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The Design of Vehicle Interior Noise Using Binaural Transfer Path Analysis

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1. INTRODUCTION

For the prediction of sound quality in vehicles not only in terms of numbers, but also as acoustic binaural representation the so-called "binaural hybrid model" was developed and already described in various publications. The methodology based on a combination of test rig measurements and acoustic simulation was started within a European research project and has been applied in meantime for several tasks related to efficient sound design processes of vehicle interior noise.

The scope of this paper is to describe methodology improvements for the use in engineering work and application possibilities.

It explains simplifications and limitations of this approach. The usefulness of the presented proceeding is shown using a case study.

2. BACKGROUND

There exist several methods for the investigation in transfer paths at vehicles. The two main categories are the force vector method based on measurements of forces and displacements, and the matrix path method using acceleration data /1/. Both approaches have their particular advantages and disadvantages.

For measurements at complete vehicles the matrix path method means high efforts in testing, but does allow the determination of mounts dynamic characteristics without further measurements /2/ - which are not required for the kind of transfer path analysis used for binaural simulation

The "Binaural Hybrid Model" as described in /3/ is based on the latter approach but includes some particularities:

- Its aim is the prediction and auralization of interior noise characteristics more than the calculation of an absolute SPL value.
- The binaural playback of the simulated interior noise is possible.
- The dynamic behavior of mounts is sufficiently approximated by measurements at the vehicle during operation.

Details may be found in the reference given above and will not be repeated here.

The prediction of interior noise characteristics means that the simulation of spectral patterns and time structure during defined operational conditions is required. The calculation is based on the determination of complex airborne and structure-borne noise transfer paths. Details about the procedure are given in chapter 3.

The need for playback of interior noise simulation leads to the use of an Artificial Head during the measurements. Consequently, all transfer paths are determined binaurally. The major advantage of this method is the possibility to listen to the sound in an aurally-equivalent way. This allows more reliable comparisons of different modifications than analysis diagrams. Sometimes it is the only solution for the derivation of ranking orders due to the particular high-sensitive characteristics of human hearing.

The determination of triaxial stiffnesses of mounts in a frequency range up to 2 kHz requires the set-up of specially designed test rigs that are extremely expensive and are seldom available. For the model presented it was decided to determine the corresponding "operational values" in measuring the accelerations on engine side and car-body side while the vehicle is driven on a roller-bench. The conditions selected for operation are run-up at full and partial load.

The validity of the approach described is based on the prerequisite that the impedances of mounts are low compared to those of car-body and engine. The resulting errors are negligible in our context.

For the measurements of airborne transfer paths it is necessary to approximate the acoustics radiation of the engine by loudspeaker(s). The complex transfer functions are calculated from nearfield microphones in the engine compartment to both ears of the Artificial Head.

For simulation purposes using acoustic data of engine test rig measurements the transfer from the corresponding free field microphones to the nearfield positions is required. Its realization is described in chapter 3.

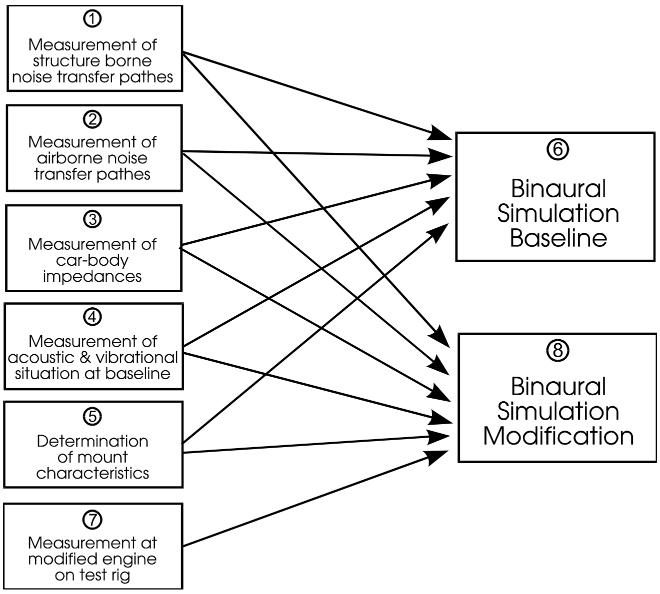

Fig. 1: Methodology of binaural simulation

3. METHODOLOGY

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 as shown in fig. 1 was developed that includes the following steps:

1. Measurements of structure-borne noise transfer paths from (engine) mounts to passenger ears.

2. Measurements of airborne noise transfer paths from engine compartment (and exhaust system) to passenger ears.

3. Measurements of car-body impedances at (engine) mount locations.

4. Measurement of binaural acoustic and vibrational situation at passenger seat(s) during operation using baseline configuration.

5. Determination of mounts' transfer characteristics.

6. Simulation of binaural acoustic situation for baseline using results of measurements in steps 1 to 3 and 5 in combination with engine test rig measurements.

7. Comparison of results in step 4 and step 6.

8. Binaural simulation for new "input" data, e.g. modified engine, and presentation of resulting acoustic situation.

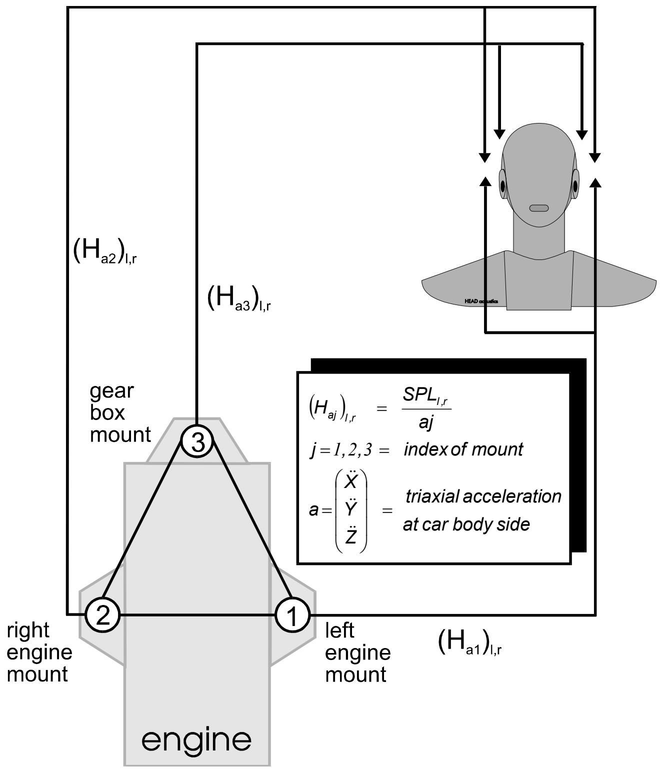

Fig. 2: Measurement of structure borne noise transfer paths for engine with 3 mounts

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

During all measurements of steps 1 to 4 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.

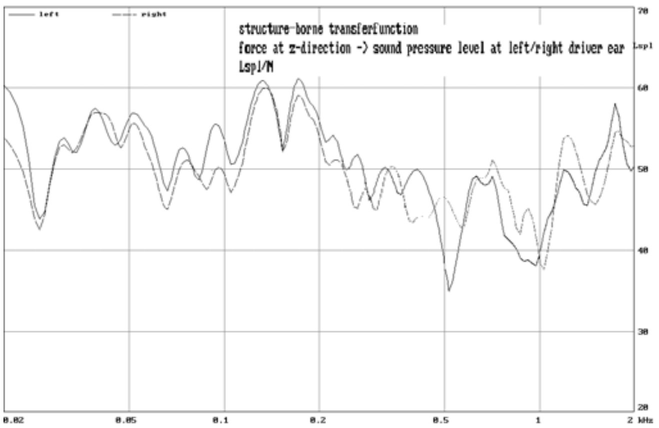

Fig. 3: Example of structure-borne transfer function (smooth spectrum)

For the **measurement of structure borne transfer paths** a set-up as shown in fig. 2 is used: Triaxial impact excitation is done at all engine mounts ℵ to ℜ 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. 3.

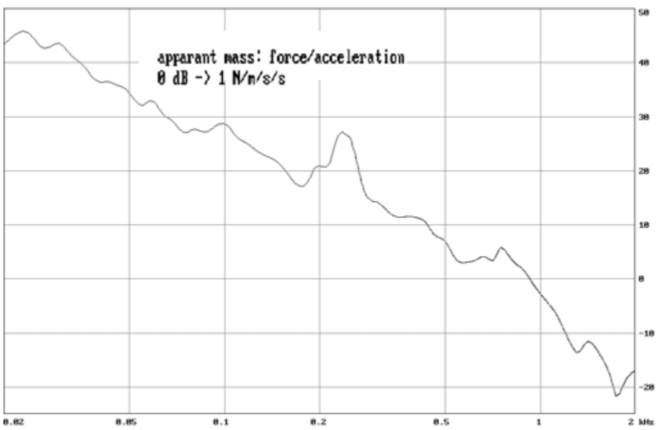

Fig. 4: Example of apparent mass for car-body in z-direction

The acquisition of accelerations at the location of impact excitation allows the additional determination of **input car-body impedances**. The corresponding measurements require experience in order to receive reliable results. Examples for the apparent mass are shown in fig. 4.

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.

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. 5) 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.

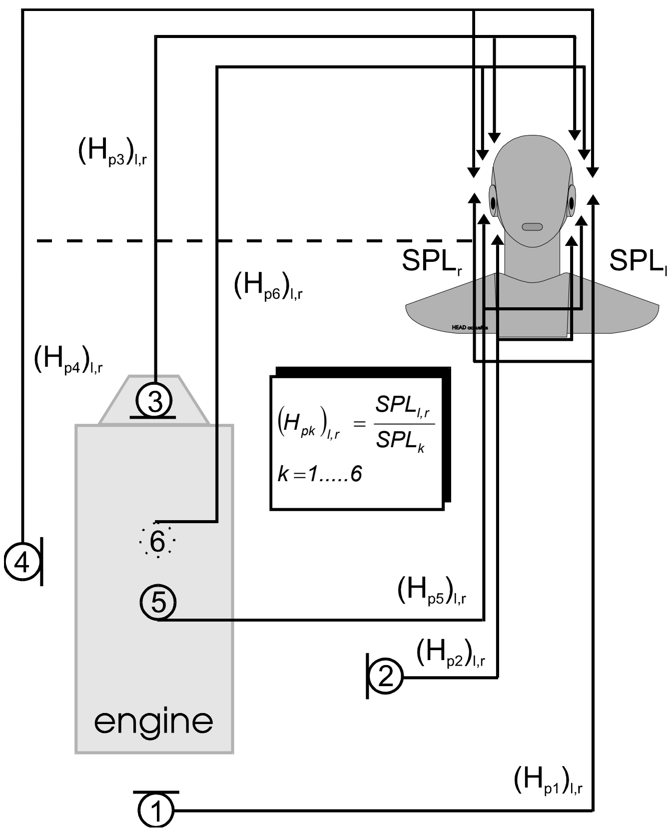

Fig. 5: Measurement of airborne noise transfer paths.

An example airborne noise transfer function is shown in fig. 6.

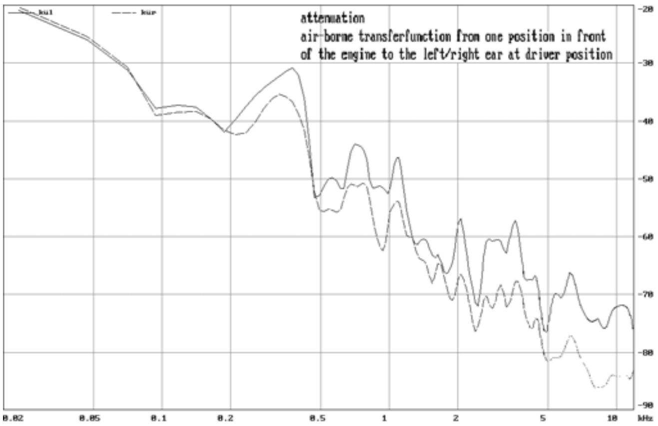

Fig. 6: Example of airborne noise transfer function (smooth spectrum)

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 **mounts' transfer characteristics** up to 2 kHz if the following prerequisites are valid:

- mounts' 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. 7.

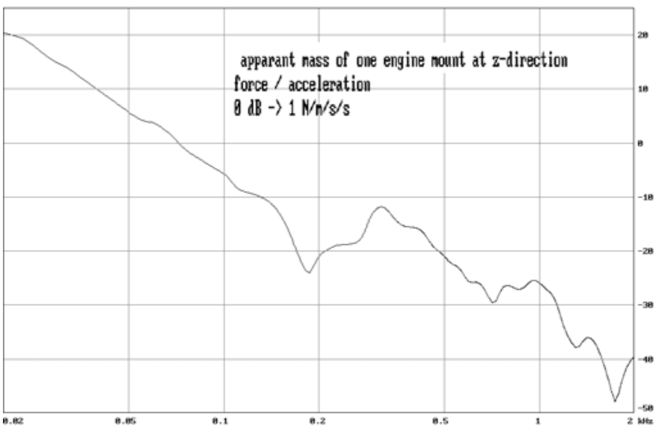

Fig. 7: Example of apparent mass for engine mount in z-direction

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. Here, the results of steps 1-5 are required in combination with engine test rig measurements. The procedure is shown in fig. 8 for the simulation of engine noise.

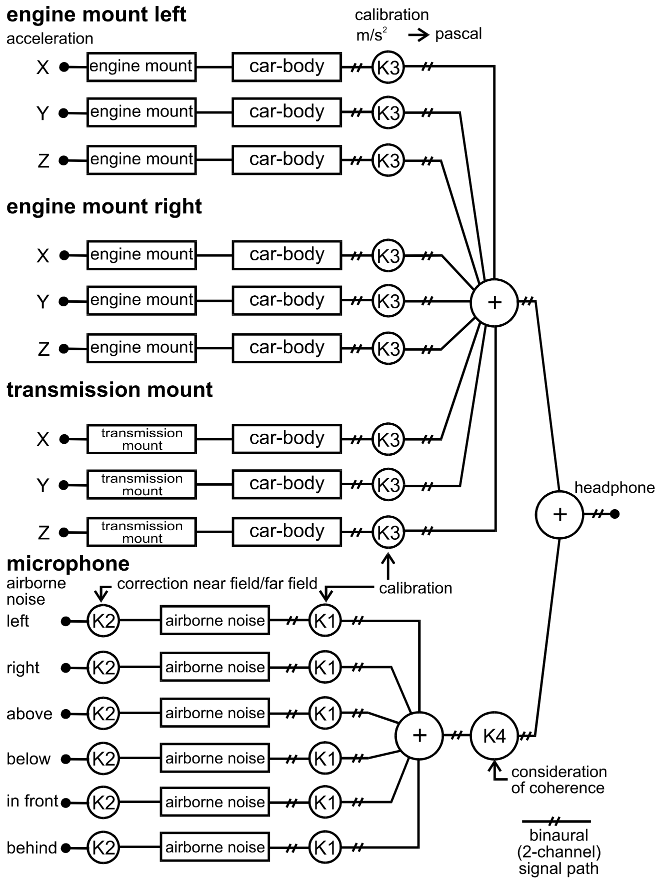

Fig. 8: Binaural Simulation

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

In parallel, the measured acoustic data at the engine (normally at 1 m distance) 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).

Additionally, the re-calculation form the far field microphone positions during engine test rig measurements to the nearfield positions in engine compartment is necessary. In the approach presented this is done by a correction considering the SPL at different distances and the delay time.

This leads to that interior noise share which is caused by airborne excitation.

The resulting binaural signal can be used to compare the baseline situation with the simulation results both by acoustic reproduction and by analysis.

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. 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. 9 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.

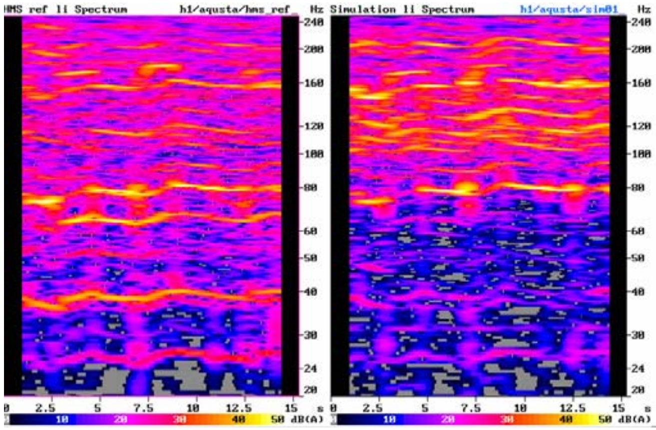

Fig. 9: Comparison of baseline and simulation

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. 9 the following figures represent particular components. This allows the determination of annoying noise shares and the responsible sources and transfer paths.

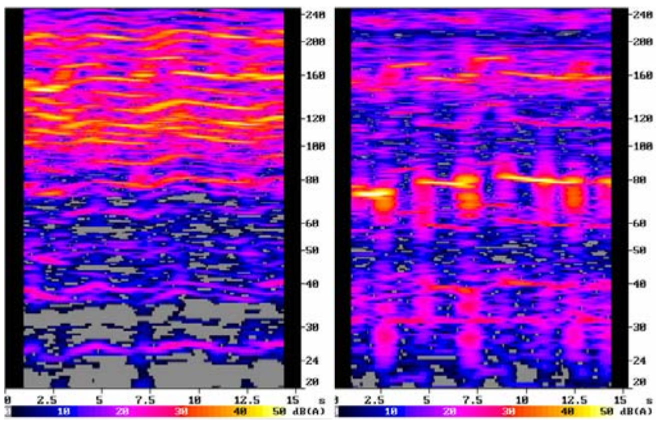

Fig. 10: Comparison of structure borne (left) and airborne noise contribution (right)

Fig. 10 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. 11.

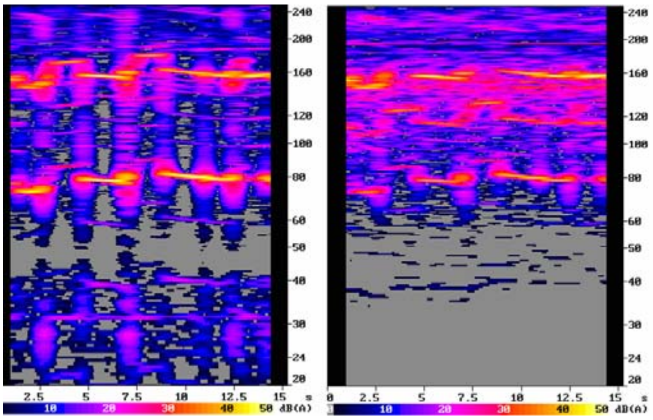

Fig. 11: Comparison of airborne noise contribution by exhaust system (left) and engine (right).

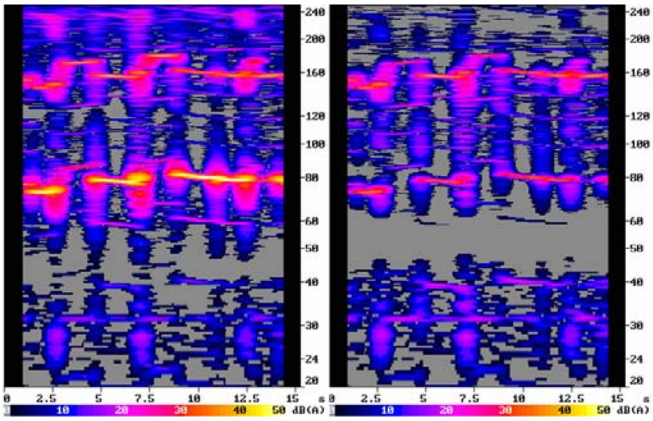

Fig. 12: Airborne noise contribution by left and right tail pipe

For further examination, in fig. 12 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.

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.

5. SUMMARY

The use of the "Binaural Hybrid Model" including the "Binaural Transfer Path Analysis" was described for applications in automotive industry. It has been shown that this approach allows the determination of structural elements and single transfer paths relevant for particular (annoying) noise shares in the interior of vehicles. The transfer to sound design tasks not only is possible, but means an origin aim. The focus has been set on a solution useful for daily business purposes which primarily includes the simplification of measurements.

6. LITERATURE

/1/ P. Glibert, N. B. Møller, E.-U. Saemann,
Noise Path Analysis as a trouble shooting tool
ISMA23, 1998, Volume 2, page 1039 – 1046

/2/ U. Fingberg, T. Ahlersmeyer
Geräuschpfadanalyse einmal anders – Ein neuer Ansatz aus der Praxis –
3. Fahrzeugakustik-Tagung
"Geräuschminderung in Kraftfahrzeugen" 10./11. März 1992, Haus der Technik, Essen

/3/ K. Genuit, N. Xiang
Binaural "Hybrid"-Modell for Simulation of Engine and Wind Noise in the Interior of Vehicles
SAE'97, 20.-22.05.97, Traverse City, Mi, USA