

Application of Binaural Transfer Path Analysis to Sound Quality Tasks

Dr.-Ing. Klaus Genuit
HEAD acoustics GmbH

1. INTRODUCTION

The Binaural Transfer Path Analysis was developed in order to predict the interior noise of vehicles for modifications at input signals of the engine or at single transfer paths. This tool considers airborne noise shares up to 12 kHz and structure-borne noise shares with an upper frequency limit of 2 kHz. A definite distinction between these both main origins is essential for investigations in vehicle interior noise.

The approach presented enables the user not only to calculate resulting parameter data, but also to listen binaurally to the noise situation in an aurally-equivalent way. In consequence, it can be used to solve Sound Quality and Sound Design tasks in automotive industry efficiently. The reduction of efforts required for investigations is ensured by combining transfer path measurements at vehicles and acoustical measurements at engines with the simulation tool. All measurements at the vehicle are carried-out without the necessity to remove the engine or other components that influence the structural behaviour.

The simulation leads to binaural sound samples for each transfer path under investigation and their combinations. They can be used in listening sessions and allow the subjective judgement of the effect on sound patterns by modifications.

An application example presented in the paper shows clearly how the cause for an annoying share in the interior noise can be determined precisely and allows target-oriented modifications.

Within the scope of the presented 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 the aurally-equivalent, binaural simulation of noise created in the interior of a vehicle by wind and engine. The presented model is based on measurements made with a vehicle or 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 on driver's seat.

2. MODEL DESCRIPTION

The complete binaural acoustic response recorded in a vehicle with the Artificial Head representing passenger's head can be mathematically defined as the sum of several mechanical and acoustical sources propagating waves which impact 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.

This model for the prediction of interior sound with respect to the engine is based on the vibration signals (triaxial) at engine side and some (4 or more) microphone signals close to the different surfaces of the engine. The vibration are transmitted through the engine mounts into the chassis. In dependence on the engine stiffness and the chassis inertance the force can be calculated which is transmitted into the chassis and creates the structure borne related

sound. The complex superposition with the airborne transmitted sound produces the total sound simulation inside of the vehicle with respect to the engine.

3. SIMULATION METHODOLOGY

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

Structure-borne transferpaths

For the determination of the structure-borne transferpaths a new method was developed which enables the user to measure the effective relevant structure-borne transfer characteristic in a build-in situation. That means it is not necessary to disassemble the engine from the car, so this new method is a very time and cost saving procedure. The effective relevant transfer characteristic of the engine mounts is based on a measurement of the triaxial acceleration measurements at engine and chassis side and will be calculated in combination with the inertance of the chassis.

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

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

Based on these aims, a methodology was developed that includes the following steps:

1. Determination of mounts' transfer characteristics.
2. Measurements of structure-borne noise transfer paths from (engine) mounts to passenger 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 passenger ears.
5. Measurement of binaural acoustic and vibrational situation at passenger seat(s) during operation using baseline configuration.

In the following, details of this procedure will be described:

During all measurements the engine keeps installed in the vehicle. Although this means some particular difficulties with respect to (structure) excitation, this proceeding includes some important advantages:

- Structural characteristics for the real system (no influence by absence of engine that can only be replaced partly by additional weights with respect to structural behavior);
- no influence on structural characteristics by removing and reinstalling the engine;
- reduced time required.

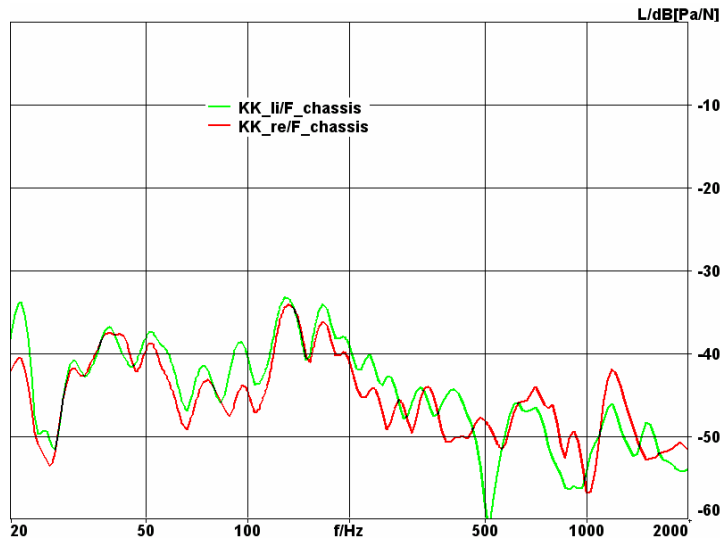


Fig. 1:
Example of structure-borne transfer function (smooth spectrum) left and right ear

Triaxial impact excitation is done at all engine mounts on car-body side, respectively additional excitation at mounts of the exhaust system. In parallel, triaxial accelerations at all mount locations (a_j) and the sound pressure level at dummy head ($SPL_{l,r}$) are measured time-synchronously. Based on these data, the calculation of transfer functions up to 2 kHz can be done. Samples of such transfer functions are shown in fig. 1.

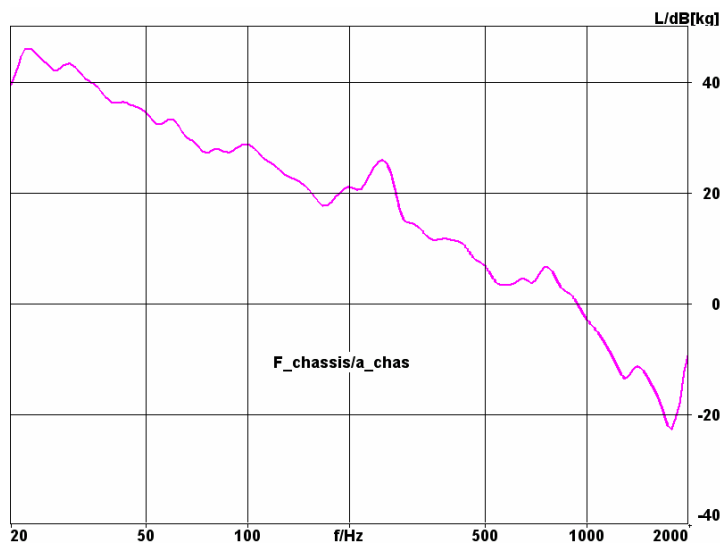


Fig. 2:
Example of apparent mass for car-body in z-direction

The acquisition of accelerations at the location of impact excitation allows the additional determination of **input car-body inertance**. The corresponding measurements require experience in order to receive reliable results..

An impact test device is used due to practical reasons. Electro-dynamic shakers offer advantages with respect to energy input especially at low frequencies but require more space for application.

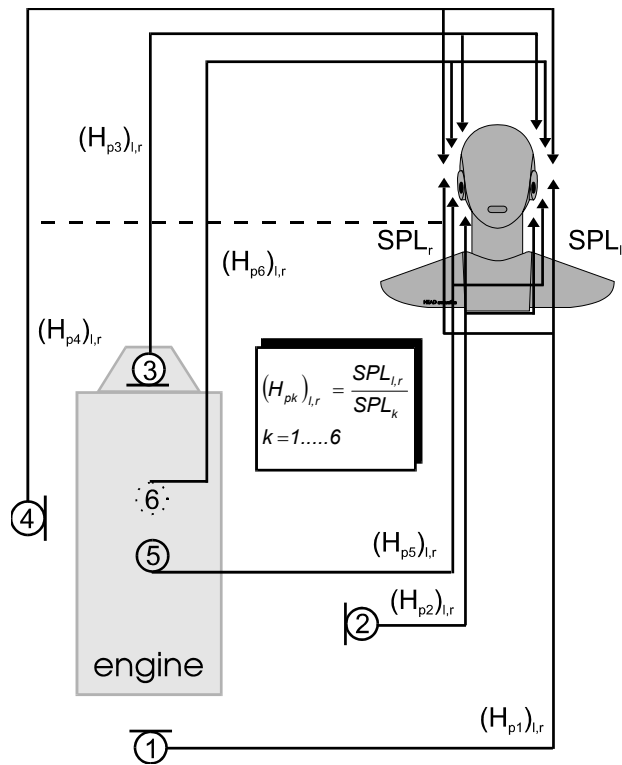
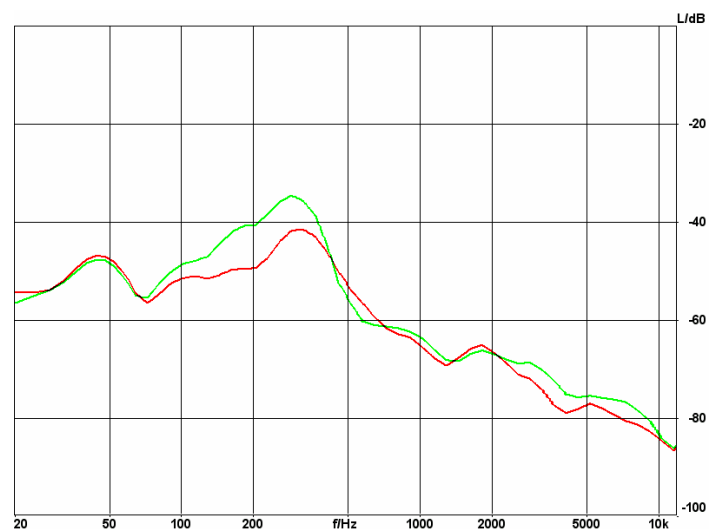


Fig. 3: Measurement of airborne noise transfer paths.

An example airborne noise transfer function is shown in fig. 4.

For the **measurements of airborne noise transfer paths** a special reference sound source is used that realizes high levels at low frequencies and is small in dimensions. The airborne excitation is done in the engine compartment (and at particular positions at the exhaust system) with a suitable signal up to 12 kHz using a microphone arrangement similar to the engine test rig configuration (fig. 3) and the dummy head positioned in the interior of the vehicle. The measurements are repeated for several positions in the engine compartment. Based on this, the average transfer functions from each microphone to the dummy head are determined.

Fig. 4: Example of airborne noise transfer function (smooth spectrum)



Following **binaural acoustic measurements** at several operational conditions (i.e. run-up at full and/or partial load) mean the acquisition of base line interior vehicle sound. Additionally, it allows the determination of **mounds' transfer characteristics** up to 2 kHz if the following prerequisites are valid:

- mounds' stiffnesses are low;
- stiffness of car-body is high;
- the system can be seen as a minimal-phase one;
- dynamic characteristics are considered as linear in the frequency range interesting for acoustical purposes.

In this case both the amplitude of the dynamic behavior and stiffnesses can be calculated based on the measurement data of accelerations on engine side and on car-body side, and on the impedances of the car-body. The corresponding phase values are determined by using the HILBERT transformation. An example result is shown in fig. 5.



Fig. 5: Example of an effective engine mount transfer characteristic acceleration a into for F for an engine mount in z-direction

This simplified approach of transfer function determination compared to measurements on particular mount test rigs is sufficient for the described objectives.

In a further step the **binaural simulation of the baseline situation** may be used for verification. The procedure is shown in fig. 6 for the simulation of engine noise.

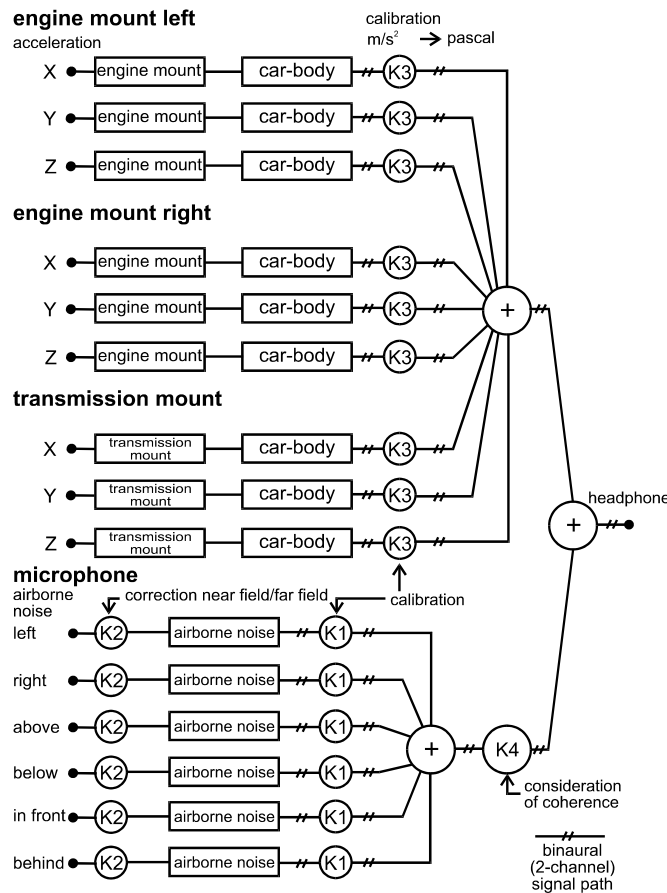


Fig. 6: Binaural Simulation

The triaxial accelerations at all engine mounts on engine side are combined with mount transfer characteristics, car-body inertance and structure-borne transfer paths to receive the interior noise caused by structure-borne excitation.

In parallel, the measured acoustic data at the engine are combined with the airborne transfer paths considering the particularities of coherence.

In this context it has to be considered that – in any case – the interior sound is independent of the number of measuring microphones. Therefore, the mixture of the single airborne noise signal to a summarized overall signal requires a correction factor dependent on coherence. This factor is applied to the binaural simulation (K4).

In this context the following assumptions have to be made:

- The current version of the Binaural Transfer Path Analysis considers the contributions by engine and intake/exhaust-system. This implies that a prediction of SPL is only possible for these main causes of interior vehicle noise.
- For the aim of working on sound quality and sound design tasks it is important to simulate characteristic signal patterns. Based on this, several configurations may be compared subjectively. An example in chapter 4 shows the suitability of the presented approach for sound quality tasks.
- With both the measurement and simulation results 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, engines with different airborne and structure-borne excitation 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, by using the Binaural Hybrid Model it is possible

- to determine and auralize the influence of modifications at components on the interior noise;
- to determine those structural characteristics of transfer elements (mounts, car-body etc.) which have to be modified in order to get a particular (designed) interior noise;
- to investigate the effect of various engines (and/or exhaust/intake systems) on the interior noise.

4. AERODYNAMIC NOISE SIMULATION

Aerodynamic noise becomes dominant for the interior sound above a certain speed, the limit of which depends on the type of vehicles 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 this procedure as shown in Fig. 7, binaural recordings at the driver or co-driver position in the interior of the vehicle can be used for estimating noise transfer paths of different panels.

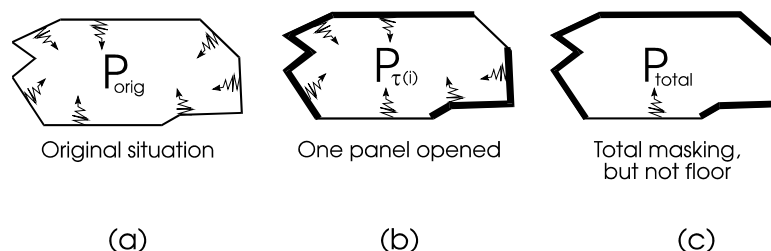


Fig. 7: Masking procedure for separating transfer paths of aerodynamic noise with removal of panel(s).

In the complex aerodynamic noise situation with transmission through all panels as shown in Fig. 7(a), 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 $P_{T(i)}$ (Fig. 7(b)) is performed one after another for each panel under test. The rest signal of total masking P_{total} (Fig. 7(c)) has also to be recorded since the floor part of the vehicle can not be easily masked.

These binaural recordings corresponding to the given panels are used to generate an estimation of the magnitude of panel frequency response functions. The magnitude of the individual transfer function (given here in the frequency domain) is calculated by using equation (1):

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

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

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

Once the magnitude of these transfer functions is estimated, the corresponding minimum-phase impulse responses $h_{C(i)}(t)$ of FIR filters can be straight-forwardly achieved by using the HILBERT transformation.

From experimental studies of wind tunnel recordings resulted 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:

$$P_{simu}(t) = P_{orig}(t) * h_{low}(t) + \sum_{i=1}^m h_{C(i)}(t) * [P_{orig}(t) * h_{high}(t)], \quad (3)$$

where $h_{low}(t)$, $h_{high}(t)$ stand for IIR impulse response of low pass and high pass filter respectively.

Eq. (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 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 $h_{\tau(i)}(t)$, so that the simulation of exchanging n -th panel is straightforwardly performed using:

$$P_n(t) = P_{orig}(t) * h_{low}(t) + h_{\tau(n)}(t) * h_{C(n)}(t) * [P_{orig}(t) * h_{high}(t)] + \sum_{i=1}^{n-1} h_{C(i)}(t) * [P_{orig}(t) * h_{high}(t)] + \sum_{i=n+1}^m h_{C(i)}(t) * [P_{orig}(t) * h_{high}(t)]. \quad (4)$$

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 Fig. 8.

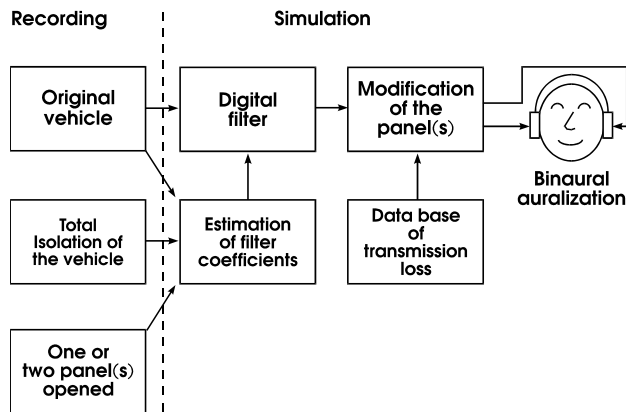


Fig. 8: Hybrid model for aerodynamic noise study in terms of binaural recording and simulation.

The simulation results were evaluated by measurements at a front-wheel driven car of the lower middle range. For the aerodynamic study the binaural recordings were conducted in a wind tunnel. The separating frequency of $h_{low}(t)$, $h_{high}(t)$ in eqs. (3-4) for this vehicle is approximately 250 Hz. In order to demonstrate the agreement of binaural simulation results with binaural recordings in the original situation, a comparison between P_{simu} and P_{orig} in eq. (3) in terms of a 3rd-octave frequency analysis is illustrated in Fig. 9 for one experimental case. Extensive results from psychoacoustic A-B comparisons also confirmed satisfactory agreements between responses to $P_{orig}(t)$ and $P_{simu}(t)$ in eq. (3) and between recordings and simulations of individual panels in eq. (4).

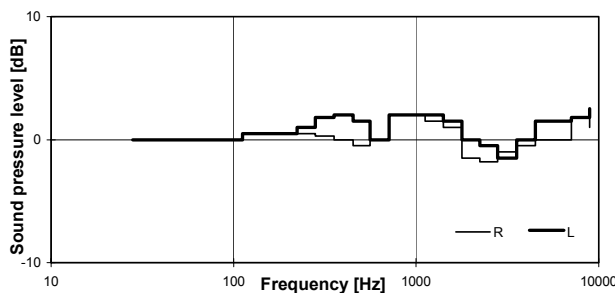


Fig. 9: Difference in level between the simulation results and the original binaural recording of aerodynamic noise.

5. APPLICATION

In the following, results will be presented that show in which way the binaural transfer path analysis allows a prediction of those sources and transfer paths responsible for a particular low frequent annoying noise share. Fig. 10 shows a comparison between the measurement of the baseline interior noise on test rig (left side) and the corresponding simulation for the contribution by engine and exhaust system (right side). The diagrams show on the x-axis the recording time and on the y-axis the frequency while different shadings indicate different level. The signals represented are those of the left ear of the Artificial Head. Below 80 Hz differences between simulation and the original measurement can be detected which are caused by the drive unit including excitation by wheels. These transfer paths are not considered for the simulation.

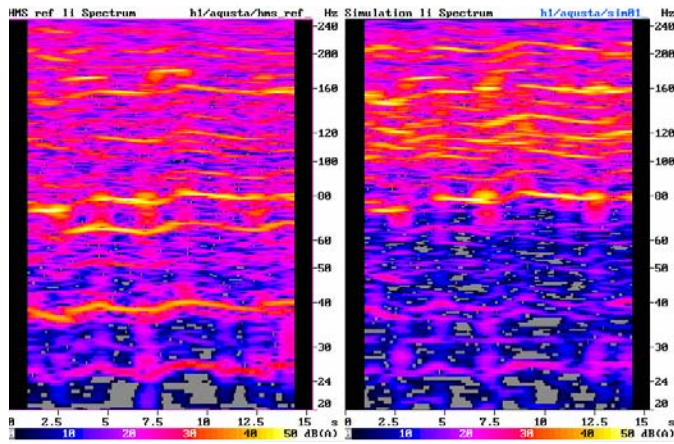


Fig. 10:
Comparison of baseline and simulation

Nevertheless, the sound phenomenon at approximately 80 Hz that has been judged subjectively as annoying is clearly visible.

The main advantage of the binaural simulation is the representation and auralization of single sources and single transfer paths. Based on the simulated overall situation in fig. 10 the following figures represent particular components. This allows the determination of annoying noise shares and the responsible sources and transfer paths.

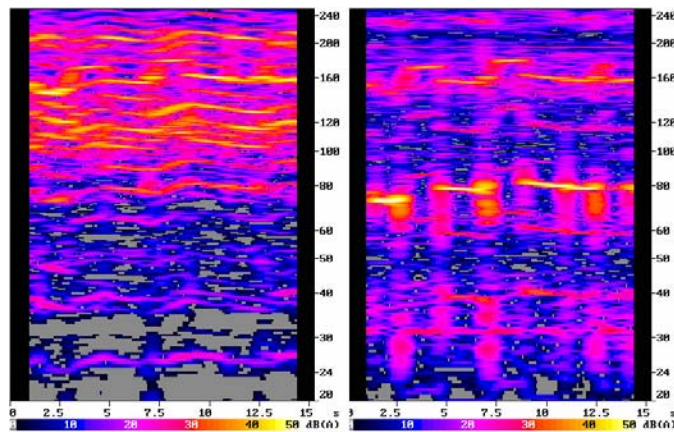


Fig. 11:
Comparison of structure borne (left) and airborne noise contribution (right)

Fig. 11 shows that for the annoying noise phenomenon at approx. 80 Hz the airborne noise transfer paths are much more significant than those of structure-borne noise. For the first, the share by the exhaust system is higher than that of the engine as shown in fig. 12.

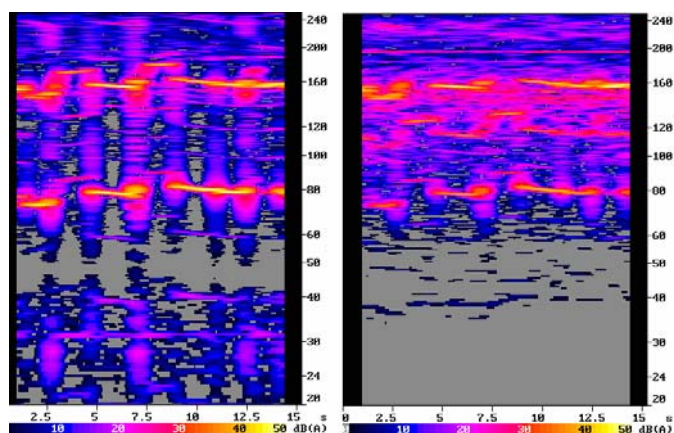


Fig. 12:
Comparison of airborne noise contribution by exhaust system (left) and engine (right).

For further examination, in fig. 13 the airborne noise contributions by the left and the right tail pipe are shown. Although the levels at left and right tile pipe are approximately the same, the different transfer path characteristics lead to different levels at driver's left ear.

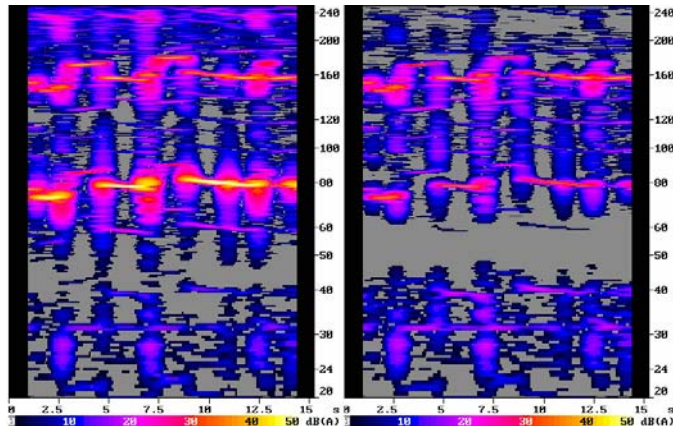


Fig. 13:
Airborne noise contribution by left and right tail pipe

Based on these results it can be concluded that the major part of the annoying noise share is caused by the left tail pipe in combination with the corresponding transfer path. A damping of this particular path by 10 dB in the frequency share around 80 Hz probably will completely reduce the annoying effect.

All other sources and transfer paths are not relevant for the phenomenon under investigation.

6. SUMMARY

The development of a binaural “hybrid“ model for the prediction of sound quality based on measured and calculated data means an important step towards an efficient process of sound design. The results for aerodynamic noise prove the suitability of this method. Further research work is necessary for the extension of the model to other noise shares which leads to a tool usable for diverse applications.

7. ACKNOWLEDGEMENT

The present work was funded by the European Union under BRITE EURAM. The authors would like to express their acknowledgment to the European Commission for supporting this BRITE AQUESTA project, particularly to Mr. Andrieu and Mr. Kruppa as EEC Coordinators.

8. REFERENCES

- [1] 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
- [2] Synthesis Report AQUESTA: Improvement of the structural Acoustic Quality of transportation vehicles Using Simulation Techniques of binaural Analysis, December 1992