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DESCRIPTION OF BROADBAND STRUCTURE-BORNE AND AIRBORNE NOISE TRANSMISSION FROM THE POWERTRAIN

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ABSTRACT - Binaural Transfer Path Analysis (BTPA) was originally developed for assessing the binaural contributions of individual vehicle noise paths. It is a powerful modeling tool enabling engineers to explore noise transfer mechanisms by distinguishing between excitation source strengths and the transfer behavior of individual elements. The method is well-known for powertrain noise analysis, including point-coupled structure-borne source paths and identified airborne source paths to a receiver location. Binaural Transfer Path Synthesis (BTPS) is the process of creating listenable vehicle interior noise data based on a BTPA model, also allowing for modifications.

Modern methods of combustion (TDI, CDI, fuel direct injection etc.) in combination with new generations of valve trains and more light-weight materials in engine construction have produced changes in the temporal and spectral behavior of primary oscillation factors. As a consequence, the in-car noise produced by the engine is being determined more and more by higher frequency components. The methods used in Binaural Transfer Path Analysis and Synthesis are now more frequently confronted with limitations which can only be overcome by detailed observation of the various influencing variables. New, future-oriented methods for this purpose are described in the project at hand.

Engine noise transmission fundamentally occurs in two ways, which have to be examined separately: a) the structure-borne path which is stimulated by the engine mountings and b) the airborne path which is fed by the direct sound radiation of the engine. For both paths, improved models which are traceable in signal and system theory are presented and their methodology is described. Starting by describing and measuring the source properties and transfer functions as exactly as possible, we arrived at an extremely simplified yet adequate model version of the complicated structure.

An especially important improvement of the structure-borne transfer paths we introduce here is the description of the mechanical interfaces via complex four-pole parameters. Considering airborne sound transmission, we are reducing the in-car source measurement that was previously mandatory by describing the engine with an alternative source model which could be highly simplified through multi-pole source synthesis and which can be derived from test-bench measurements. Using this simple model, the user receives a tool by means of which changes in transfer paths (e.g. the influence of the engine mounting) can be modeled in a theoretically correct way and the results can be made audible immediately.

1 INTRODUCTION

Based on the demands of the automotive industry, Binaural Transfer Path Analysis and Synthesis techniques have been developed for optimizing sound quality in vehicles at an early stage of development. Frequently, the combustion engine in combination with intake and exhaust systems (powertrain) are, for various driving conditions, the dominant noise sources with respect to interior noise. Engine noise transmission fundamentally occurs in two ways which must be examined separately: a) the structure-borne path which is stimulated by the engine mountings and b) the airborne path whose source is the direct sound radiation of the engine. For structure-borne noise, transfer functions from the engine mount to both ears are measured reciprocally for each individual noise path. For airborne noise, acoustic transfer functions are determined similarly (Fig. 1).

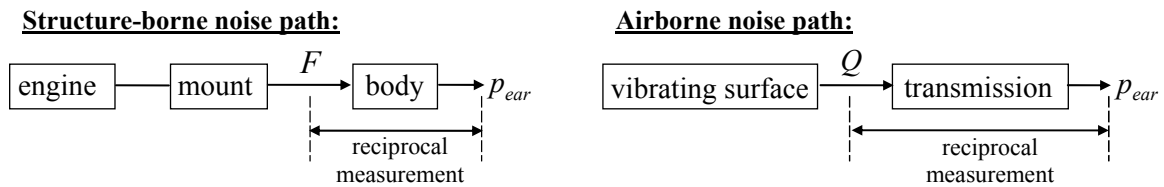


Fig. 1: Transfer functions used for BTPA

Starting by describing and measuring the source properties and transfer functions as precisely as possible, we arrive at an extremely simplified yet adequate model of the complicated structure [1].

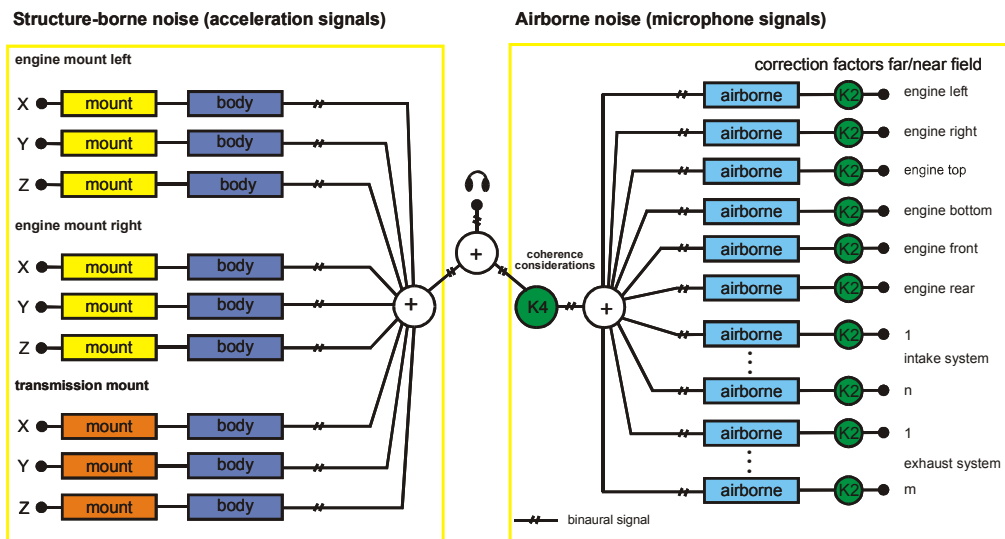


Fig. 2: Example of a BTPS model, separated for structure-borne and airborne sound paths. Frequency-dependent correction factors for airborne sound paths are applied to consider coherence effects at low frequencies where the engine compartment acts as a pressure chamber, or in the case of far-field measurements at an engine test rig (1 m distance), taking into account distance-dependent level differences and different room acoustics.

Binaural Transfer Path Synthesis (BTPS) is the process of synthesizing interior noise by combining selected noise paths (Fig. 2). Each individual path or combination of paths may be auditioned independently, in order to assess their respective impact on the overall sound quality. The contribution of individual paths is calculated by filtering the input signals with the corresponding transfer functions. Paths may be modified to simulate countermeasures and their effect on the interior noise. Operating data measured on different sources, such as an engine test rig, may also be placed in the model.

For engine and transmission mounts, vibration signals in all three directions (x, y and z) are considered. In general the interface between source signal and transfer function is defined at the engine mounts. In the past, the velocity v_{es} at the engine side of the engine mount was measured and linked with the engine mount transfer characteristic (v_{bs} / v_{es}), the input impedance of the body $Z_l = F / v_{bs}$ and the acoustical transfer function $ATF = (p_{ear} / F)$, in order to get the sound pressure p_{ear} at the driver's ears:

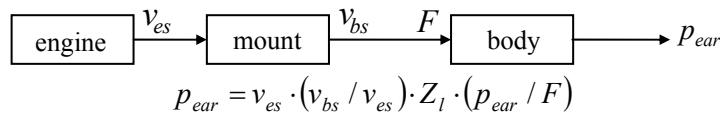
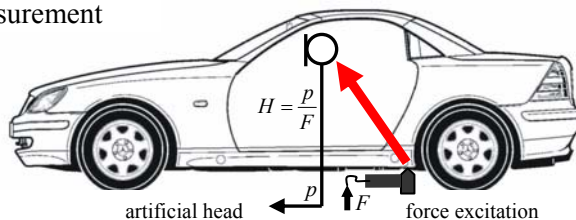


Fig. 3: Previous treatment of structure-borne path

The upper part of Fig. 4 illustrates the general principle of direct measurement of transfer functions used in the past. Determining binaural vibro-acoustic transfer functions requires excitation with a calibrated impact hammer at various positions of interest, as well as simultaneous recording with an artificial head in the vehicle interior. The excitation in the engine compartment at the body side of the engine mounts, necessary for our application (not shown in Fig. 4), is sometimes difficult because of space limitations.

Direct measurement



Reciprocal measurement

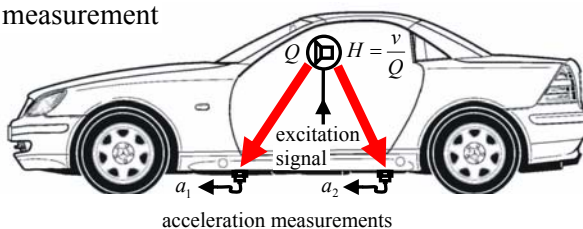


Fig. 4: Comparison of direct and reciprocal measurements (left), and a binaural sound source (right) with additional low-frequency cabinet for frequencies below 200 Hz. The geometry of the head is quite similar to the artificial head used for interior noise measurements. The directional patterns of source and receiver are the same: the basic requirement to apply the reciprocity method [2],[3].

The advantages of taking reciprocal measurements of acoustic transfer functions, shown in the lower part of Fig. 4, are evident: First, significant time is saved, since all paths can be measured simultaneously. Second, less space is required for sensors than for sources. Thus the measurement positions can be chosen almost without restriction, leading to higher accuracy. For the reciprocal method the measurements of the ATF can be carried out at the position of the triaxial accelerometers, whereas the impacts for the direct measurements must be applied in the vicinity of the accelerometer. Thus additional errors may occur, especially toward higher frequencies. However, in general, the results of direct and reciprocal measurements agree well.

An especially important methodology improvement for structure-borne transfer paths that we introduce here, is to describe the mechanical interfaces via complex four-pole parameters. The goal of these efforts is to divide each transfer path into partial structures taking into account the coupling between the subsystems. Each subsystem which can be considered a point-to-point connection (single input – single output) can be modeled by input, transfer and output impedances (Fig. 5). This requirement is fulfilled for most engine mounts. If only one component is modified, the simulation only needs to be performed for the modified substructure rather than for the entire transfer path.

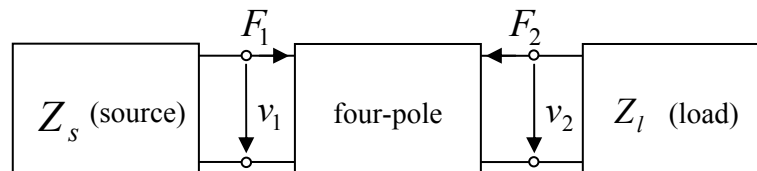


Fig. 5: A four-pole system with source and load impedance

This method allows engine test rig measurements for simulating structure-borne contributions in cars without installing the separately-measured mounts inside the car, taking into account the different impedances of body and test rig. The description of a component using four-pole parameters is independent of the load. Knowing the impedances of the car at the engine mount positions (engine and body side) and the four-pole parameters of the engine mount, a complete simulation of the signal transmission from engine to body and finally to the driver's ears can be carried out. Any combination of test rig data and vehicle data is possible.

2 APPLICATION EXAMPLE OF TRANSFER PATH ANALYSIS

The interior sound of a passenger car caused by a 4-cylinder gasoline engine has been analyzed. All measurements were carried out on a four-wheel-driven chassis dynamometer in an anechoic chamber. The interior noise synthesis requires the following measurements:

1. Measurements under running conditions to determine the transfer characteristics of the engine mounts (v_{bs} / v_{es})
2. Impact measurements to obtain body impedances $Z_l = F / v_{bs}$
3. Impact measurements to determine acoustical transfer functions (p_{ear} / F) from the engine mount positions at the body sides to both ears of the artificial head on the driver's seat, and alternatively, reciprocal measurement
4. Measurement of the airborne transfer functions from different positions in the engine compartment, at the intake system and at the exhaust pipe, to both ears of the artificial head on the driver's seat
5. Measurement of the excitation signals under running conditions serving as input signals for the binaural interior noise synthesis

2.1 CONTRIBUTION OF STRUCTURE-BORNE PATHS

The measurements of engine mount characteristics and body impedances are used to calculate the transfer impedances, describing the relation of induced force at the body side of the engine mount to the velocity at the engine side of the mount. The impact measurements used to determine the body impedances can be used additionally to determine acoustical transfer functions, if the artificial head signals are recorded at the same time as force and velocity at the location of the impacts. There are four different connecting points, resulting in 12 different structure-borne transfer paths (three directions x, y, z) with 12 transfer impedances and 12 acoustical transfer functions for each ear.

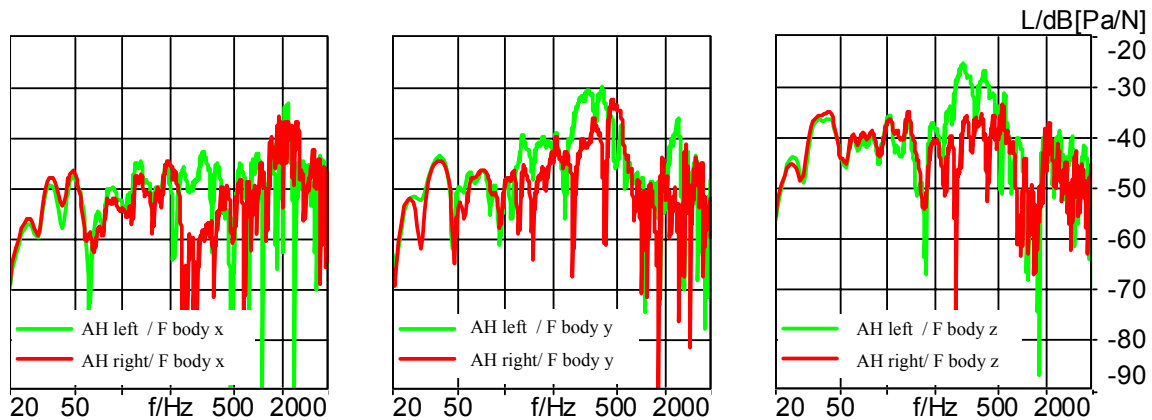


Fig. 6: Acoustical transfer functions, measured at one engine mount for x-, y- and z-direction

Fig. 6 shows as an example the three (unsmoothed) acoustical transfer functions of one specific engine mount for the left and the right ear. In addition, the acoustical transfer functions were measured reciprocally (Fig. 7 shows smoothed versions of the ATF for the z-direction) by means of the binaural volume velocity source shown in Fig. 4.

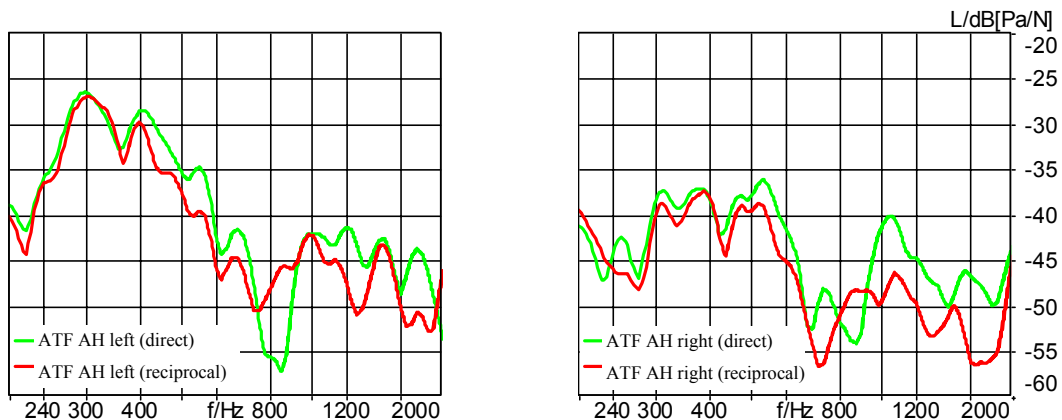


Fig. 7: Comparison of direct and reciprocal measurements of the ATF (z-direction, smoothed)

2.2 CONTRIBUTION OF AIRBORNE PATHS

The airborne transfer functions are measured by relating the artificial head recordings with the microphone signal in the vicinity of the loudspeaker used for excitation (or using the reciprocal approach shown in Fig. 4). Microphone signals in the near field of assumed sound sources provide the input signals for the airborne noise transfer synthesis. All excitation signals (acceleration and sound pressure) are simultaneously measured.

The novel approach presented in Chapter 3 using multi-pole substitution of the engine's radiation to simulate the airborne sound paths was not used here due to the state of the research, that was too new for application.

2.3 VALIDATION

The new method is validated by a virtual exchange of an engine mount in the Binaural Transfer Path Synthesis. Therefore the following steps must be fulfilled:

1. Determine the four-pole parameters of the new engine mount
2. Consider these parameters for synthesizing the structure-borne path
3. Install the new mount in the passenger car
4. Measure the interior noise and compare it with the synthesized noise

For the validation, the left engine mount was exchanged with a substantially stiffer mount having the same geometrical properties. The dynamic stiffness of the original and the exchanged mounting are 115 N/mm and 300 N/mm. The virtual exchange requires considering the coupling between the four-pole “engine mount” and the connecting subsystems (Fig. 5).

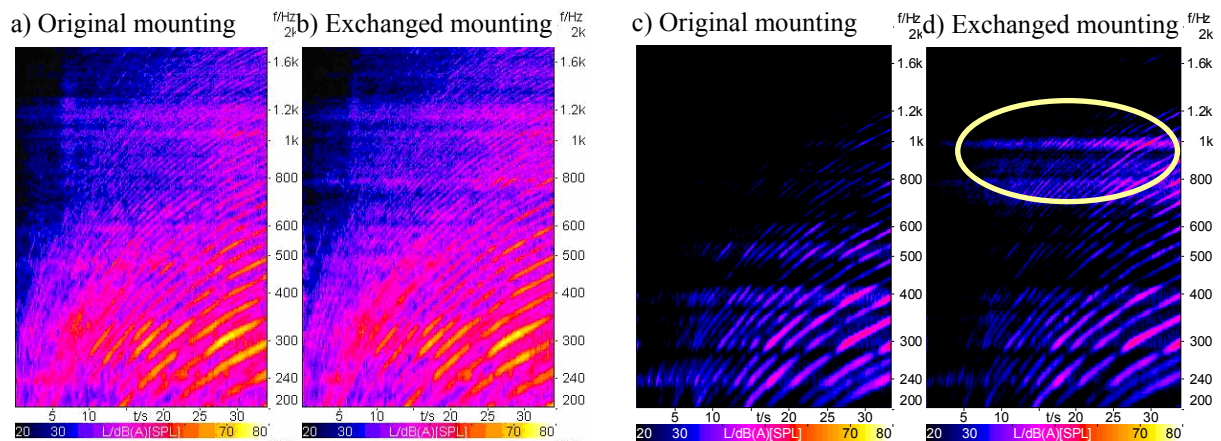


Fig. 8: Consequence of the modified mounting with respect to the interior noise; a, b: measurement of the left ear-signal of a run-up at full load; c, d: noise components of the left ear signal, caused by the left engine mounting (component in z-axis of the structure-borne sound)

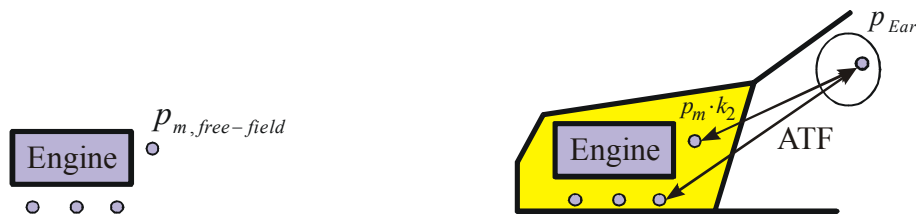
After determining the four-pole parameters in the three directions, the stiffer engine mount was installed in the car. Figures 8 a, b show the comparison of interior noise measurements using a run-up at full load for the original and the exchanged mounting (left ear of artificial head recording). In spite of the substantially higher stiffness and the corresponding higher transmission of the exchanged mounting, only a minor effect on the interior noise is observed (Figures 8 a, b). The binaural interior noise synthesis delivers the same results. Moreover, the BTPS allows considering a single transfer path more in detail. For example, the contribution of the structure-borne path of the left engine mount can be analyzed and auralized. Of course, this result is not achievable by any direct measurement. Figures 8 c, d show the most dominant noise share responsible for the level increase due to installing the stiffer mount. For this path a level increase of up to 15 dB in the frequency range between 700 Hz and 1200 Hz is predicted.

In this particular case the influence on the overall interior noise is slight, because of the superposition of many different noise shares, despite the significant change of one path. Analysis of the measured acceleration confirmed the influence of the higher transmission. Thus, the measured and predicted results agree very well. The previous methodology, based on the in-situ damping characteristic of the engine mount without considering coupling effects, overestimates the influence of the exchange by approximately 10 dB at higher frequencies.

After the measurements with the exchanged mounting, the original mounting was reinstalled. A control survey showed similar results compared to the first measurements with the original mounting. Thus the observed changes of the interior noise can be traced back to the modifications of the engine mount, and not to modified conditions caused by different installation situations.

3 GENERALIZED AIRBORNE SOUND PATH CHARACTERIZATION

3.1 THE TRANSFER PATH FOR AIRBORNE SOUND



*Fig. 9: Conventional definition of the air borne sound path
near field sound pressure in free field on a test bench correction of the near field pressure considering the final installation, for BTPS*

The connection between source and transfer path for airborne sound is not as well-defined as for the structure-borne sound path. In Fig. 9 the typical approach for measuring airborne sound contribution is depicted. Usually, the sound is recorded with five to six microphones in the near field of the engine (left figure). The same positions are taken as the input locations for the ATFs that can be measured in the aforementioned reciprocal method (right figure). Due to the air volume in the engine compartment and the modal behaviour of this cavity at higher frequencies, all separately-recorded sounds (the microphone signals) are mixed and it is very likely that the sources cannot be localized from the driver's or co-driver's position. Therefore the method shown in Fig. 9 is misleading with respect to the contribution of the different microphone signals that are picked up in a free field situation. Nevertheless, with correction spectra $k_2(f)$ it is quite possible to achieve good agreement between real sound recordings and BTPS-simulated sound fields in practice. Unfortunately, the correction spectra are specific for a particular combination of engine and car body. Therefore the exchange of an engine requires the re-measurement of all: the sounds on the test-bench, the ATFs, and the correction spectra, which can only be accomplished by assembling the entire car.

The new method described here aims to overcome these disadvantages by substituting the sound source (engine) with a simplified but nevertheless accurate model which subsequently is placed in a second model for the engine compartment. The sound field is calculated by numerical methods (FEM: finite element method, BEM: boundary element method) and provides input data for the ATFs which again are available from measurements.

The multi-pole synthesis in principle is a known method [4], [5] that is used to substitute a sound source, generating a sound field of any complexity and shape, by an arrangement of multi-poles that are chosen accordingly to create the same sound field within certain boundaries. Each multi-pole is an array of monopoles with a common origin but different phase relation, e.g. a dipole can be regarded as two monopoles with same magnitude and 180° phase difference. To model distributed sound sources a number of multi-poles can be arranged side-by-side. The contribution (i.e. the weight) of each multi-pole is computed by an optimization algorithm, taking into account the measured sound pressure of the real sound field.

3.2 PROCEDURE FOR MODELLING THE ENGINE

In a first step (Fig. 10 a) the sound field of the engine under investigation is recorded with N microphones at all operating conditions. The microphones should be placed at far-field positions (1 – 2 m) as well as in the near field. All microphone signals are recorded synchronously, thus allowing the complex derivation of the spatial radiation. The next step is to place an appropriate number of multi-poles inside the engine's envelope and to remove the engine. With the results from the measurement it is now possible to compute the weights for each multi-pole and to verify if the multi-pole sound field creates an equivalent sound pressure at the positions of the microphones (Fig. 10 b).

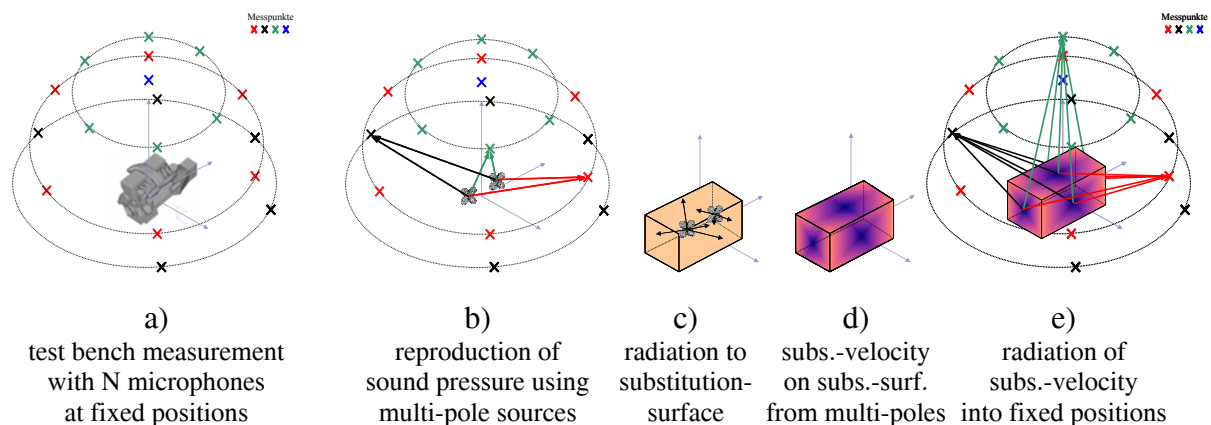


Fig. 10: Steps to synthesize the multi-pole field, and subsequent modelling of the radiated sound field of an engine, initially measured on the test bench, by substitution with a surface velocity created by the multi-poles on a simplified engine surface

Since the detailed engine cannot be used for numerical calculations, it is now substituted by a very simple structure with convex surfaces (Fig. 10 c). The velocity originating from the multi-poles at the locus of the substitution surface is then applied (embossed) to this surface (Fig. 10 d) to reproduce the original sound field (Fig. 10 e).

The comparison of the original sound pressure of the measuring microphones and the reproduction by BEM-calculation with the substitution velocity applied on the model-engine surface shows that the difference depends very much on the number of microphones used initially for the measurement and on the complexity and order of the multi-pole synthesis. It is obvious that the model can be improved by using *a priori* knowledge of the vibration modes of the engine and a subsidiary measurement of the surface velocity at certain points on the original engine. Nonetheless, the results achieved are promising and the method must be proven in practice.

3.3 ENTIRE MODEL FOR THE AIRBORNE SOUND PATH

The above-obtained velocity (on the substitution surface) now is used to excite the engine compartment. The sound pressure distribution in the cavity is computed using FEM and can be used as input for the airborne ATF derived from the BTPA.

The sound propagation from the engine surface to the driver's ears involves several substructures of the car body and, in comparison to the structure-borne sound paths, cannot be located at dedicated transmission points (like the mountings), but employs distributed surfaces like the separation wall between the passenger and engine compartments or the windshield. However, with respect to the desired 'general approach' of the model the interface between different subsystems must be robust against the exchange of parts in the chain. Therefore, the most demanding task of this model is the choice of the interface between the engine compartment sound field and the ATFs to the (co-)driver's ears. The current use of an arbitrarily chosen point (i.e. available for placing a microphone) anywhere inside the engine compartment creates several problems. The placement of the microphones is at random; the comparability of different cars and engines therefore is quite limited. Furthermore, the use of free-field measurements requires frequency-dependent corrections that in general can only be obtained for dedicated combinations of engine and car body.

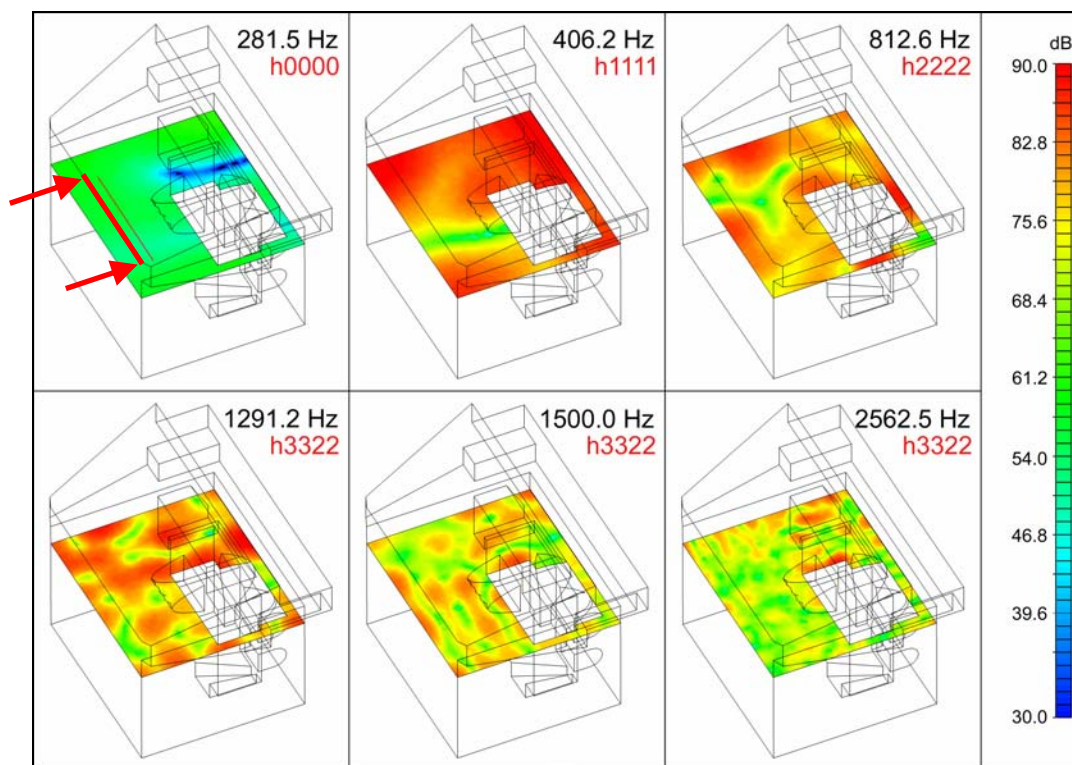


Fig. 11: Sound pressure distribution adopted by FEM-calculation in a simplified engine compartment with a 4-cylinder 1.4-l engine (arrows mark the line where frequency responses were calculated, see Fig. 12).

Fig. 11 shows the sound pressure distribution from FEM calculations. The excitation comes from the multi-pole synthesis carried out for a 4-cylinder engine of 1.4 litres. The damping of the cavity due to hoses and foam absorbers was taken into account by creating a lossy medium (air with damping constant $m=0.06$). For all frequencies shown here the sound field shows a statistical distribution depending mainly on the modal structure of the sound field. The location of particular sources is probably impossible. This proves that a dedicated replication of single sources is not required and not helpful for the identification of the connection nodes for the interface between sound-field and ATF.

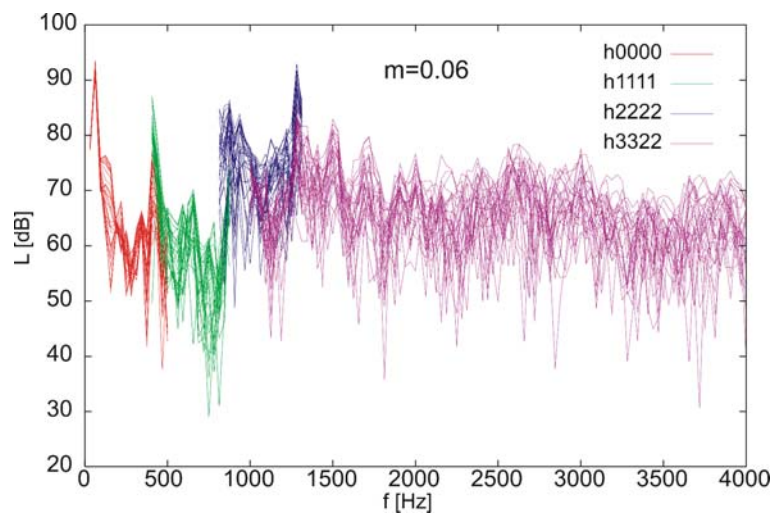


Fig. 12: Frequency response variation inside the engine compartment for identical excitation but with moving receiver position along a line of 70 cm length in front of the engine (refer to upper left figure in Fig. 11). Results adopted with FEM simulation.

These figures show only results for 6 single frequencies. A different plot is shown in Fig. 12, where sound pressure frequency response curves for identical excitation but with a moving receiving point were recorded. The receiving point (position of the microphone) was moved along a straight line of 70 cm length in front of the engine. It is quite clear that the average energy value for all curves lies at the same level, but the variation between minimum and maximum level shows a spread of up to 30 dB for almost any frequency. This again makes clear that the choice of a particular point inside the cavity to connect to the ATF is arbitrary.

The same situation can be found if the sound pressure distribution on the separation wall between engine and passenger compartment is computed. This is shown in Fig. 13 and again it is quite difficult to argue whether to favour one particular point on this surface over any other. The problem arises due to the nature of the connecting medium between engine velocity and car body which forms a multi-resonator with complicated modal structure, especially at higher frequencies.

Therefore the only meaningful and robust interface so far is the surface of the engine model itself. At one hand the definition of the interface with respect to geometry and energy flow is very clear. On the other hand the source is totally robust against a change of the environment since it is of no significance for the surface velocity if the engine runs inside the car, or on the test bench, or anywhere else.

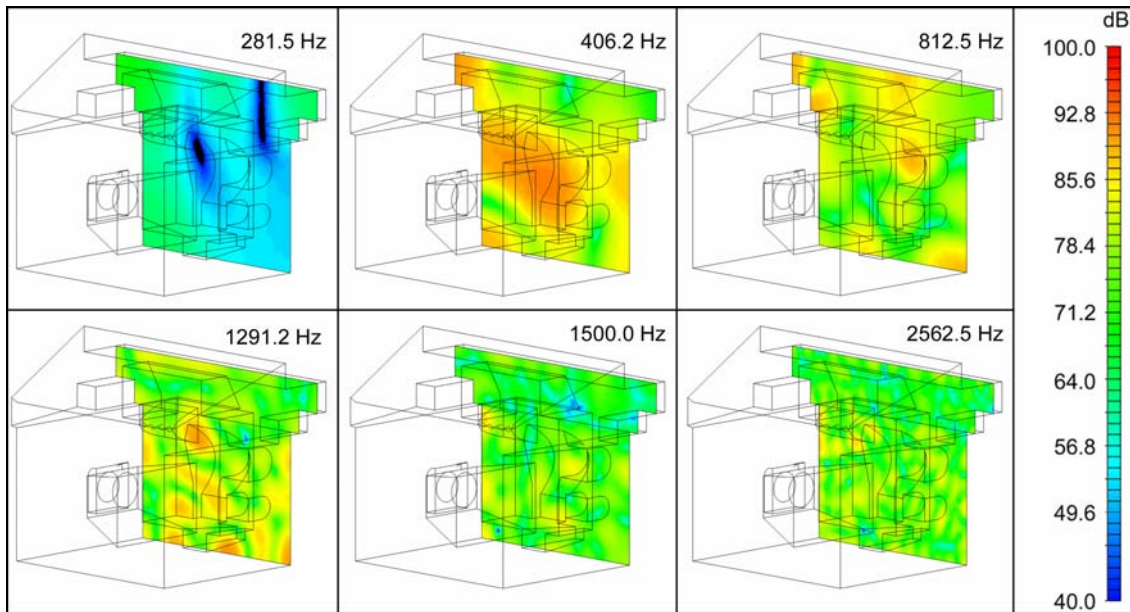


Fig. 13: Sound pressure level distribution on the compartment wall calculated for the same frequencies as in Fig. 11

This leads to the entire model for the airborne sound transmission which is presented in Fig. 14. It introduces a number of n channels (ATFs) that are used to connect the surface velocity to the sound pressure at the driver's ears.

One unsolved problem remains requiring further investigations, namely the question: which amount of the surface area and hence of the velocity must be taken into account to calculate for the input sound pressure of one particular ATF. It is the aim of future research to use numerical methods for a more general description of this missing link.

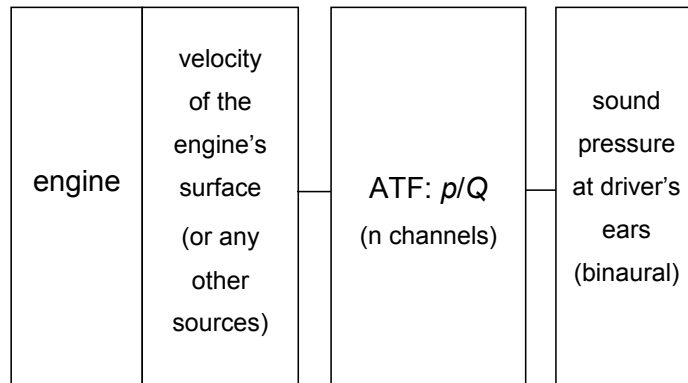


Fig. 14: Entire model for the airborne sound transmission using n channels with complex addition

4 CONCLUSIONS AND OUTLOOK

The results represent a considerable milestone with respect to acoustic simulation and auralization. BTPA and BTPS are tools for analyzing and optimizing the transfer mechanisms between various sound sources and the resulting sound perception inside vehicles. These techniques separate the source and transfer characteristics, permitting studies of selective countermeasures applied to a single component or path with respect to the perceived interior sound.

At present, the improvements of BTPA and BTPS based on the system-theoretical method of four-pole theory allow simulating the combination of different subsystems and enable the physically correct description of structure-borne transmission under different load conditions of the engine (test rig or vehicle measurements). Using these recently-developed techniques a significant reduction of laborious measurements with repeatedly-reconstructed vehicle prototypes is achievable.

Recent work is related to improving the source characterization for directly-radiated airborne sound using the multi-pole approach, and to developing a methodology for using data resulting from acoustical numerical simulation.

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