The sound quality of vehicle interior noise: a challenge for the NVH-engineers

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Abstract: The sound quality of vehicle interior noise has become a very important task for the acoustic engineers since more than 20 years. As vehicles become more and more quiet, the customer's sensitiveness for the acoustical comfort increases. On the one hand, no disturbing noises should be heard and on the other hand, the perceived sound quality, for example from the powertrain, should fulfill the expectations of the listener with respect to the sound design. The development of a good sound quality is in conflict with other targets. The development time of a new car has to be reduced and the production costs have to be lower, the total weight of the car should not increase – without any negative influence on the sound quality. For the acoustical engineer it becomes important to know what kind of tools are available to measure, to analyse and to describe sound quality on the one hand and how to improve it on the other hand.

Keywords: psychoacoustics; binaural listening; acoustical comfort; vibration; transferpath analysis; simulation; prediction of sound quality; sound design.

Reference to this paper should be made as follows: Genuit, K. (2004) 'The sound quality of vehicle interior noise: a challenge for the NVH-engineers', *Int. J. Vehicle Noise and Vibration*, Vol. 1, Nos. 1/2, pp.158–168.

Biographical notes: Dr.-Ing. Klaus Genuit was born in Düsseldorf in 1952. He studied electronic engineering from 1971 to 1976 and economics until 1979 at the Technical University of Aachen. Concurrently, he attended the institute of 'Elektrische Nachrichtentechnik' to investigate different psychoacoustic effects of human hearing. He received his Ph.D. in 1984 based on work with 'A Model for Description of the External-Ear-Transfer-Function'. For the next two years, he led the psychoacoustic working group dealing with binaural signal processing, speech intelligibility, hearing aids, and telephone systems at this institute. In cooperation with Daimler Benz (Stuttgart), he developed a new, improved artificial head measurement system for the diagnosis and analysis of sound. In 1986 he founded the company HEAD acoustics GmbH which is a leading contributor in areas of binaural signal processing, analysis, auralization of virtual environments, NVH analysis, and telecommunication measurements. HEAD acoustics now has about 100 employees worldwide.

1 Introduction

The passenger of a vehicle has to be seen as part of a vibro-acoustical system. Consequently, the subjective judgement of pleasantness or sound comfort is influenced by both sound and vibration. For a task-orientated proceeding in sound design it is absolutely necessary to consider these aspects. As suitable measurement and analysis technique for the acquisition of the acoustical situation, binaural technology is normally used in the automotive industry for solving tasks related to sound quality. For the consideration of the vibro-acoustical situation in vehicles the extension of the binaural technology is necessary. Here, multi-channel measurement systems may be used that allow the recording of acoustical and vibrational data simultaneously. The combination of artificial head and conventional measurement technology allows the determination of correlations between passenger's exposition and the resulting judgement.

1.1 What is sound quality?

Although the term sound quality today is used very commonly, its meaning often seems to stay diffuse. Sound quality can be defined as the degree to which the totality of the individual requirements made on an auditory event are met. Acoustic quality comprises three different kinds of influencing variables: physical (sound field), psychoacoustic (auditory perception), and psychological (auditory evaluation) [1]. Therefore it is a multidimensional task. Physical and psychoacoustic measurement procedures alone do not allow a general and unequivocal definition of acoustic quality. This is because listeners primarily classify perceived auditory events in terms of their experience, expectations and subjective attitudes. The acoustic characteristics of a vehicle today mean an integral part of product identity. They influence significantly customer's decision. Due to the reached technical state of art the reduction of sound pressure level often does not lead to subjectively perceived improvements. Sometimes they are even contrary to essential characteristics of a product, i.e., if significantly low levels do not represent the power of a sporty car.

For current and future needs the vehicle sound must act as a criterion for distinction that supports the positive image of a car. In this context the following characteristics of sound are useful:

1. Firstly, sound is informative. It includes information of quality, functionality, danger, and environment
2. Secondly, sound implies a certain image, such as luxury, sportive or cheap
3. Thirdly, sound may identify similar to the optical impression. In this context it may be used for corporate or product sound purposes

In consequence, sound quality is an essential part of vehicle quality.

1.2 Human hearing

Human hearing differs in many respects from conventional sound measuring systems: The outer ear is a directional filter which changes the sound pressure level at the ear drum by +15 to –30 dB, depending on frequency and direction of sound incidence. These filtering properties arise through diffraction and reflections caused by the outer geometry (pinna, head, shoulder and torso) which are dependent on direction and on resonances which are independent of direction. In contrast, a standard measuring microphone has a linear, frequency independent response characteristic for all directions of sound incidence.

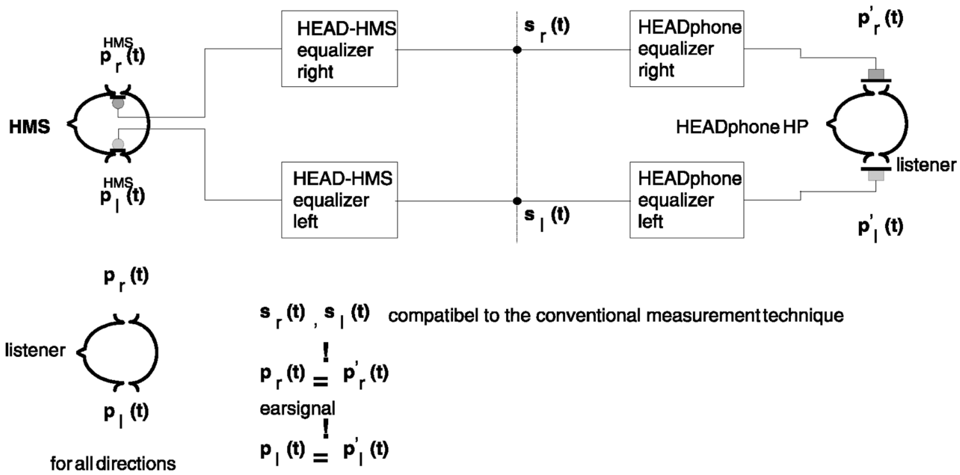
1.3 Artificial head

Objective acoustic measurement methods used up to the present time have not provided sufficiently useful algorithms for evaluation of individual sources in a complex sound field. An artificial head measurement system [2] that emulates human hearing as the 'receiver' has been introduced for the judgement and analysis of sounds. Such a system as shown in Figure 1 has transmission characteristics comparable to human hearing that can be calibrated. The analyser is not just a simple 1/3-octave or Fast Fourier Transform analyser, but one with high resolution in time and frequency domains and with a high dynamic range comparable to human hearing.

Figure 1 Artificial head measurement system with mathematically definable geometry, calibratable transmission characteristics and built-in equalizers [2]

The principle idea of head-related transmission is shown in Figure 2. Two microphone signals recorded with the artificial head, are equalized to obtain signals compatible with conventional measuring microphone output. For subjective evaluation of sound events these signals are played back using headphones equalized by correction filters. This creates the same signals in the ear canal of the listener as if the listener had been in the original sound situation measured by the artificial head.

Figure 2 Principle of head-related transmission



The binaural measurement method can be used in all fields where acoustic emissions (acoustic energy radiated by a source) and immissions (acoustic energy incident on a receiver) must be determined or where sound serves as an indicator of comfort, quality and safety. This technology is not an alternative, but an important extension of existing sound measurement techniques. In complex sound situations which cannot be defined in terms of A-weighted sound pressure level alone, aurally-equivalent measurements can be used for gathering additional data, necessary for an objective evaluation of the sound event.

1.4 Signal processing

A further difference can be explained by the evaluation of sound signals in the hearing. While evaluations by means of conventional acoustic measuring techniques are made with a simple A-weighting, human hearing has more complicated level-dependent evaluation mechanisms. A sound impression is not only determined by the sound pressure level, but also by psychoacoustic properties such as loudness, sharpness and roughness. Due to the so-called pre-, post- and simultaneous masking effects of human hearing, there can be different sound impressions at an unchanged A-weighted sound pressure level depending on the temporal structure of the signals and the spectral distribution. The measurement procedure for loudness takes into account the distributions of critical bands in the human hearing. Loudness does not only depend on the sound pressure level, but as well on the spectral composition of the sound. The measurement of loudness (unit: sone) is a considerable approach towards the correct human hearing equivalent sound measurement.

Sharpness (unit: acum) depends on the spectral composition. A sound is judged to sound sharper and thus more annoying, if the high-frequency spectral components increase in comparison with the low-frequency ones. The sound with higher sharpness is judged to be more unpleasant and more annoying.

Roughness of signals with strong temporal structure is caused by amplitude and frequency modulations, i.e., quick changes in level and frequency. Due to the filtering properties of the outer ear each change in frequency results at the same time in a more or less strong change in amplitude. A modulated signal has a higher roughness and is considerably more unpleasant independent on the A-weighted sound pressure level.

In addition to these physically describable signal properties the sound quality is also influenced by the so-called masking properties of human hearing. If, e.g., there are two sound sources with a similar frequency spectrum heard at the same time, there is the so-called simultaneous masking, i.e., the louder signal is masking the lower signal and just the louder one is heard. If, however, the spectral compositions of the sounds differ, human hearing clearly perceived two sounds.

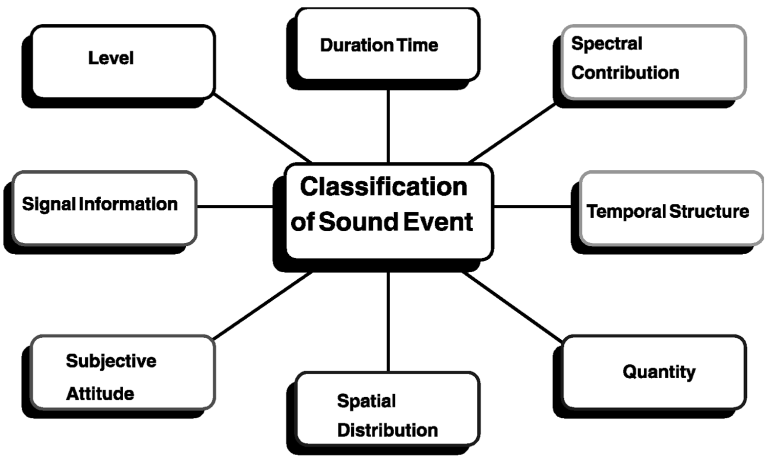
Another characteristic of the human hearing is the presence of two auditory channels. It allows spatial discrimination essential for pattern recognition in conjunction with directional hearing, selectivity and suppression of noise. This binaural signal processing is essential for everyday life, e.g. speech communication in a noisy environment is only possible through binaural signal processing.

Human hearing involves very complex signal processing, but it has very short memory. By accurately recording, digitally storing and reproducing a sound event, the comparative human ear equivalent judgement of different sounds becomes feasible and can be documented. The psychoacoustical properties of human hearing determine the subjective impression of sound events such as noise annoyance [3].

1.5 Sound evaluation

Aurally-equivalent sound measurement technology is concerned with objectively definable parameters that relate to human perception. Evaluation of a sound event by the 'communications receiver' in human hearing is influenced by numerous parameters. These are diagrammatically summarized in Figure 3.

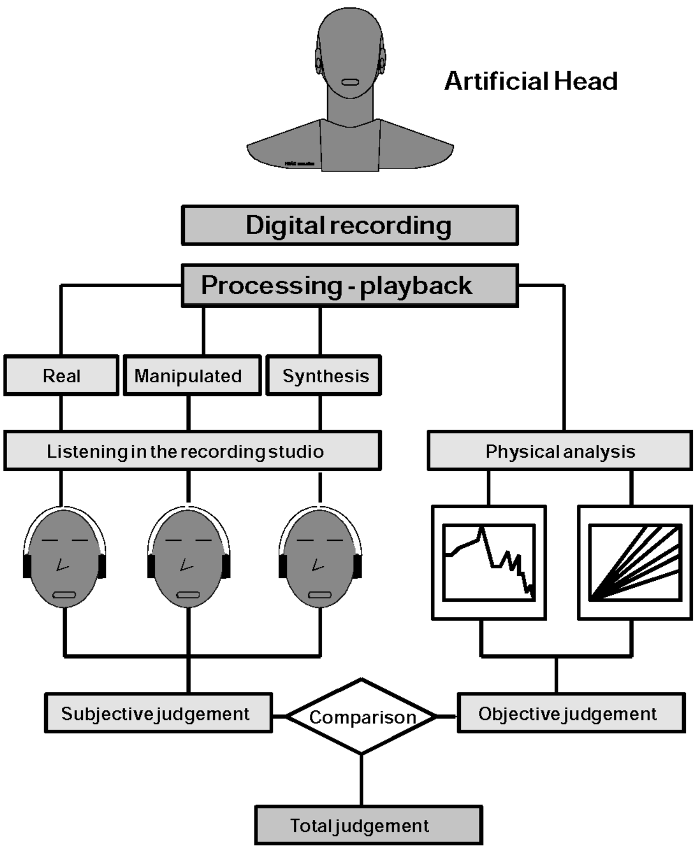
Figure 3 Parameters relevant for the classification of sound using human hearing



It shows that a sound event cannot be evaluated on the basis of a single dimension. Level is only one of numerous parameters which play a part in the evaluation of a sound event by a person. These parameters are basically of two kinds: subjective (psychological) and objective (physical and psychoacoustic). Subjective parameters are best determined statistically due to the variability of human responses to a particular situation. It is difficult to derive precise parameters from them. This underlines the need for objectively based and aurally-equivalent sound measurement technology [4].

Figure 4 illustrates how recorded information from an artificial head can be evaluated with the help of digital signal processing to identify and eliminate annoyance. Binaural digital signal processing within a computer controlled measuring system allows input, storage and processing of an event and listening to selected segments which can be continuously repeated without audible artifacts. The measuring system displays both right and left ear signals in the time and frequency domains. The sound segment sample can then be directly manipulated with the result being displayed and reproduced by headphones in 'real time'. Euphony is evaluated as part of the analysis; that is calculations of roughness, sharpness, pitch and timbre as well as loudness, which take into account the ear's pre-, post- and simultaneous-masking properties.

Figure 4 Working in a recording studio



2 Source and transferpath identification

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 20 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. This approach [5] 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.

2.1 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 including intake and exhaust system. The vibration are transmitted through the engine mounts into the chassis. In dependence on the engine stiffness and the chassis inheritance 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.

2.2 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.

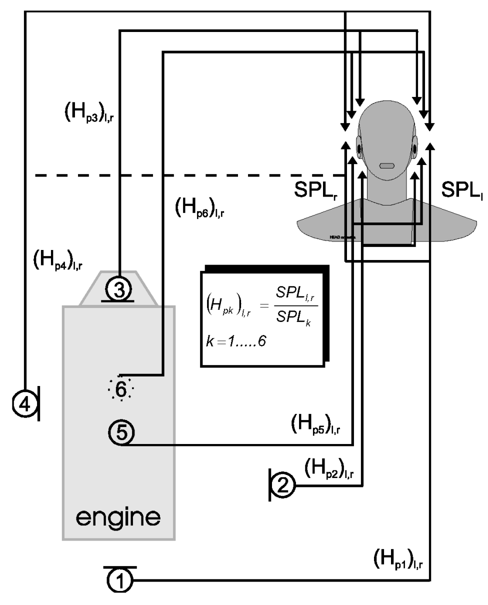
A suitable proceeding should allow the determination of qualitative differences in the acoustic situation. For practical reasons it is required to carry out all measurements at a complete vehicle. For simulation purposes the data are combined with those of measurements at engine test rigs using standard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

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 20 kHz using a microphone arrangement similar to the engine test rig configuration (Figure 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.

Figure 5 Measurement of airborne noise transfer paths



Following binaural acoustic measurements under 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:

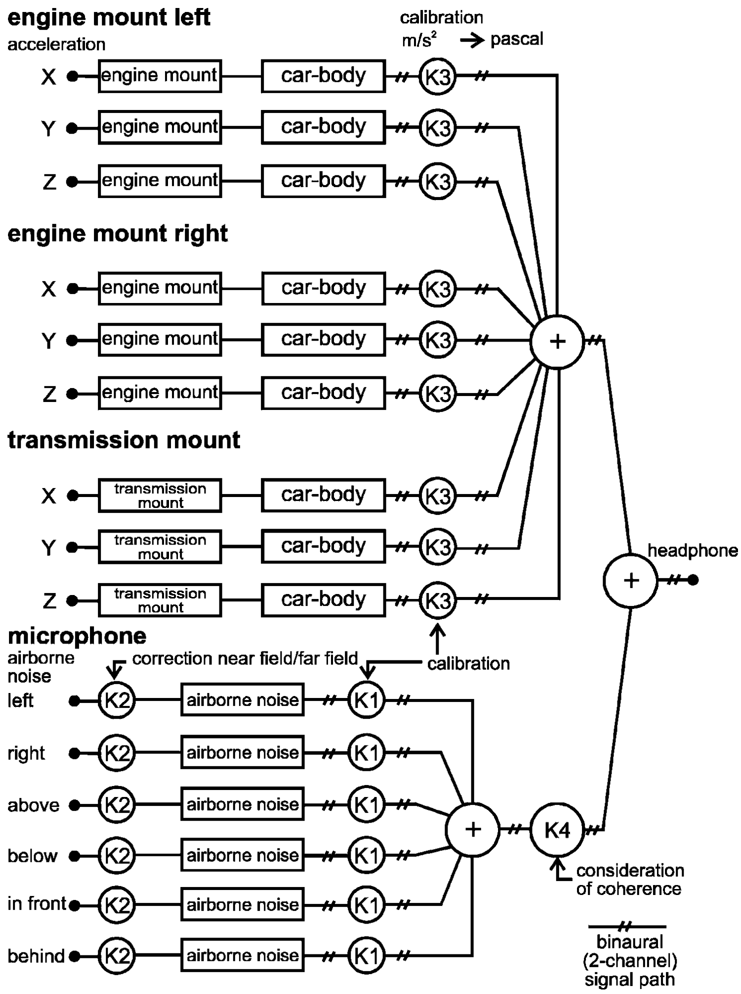
- mounts' stiffnesses are low
- stiffness of car-body is high
- the system can be seen as a minimal-phase one
- dynamic characteristics are considered as linear in the frequency range interesting for acoustical purposes.

In this case both the amplitude of the dynamic behaviour 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.

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 Figure 6 for the simulation of engine noise.

Figure 6 Binaural simulation



The triaxial accelerations at all engine mounts at 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:

1 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

2 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

3 With both the measurement and simulation results the ‘binaural hybrid model’ may be fine-tuned as a preprocess for further simulations. The latter uses 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

1 to determine and auralize the influence of modifications at components on the interior noise

2 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

3 to investigate the effect of various engines (and/or exhaust/intake systems) on the interior noise.

3 Summary

The combination of an artificial head with multi-channel measurements and improved analysis procedures allows the efficient examination of NVH-problems in automotive industry. The orientation towards the subjective feeling and judgement means an important precondition for transferring the term sound quality to practical solutions. Hence, sound and vibration should not be considered as disturbing elements in the future regarding the NVH-comfort, but they could be used to develop an acoustical and vibrational environment which influences customer’s judgement positively. Additionally, it could enable automobile companies to create sounds which imply a high product quality and help them to stand out against competitors.

Working on sound quality requires a multi-dimensional view and fundamental expert knowledge. Although discussing this topic may seem easy, the derivation of suitable descriptors and task-oriented analyses always means a challenge. To simplify the solution process several tools are available that have been described in the paper. It has to be considered that they only support expert's work – but they cannot replace it.

In the future, the integration of sound quality evaluation into the development process means an important requirement and includes the need of engineers which can handle the several domains of sound perception.

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