the interior of the vehicle. The recording of $P_{T(i)}$ (Figure 8b) is performed one after another for each panel under test. The rest or reference signal of total masking P_{total} (Figure 8c) must also be recorded since the floor section of the vehicle cannot easily be masked.

The binaural recordings corresponding to the given panels are used to generate an estimate of the magnitude of panel fre-

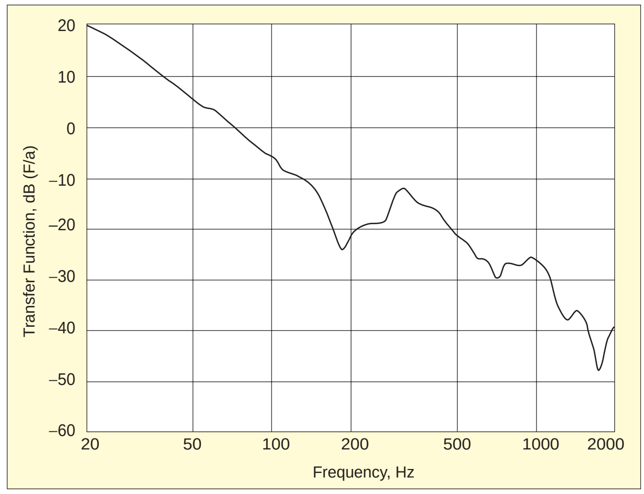

Figure 6. Example of an effective engine mount transfer characteristic for an engine mount in the z-direction.

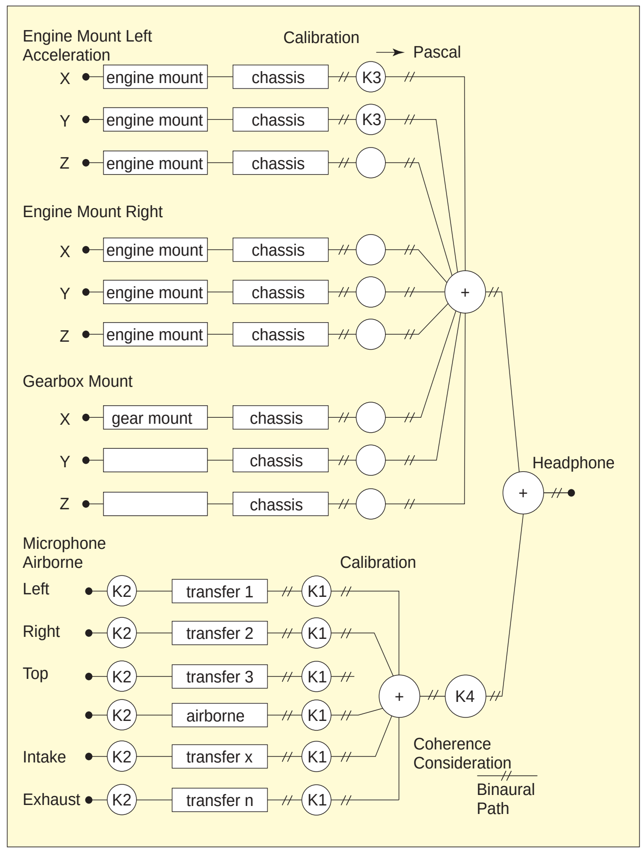

Figure 7. Binaural simulation.

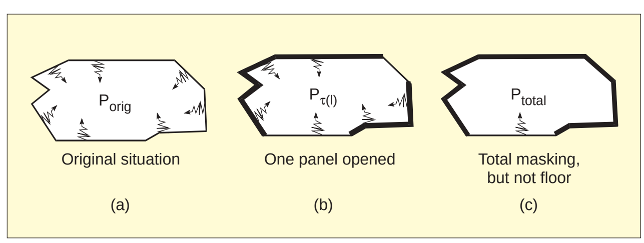

Figure 8. Masking procedure for separating transfer paths of aerodynamic noise with removal of panels.

quency response functions. The magnitude of an individual transfer function (given here in the frequency domain) is calculated by using Equation (1):

$$H_{C(i)} = \sqrt{\frac{\left|P_{T(i)}\right|^2 - \left|P_{\text{total}}\right|^2}{\left|P_{\text{orig}}\right|^2}} \quad (1)$$

In similar fashion, the magnitude of the unmasked floor transfer function (here for the m-th panel) can be estimated by Equation (2).

$$H_{C(m)} = \frac{\left|P_{\text{total}}\right|}{\left|P_{\text{orig}}\right|} \quad (2)$$

Once the magnitude of these transfer functions is estimated, the corresponding minimum-phase impulse responses $h_{C(i)}$ of FIR (finite impulse response) filters can be directly obtained by using the Hilbert transformation.

Experimental studies of wind tunnel recordings revealed that frequency components below a certain frequency do not show significant differences between individual panels. For this reason, a separation between these two frequency ranges is performed for the aerodynamic noise simulation as follows:

$$P(t)_{\text{simul}} = P(t)_{\text{orig}}\, h(t)_{\text{low}} + \sum_{i=1}^{m} h(t)_{C(i)}\, [P(t)_{\text{orig}}\, h(t)_{\text{high}}] \quad (3)$$

where $h(t)_{\text{low}}$, $h(t)_{\text{high}}$ stand for the infinite impulse response (IIR) of a low pass and high pass filter, respectively.

Equation (3) implies a useful simulation strategy when the difference between one panel currently used and another panel to be exchanged is characterized in terms of the transparency index. Here, the transparency index can be defined as the ratio of the transmitted energy to the incident energy of a panel or structure. In effect, the difference can be used to construct a minimum-phase impulse response function $h(t)_{t(i)}$, so that the simulation of exchanging the n-th panel can be calculated using:

$$P(t)_n = P(t)_{\text{orig}}\, h(t)_{\text{low}} + h(t)_{\tau(n)}\, h(t)_{C(n)} [P(t)_{\text{orig}}\, h(t)_{\text{high}}] + \sum_{i=1}^{n-1} h(t)_{C(i)}\, [P(t)_{\text{orig}}\, h(t)_{\text{high}}] + \sum_{i=n+1}^{m} h(t)_{C(i)}\, [P(t)_{\text{orig}}\, h(t)_{\text{high}}] \quad (4)$$

A physical modification of one or several panels can then be simulated in terms of FIR-filtering. The general concept of the simulation procedure is illustrated in Figure 9.

The simulation results were evaluated by measurements on a front-wheel-drive automobile within the lower middle price range. For the aerodynamic study the binaural recordings were made in a wind tunnel. The separating frequency of $h(t)_{\text{low}}$, $h(t)_{\text{high}}$ in Equations (3,4) for this vehicle is approximately 250 Hz. In order to demonstrate agreement of the binaural simulation results with binaural recordings in the original situation, a comparison between P_{simu} and P_{orig} in Equation (3) in terms of a 3rd-octave spectrum analysis is shown in Figure 10 for one experimental case. Extensive results from psychoacoustic A-B comparisons also confirmed satisfactory agreement between responses to $P(t)_{\text{orig}}$ and $P(t)_{\text{simu}}$ and in Equation (3) and between recordings and simulations of individual panels in Equation (4).

Application

In the following paragraphs, results will be presented that show how binaural transfer path analysis allows prediction of those sources and transfer paths responsible for a particular low frequency annoying noise contribution. Figure 11 shows a comparison between the measurement of baseline interior noise on a test rig and the corresponding simulation for the noise contribution from engine and exhaust system. The diagrams show the recording time on the x-axis and frequency on the y-axis, while different shadings indicate noise levels. The signals represented are those of the left ear of the artificial head. Below 80 Hz, differences between the simulation and the original measurement can be detected, which are caused by the drive unit

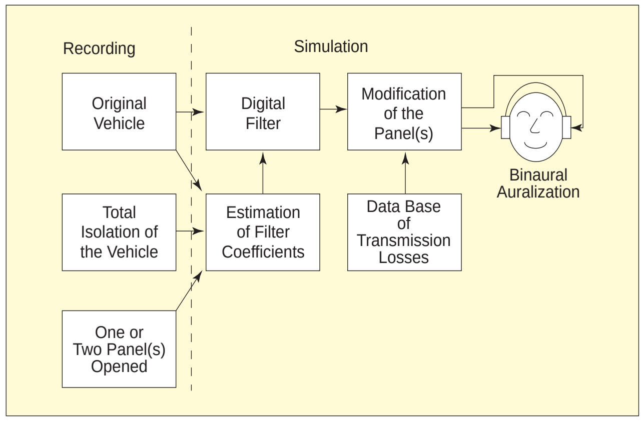

Figure 9. Hybrid model for an aerodynamic noise study in terms of binaural recording and simulation.

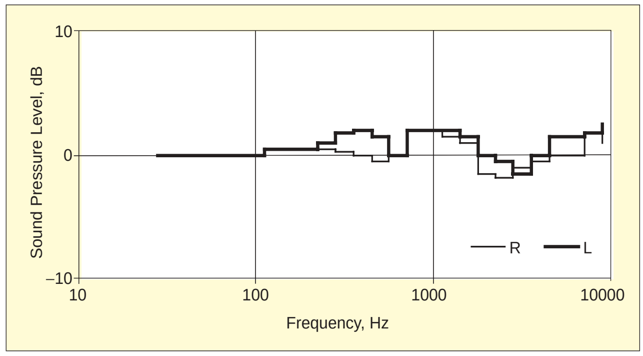

Figure 10. Difference in level between the simulation results and the original binaural recording of aerodynamic noise.

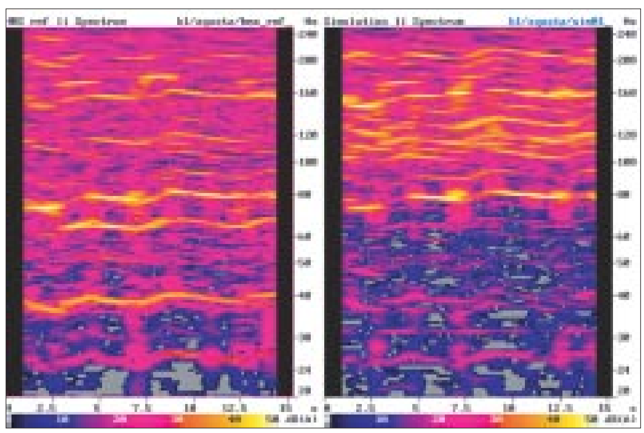

Figure 11. Comparison of baseline (left) and simulation (right).

including excitation by wheels. These transfer paths are not considered for the simulation. Nevertheless, the sound phenomenon at approximately 80 Hz that has been judged subjectively to be annoying is clearly visible.

The main advantage of binaural simulation is the representation and auralization of single sources and individual transfer paths. Based on the simulated overall situation in Figure 11, the following figures represent particular components. This allows for the determination of annoying noise contributions and their sources and transfer paths.

Figure 12 shows that, for the annoying noise phenomenon at approximately 80 Hz, the airborne noise transfer paths are much more significant than the structure-borne noise paths. For the airborne noise paths, the exhaust system component is higher than that of the engine as shown in Figure 13. Figure 14 shows the airborne noise contributions by the left and right tailpipes. Although the levels at the left and right tailpipes are approximately the same, the different transfer path characteristics lead to different levels at the driver's left ear.

Based on these results it can be concluded that the majority

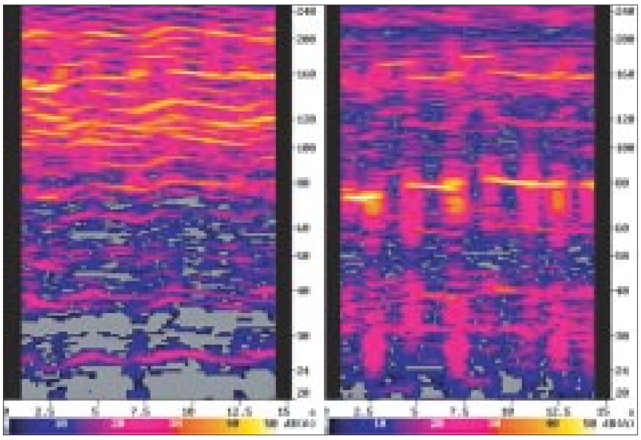

Figure 12. Comparison of structure-borne (left) and airborne (right) noise contributions.

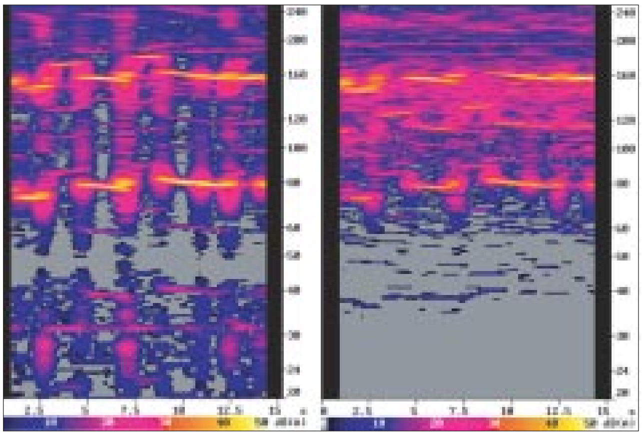

Figure 13. Comparison of airborne noise contribution by exhaust system (left) and engine (right).

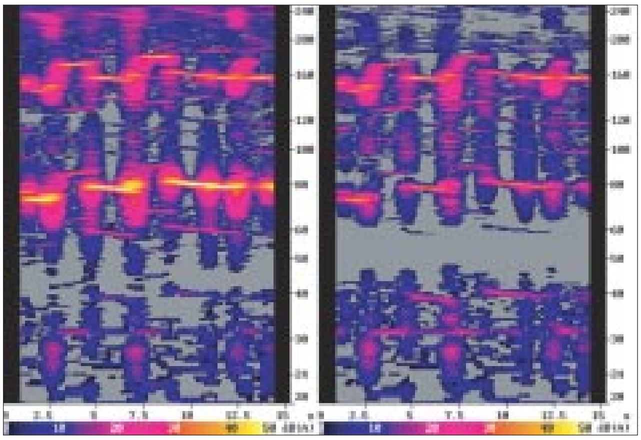

Figure 14. Airborne noise contribution by left and right tailpipe.

of the annoying noise contribution is from the left tailpipe in combination with the corresponding transfer path. Reduction of this particular path by 10 dB in the frequency range around 80 Hz will probably completely reduce the annoying effect. No other sources and transfer paths are relevant for the phenomenon under investigation.

Concept of a Sound Simulation System

The *virtual vehicle* is doubtless one of the most interesting applications of virtual environment technologies.[17] The 'driver' feels immersed in the virtual world if he/she receives plausible feedback to his/her actions. The most important feedback components are inertial, visual and vibro acoustical. Normally a "mixed reality" scenario is implemented. A real passenger compartment with real control instruments is combined with a simulation of inertial, visual, acoustical and vibrational feedback. For the present discussion the inertial aspect is not involved and will not be covered. For simulation of the driving situation the following sound components must be taken into account:[3]

- Engine sound, depending on engine type, speed and load.
- Tire sound, depending on tire type, speed and road conditions.
- Wind noise, depending on speed.
- Sounds produced by other dynamically moving objects, especially other vehicles. Those sounds depend on vehicle speed and orientation.
- Background sounds, including interior and exterior sources.
- Commands to the driver.

Depending on requirements, certain simplifications may be made concerning generation of the different sound components. If the system is to achieve an auditory impression very close to that perceived in a real vehicle, a lot of specific acoustic and vibration recordings or simulations from transfer path measurements of the vehicle must be stored in a local database. If a "good impression" is sufficient, more general sounds may be used instead. In both cases synthesized sounds can be included. For sound design applications, additional tools for interactive manipulation of sound components are required.

Engine sound is complex and dependent on the actual status of the engine described by engine speed (RPM) and load. Instead of waveform synthesis,[3] playback of an engine sound consisting of a series of sequentially-performed short recordings representing a specific RPM/load situation is preferred. For a sufficient database representation, sounds of about 200 RPM classes and 10 load conditions must be stored for each engine type to be simulated. During simulation, the recordings of parameters closest to those required are accessed and played. For constant conditions, a randomized playback of different sequences belonging to the same RPM/load class avoids the impression of periodicity. Sounds generated by this approach are comparable to sounds recorded under original operating conditions and deviations are less than 3 dB.

Binaural Simulation Data Management

For stationary sound sources, interior car sounds are binaurally recorded using an artificial head or a binaural microphone worn by a subject and are stored in a sound database. During simulation, sound segments are recalled from the database according to the current driving conditions defined by engine RPM, load and vehicle speed. Each selection of a new segment is optimized with regard to a smooth transition. Databases of binaural recordings can be used for virtual sound sources which remain in the same position with respect to the driver all the time. Thus, this principle is applicable to engine, wind, tire and background sounds.

All moving virtual sounds have to be generated by binaural synthesis from monophonic sources, i.e., by convolution of the monophonic input sound with head-related impulse responses (HRIR) that include all information about the direct sound path from a sound source at a certain position relative to both ears. HRIR sets consist of HRIRs for several directions; normally all directions required for the simulation. They must provide sufficient spatial resolution to achieve smooth movements without audible steps. In order to be compatible with the binaural recordings described above, the HRIR of an artificial head or of a subject should be used.

To move a sound pattern in virtual space, the signal must be processed by the following steps:

- Simulation of the directivity of the sound source.
- Simulation of Doppler shift (where applicable).
- Convolution with left and right HRIR according to the direction of the direct sound and, if required, for reflections from trees, houses, walls, etc.
- If needed, reverberation is added to the binaural signal.
- Binaural playback.

Since position and speed of dynamic objects always change, the system parameters (sound direction, delay, Doppler shift,

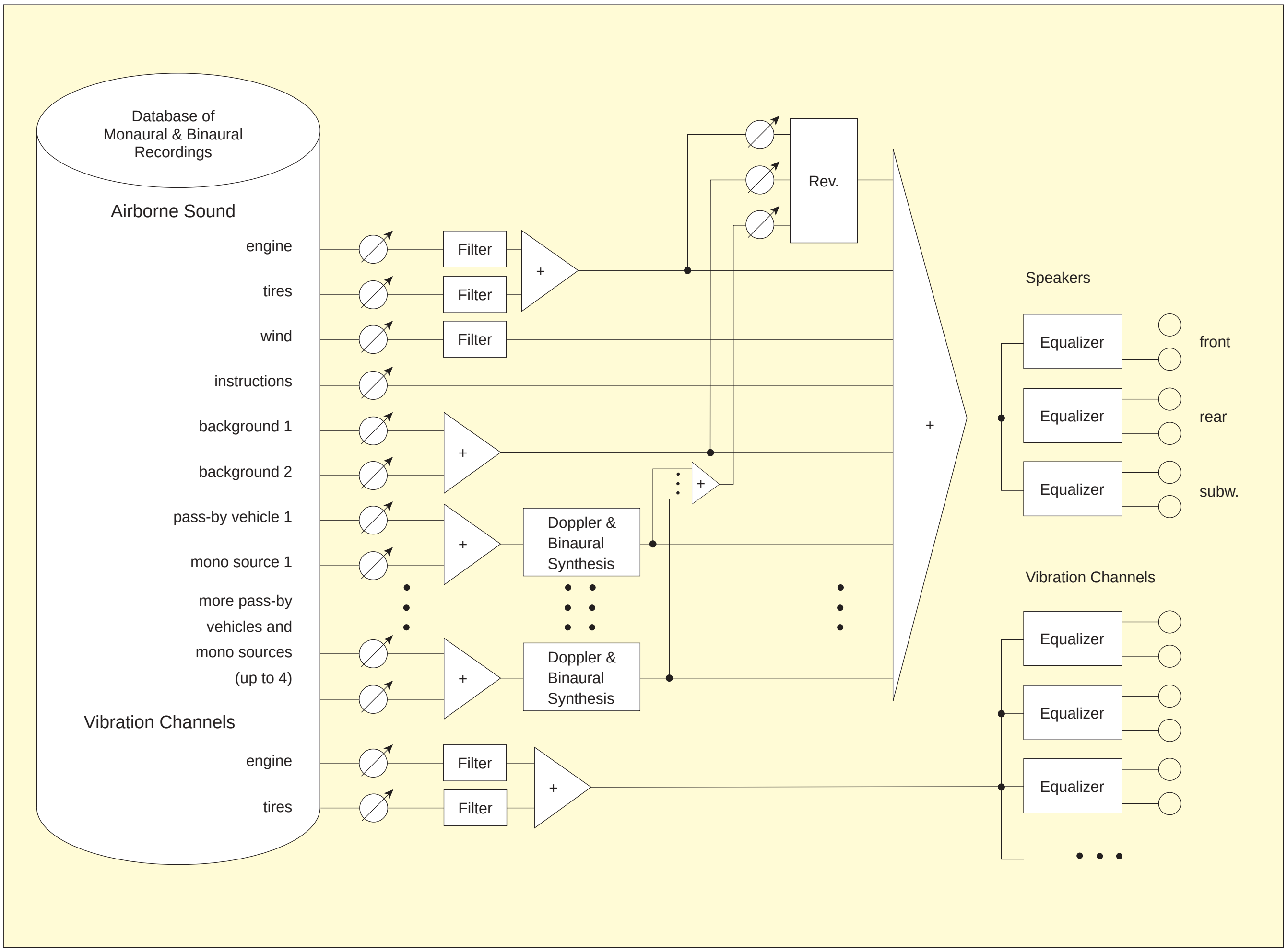

Figure 15. Sound and signal processing management system (H3S).

etc.) must be adapted in real-time. For practical applications, 20 updates per sec may be regarded as sufficient. A computer-based sound and signal processing management system 'H3S' is shown in block form in Figure 15.

Sound Design Tools

For sound design applications, the following tools can be realized online during simulations:

- Changing the complete sound scenario intuitively, simply by driving virtually.
- A/B comparison between different engines measured inside passenger cabins.
- A/B comparison between wind and tire noise.
- Online filtering of the three sound components.
- Recalculation of a binaural transfer path synthesis model as described above.
- Binaural simulation of interior car sound for different engines measured on a test rig using data from binaural transfer path analysis. For this application a correction function must be applied to the test rig data, which considers the structure-borne coupling of the engine at the test rig and the room acoustics of the engine compartment.

The major difference, compared to well-known laboratory sound design tools, is that all sound perception effects are perceived within a very realistic context, namely driving a virtual vehicle.

Reproduction of Sound and Vibration in a Car Body

As mentioned above, binaural technology is based on the idea of reproduction of ear signals in order to reproduce a complete spatial hearing sensation.[6,7] This idea implies the use of headphones since only headphone reproduction ensures that no crosstalk between the channels of the binaural signal occurs within the reproduction system, i.e., the right ear receives only the signal recorded in the right ear and the left ear only that recorded in the left ear.

Sometimes, in driving simulations, headphone reproduction is not desirable in order to achieve a virtual situation in which all aspects are close to reality. In such cases, loudspeaker reproduction is required.

During the development of the artificial head,[8] theoretical research and numerous experiments with loudspeaker reproduction were performed. Since head-related interaural time differences are included in the HRTF, the spatial definition of auditory events in a loudspeaker playback situation based on artificial head signals often delivers better results than solutions using coincident or semi-coincident microphone techniques. The HRTF is still present in loudspeaker playback but without coloration of timbre, due to normalizing equalization of the artificial head (e.g., free-field, independent-of-direction ID or diffuse field equalization). Head-related time- and frequency-domain information remain in loudspeaker reproduction despite the non-binaural presentation mode giving excellent imaging and transparency.

Two-Loudspeaker Arrangement. Arrangements for loudspeaker reproduction using crosstalk-cancelling techniques have been described.[9,10,11,12] Under ideal conditions (anechoic chamber, exact positioning of the listener, correct equalization) it is possible to achieve the same or even better reproduction quality for binaural signals compared to headphones. The disadvantage of this method, however, is that these environmental conditions are not easily realized in car bodies.

Four-Loudspeaker Arrangement. As an alternative solution, a 4-loudspeaker arrangement has been developed for rectangular listening studios[13] It was later adapted to car bodies. The principle of this technique is very simple: the left speakers are

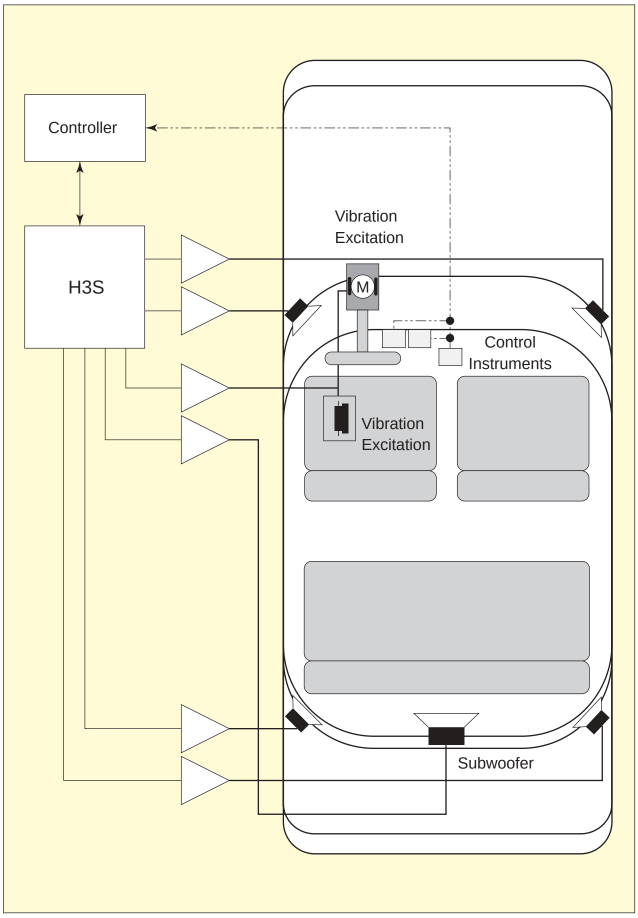

Figure 16. Arrangement for sound and vibration reproduction in a car body.

fed by the left channel of the binaural signal; the right speakers are fed by the right channel of the signal. Typically, identical levels are produced by front and rear loudspeakers. Each loudspeaker is separately equalized for correct timbre of the overall sound and delays resulting from different distances to the listener are compensated. The big advantage of this type of reproduction is that small movements of the listener's head do not disturb the acoustical image, sound sources remain virtually stable in place and no discoloration of the sound is perceived. It is not necessary to adjust the arrangement for listeners with different body sizes or seat positions. Localization tests[13] showed that localization accuracy achieved by a 4-loudspeaker arrangement is similar to that of headphone reproduction. In addition, it can be stated that localization in reverberant rooms improves, compared to anechoic test rooms. Additional experiments using the loudspeaker arrangement in a car body showed a reasonable spatialization capability.[14] Due to problem acoustics in a car body, localization accuracy is slightly reduced when compared with headphone reproduction. Figure 16 shows a typical application in a car body. The installed audio system loudspeakers may usually be used for sound reproduction. The four speaker levels must be balanced carefully. In order to give a more realistic simulation, low frequency airborne sound down to 20 Hz is generated by a high quality subwoofer system.

Integration of Vibration Simulation. Realism of virtual environments is significantly enhanced by the integration of feedback channels addressing the whole body – very low frequency airborne sound as well as structural vibration. Binaural technology described above must be extended for this purpose. Multichannel measurement systems must be used that allow for simultaneous recording of acoustic and vibration data. For some applications (e.g., driving simulations for training purposes), it is sufficient to generate 'cue' vibration components directly from the binaural recordings by lowpass filtering and equalization.

Vibrational simulations in a passenger compartment can be divided into two main categories:

- Excitation through operational devices, i.e., engine, transmission system, wheels and suspension system. A typical example is the second order of a 4-cylinder engine.
- Vibrational contribution of "comfort features," such as power windows, electric sunroof, power seats and electrical mirrors. Electrical devices primarily cause low frequency noise components such as 'booming' and vibration.

At present, there is no detailed research on the dependencies between vibrational and acoustical perception. Examinations have shown trade-off phenomena between sound and vibration when the vibration level is in the range of the perception threshold; loudness is judged higher when vibration is present.[15] Experience in dealing with vehicle complaints has shown that it is usually sufficient to consider vibrations at the passenger's seat and rotational vibrations at the steering wheel for a first approach. These vibrations represent the major part of relevant judgement influences. For particular devices – power windows for example – the excitation of other points of the car body may be considered. Introductory research tests within the European research project OBELICS (BRPR CT96-0242) have shown that the use of combined vibro-acoustic playback systems leads to more reliable judgements of sound characteristics and sound quality. Based on this, a suitable vibro-acoustic playback system may consist of airborne sound via head phone(s), low frequency sound (20-150 Hz) via subwoofer(s) and vibrations of steering wheel and seat via excitation devices.[16] The setup of such a system is shown in Figure 16.

References

1. Synthesis Report AQUSTA, "Improvement of the Structural Acoustic Quality of Transportation Vehicles Using Simulation Techniques of Binaural Analysis," December 1992.
2. K. Genuit, X. Bohineust, M. Rehfeld, "Binaural 'Hybrid' Model for Simulation of Noise Shares in the Interior of Vehicles," Inter-Noise '97, 25-28.08.97, Budapest, Hungary.
3. W. Krebber, H. W. Gierlich, "Acoustical Feedback System for Virtual Vehicles," ATA 1997, 26-28.02.1997, Florenz, Nr. 97A1045.
4. K. Genuit, J. Poggenburg, "The Design of Vehicle Interior Noise Using Binaural Transfer Path Analysis," SAE '99, 17-20.05.1999, Traverse City, MI.
5. K. Genuit, "Application of Binaural Transfer Path Analysis to Sound Quality Tasks," European Conference on Vehicle Noise and Vibration 2000, 10-12.05.2000, Imeche 2000, London, UK, pp. 241-250.
6. J. Blauert, *Spatial Hearing*, MIT Press, Cambridge, MA, 1983.
7. H. J. Platte, "Zur Bedeutung der Außenohrübertragungseigen schaften für den Nachrichtenempfänger 'Menschliches Gehör,'" Ph.D. thesis RWTH, Aachen, 1979.
8. H. Möller, "Fundamentals of Binaural Technology," *Applied Acoustics*, submitted for publication.
9. P. Damaske, V. Mellert, "Ein Verfahren zur richtungstreuen Schallabbildung des oberen Halbraumes über zwei Lautsprechern," *Acustica* 22, 1969, pp. 154-162.
10. D. H. Cooper, J. L. Bauck, "Prospects for Transaural Recording," *J. Audio Eng. Amer.*, Vol. 37, 1989, No. 1/2, pp. 3-19.
11. G. Neu, E. Mommertz, A. Schmitz, (1992), "Untersuchungen zur richtungstreuen Schallwiedergabe bei Darbietung von Kopfbezo genen Aufnahmen über zwei Lautsprecher," *Acustica*, 76 (1992), pp. 183-191 and 77 (1992), pp. 153-161.
12. H. Möller, "Reproduction of Artificial Head Recordings Through Loudspeakers," *J. Audio. Eng. Amer.*, Vol. 37, 1989, No. 1/2 pp. 30-33.
13. K. Genuit, H. W. Gierlich, U. Künzli, "Improved Possibilities of Binaural Recording and Playback Techniques," 92nd Convention of AES Vienna, 1992, 24.-27.03, 1992, Preprint 3332.
14. W. Krebber, H. W. Gierlich, "Auditory Displays Using Loudspeaker Reproduction," Joint meeting EAA/ASA, Berlin 1999.
15. Y. Tamura, M. Hiraga, "The Effect of Low Frequency Vibration on Sound Quality of the Automobile Audio System – Proposal of a New Automotive Audio System."
16. K. Genuit, J. Poggenburg, "The Influence of Vibrations on the Subjective Judgement of Vehicle's Interior Noise," Noise-Con '98, Ypsilanti, MI, USA.
17. W. Krebber, R. Sottek, "Interactive Vehicle Interior Sound Simulation," ISATA 2000, Dublin, Ireland.

The authors can be contacted at: Klaus.Genuit@head-acoustics.de, wbray@headacoustics.com.