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Binaural transfer path analysis and synthesis (BTPA/BTPS) using sub-structuring techniques based on finite element analysis (FEA) and measurements

Roland Sottek and Bernhard Müller-Held
HEAD acoustics GmbH, Herzogenrath, Germany

ABSTRACT

Binaural **T**ransfer **P**ath **A**nalysis and **S**ynthesis (BTPA/BTPS) were originally developed for assessing the binaural contributions of individual vehicle noise paths. They are powerful modeling tools, enabling engineers to explore noise transfer mechanisms by distinguishing between excitation source strengths and the transfer behavior of individual elements. The methods used in BTPA and BTPS are now more frequently confronted with limitations which can only be handled by detailed observation of the various influencing variables. A promising method is to describe the mechanical interfaces via four-pole parameters. Using this technique, changes in transfer paths (e.g. exchange of engine mounts) can be simulated by a tool providing immediately-audible results.

INTRODUCTION

The methods of BTPA/BTPS have been developed and refined during the past decade. They have successfully been used for troubleshooting and sound design of engine-related vehicle interior noise. These tools enable exploring the causative mechanisms for noise transfers, based on measurements of excitation source strengths and the corresponding structure-borne and airborne transfer paths to a receiver position (e.g. the driver position). The engineer can analyze and listen not only to the overall sound comparable to a binaural recording of the vehicle interior sound, but also to components of the total noise transmitted via a single path or a combination of paths to identify the cause of a particular disturbing noise pattern [1].

The next step in a sound design process includes modifying noise and vibration sources and/or transfer paths. This paper will introduce a new extended BTPS approach allowing the engineer to predict the impact of particular structure-borne transfer paths with the help of four-pole parameters [2], [3] calculated by **F**inite **E**lement **A**nalysis (FEA). The simulated transfer paths can be substituted for the original measured paths in the BTPS-model. This approach offers new sound design possibilities by virtually changing the geometry (e.g. shape, wall thicknesses…) and/or material properties. The effects of the modifications on the vehicle interior sound can be analyzed and subjectively evaluated during listening tests even in the early design phase.

For demonstration purposes, the described method is applied to a small vehicle simulator with reduced complexity. This model allows for fast structural changes, and its operation is also very flexible with respect to source strength modifications. The results of the measurements and simulations will be presented.

VEHICLE SIMULATOR FOR BTPA DEMONSTRATION

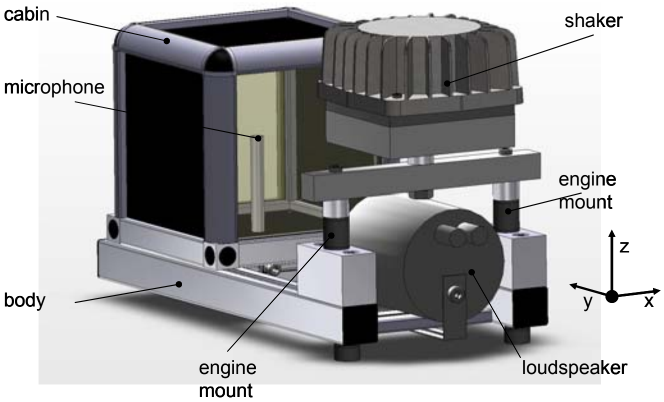

Fig. 1: Vehicle simulator

In Fig. 1 a small vehicle simulator is shown. A chassis is placed with three mounts on a soft, damped base plate to prevent external disturbances. On one side a cabin with Plexiglas is attached. Inside the cabin is a microphone, representing the driver's ear. On the other side of the chassis are two sources which together represent an engine. A shaker mainly produces structure-borne noise. It is fixed to a beam which is screwed with two thin engine mounts to the chassis. A loudspeaker is integrated into the model to produce mainly airborne noise. This vehicle simulator has accordance to a real vehicle, in the sense that a cabin is coupled over a chassis and different engine mounts to the engine. Also the airborne transfer path of the engine is taken into account.

INTRODUCTION INTO BTPA/BTPS

The challenge of the BTPA/BTPS method is to break down a complex noise into its components. Therefore all acoustically-relevant sources must be detected and taken into account in the BTPA/BTPS model. These sources are divided into the structure-borne and airborne paths which will be introduced in the next paragraphs.

STRUCTURE-BORNE TRANSFER PATH

Each structure-borne transfer path from the engine to the driver's head can be described using three transfer functions, one after another: the mount transfer, the apparent mass and the acoustical transfer function.

The mount transfer function a_{body}/a_{engine} can be determined in real cars under running engine conditions. In the example of the vehicle simulator the acceleration at both terminals of the engine mount is measured with shaker excitation using a sweep signal or with impact measurements at the engine side of the mount.

The apparent mass, which is the ratio of the force to the acceleration at the body-side F_{body}/a_{body}, and the acoustical transfer function, which is the ratio of the sound pressure level at the driver's head to the force at the body side p_{driver}/F_{body}, will be simultaneously measured by body-side impact hammer measurements. Alternatively, the acoustical transfer function can be determined by reciprocal measurements [4]. In the case of the vehicle simulator the sound pressure in the cabin will be measured monaurally with one reference microphone. These measurements must be repeated for each mount in all three directions in space.

AIRBORNE TRANSFER PATH

The airborne transfer functions can be defined as p_{driver}/p_{engine} for each possible sound source. In real cars, these sources can be at different positions in the engine compartment, at the intake system and at the exhaust pipe. To determine these transfer functions the sound pressure is measured at both ears of an artificial head placed on the driver's seat while exciting with a loudspeaker in the vicinity of the assumed sources. Another approach is based on reciprocity [4].

In the case of the vehicle simulator the sound pressure is measured with two microphones, one in front of the loudspeaker and one inside the cabin. A sweep signal is played via the loudspeaker in order to measure the airborne transfer function.

BINAURAL TRANSFER PATH SYNTHESIS

The calculated transfer paths will be used as filters that place any chosen value of the engine-side acceleration in relation to the output signal, the sound pressure which can be measured at the driver's ear. Therefore an input measurement has to be made to define the value of the above-mentioned acceleration.

Under running engine conditions the acceleration before each engine mount and the sound pressure at all different airborne excitation sources are measured as input, and the binaural sound pressure of an artificial head at the driver position inside the cabin as output.

In the case of the vehicle simulator, the acceleration before each mount and the sound pressure in front of the loudspeaker is measured as well as inside the cabin. For those measurements a real engine run up-recording is used as input signal. An engine airborne sound is played via the loudspeaker and an engine acceleration signal via the shaker.

The measured input acceleration before the engine mount is convolved with the three transfer functions for each direction in space and each mount to get the synthesized structure-borne part of the noise at the driver's position. All these transfer paths can be summarized into one structure-borne path (Fig. 2).

$$\overset{\text{input measurement}}{\boxed{a_{engine}}} \bullet \underset{\text{mount transfer measurement}}{\boxed{\frac{a_{body}}{a_{engine}}}} \underset{\text{impact measurement}}{\boxed{\frac{F_{body}}{a_{body}} \frac{p_{driver}}{F_{body}}}} = \overset{\text{synthesized structure-borne sound}}{p_{driver}}$$

Fig. 2: Structure-borne transfer path

To calculate the synthesized airborne sound contribution at the driver's position the sound pressure in front of the loudspeaker can be convolved with the separately-measured transfer function p_{driver}/p_{engine}.

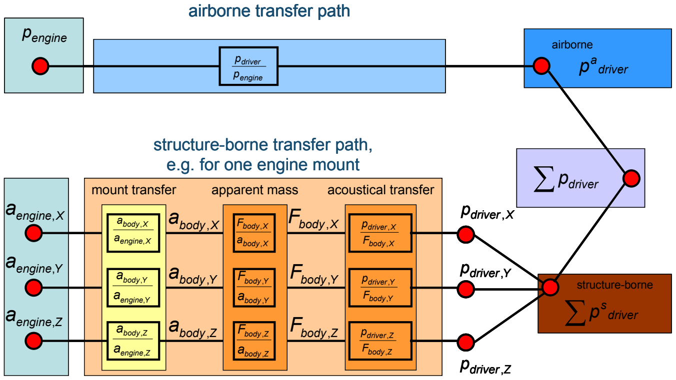

Fig. 3: BTPA/BTPS model with one airborne and the structure-borne transfer paths for one mount.

By summing both the structure-borne and airborne contributions, the total sound pressure at the driver's position can be synthesized (Fig. 3). Due to the fact that the sound pressure at the driver's position is measured in the input measurement as well, the synthesized sound pressure can directly be compared with the measured reference signal. Fig. 4 shows both measurements without any compensations or corrections of the transfer functions.

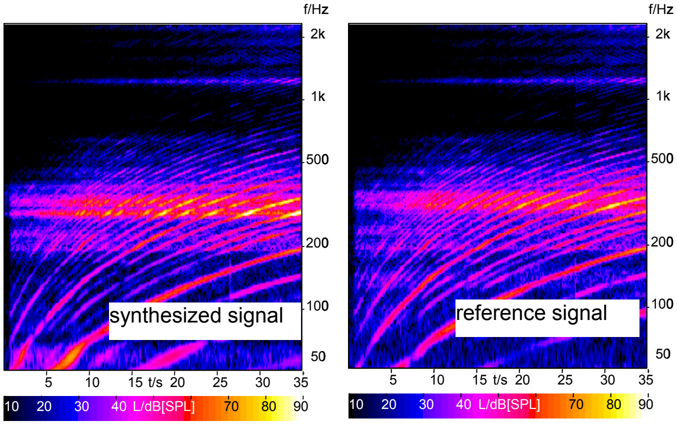

Fig. 4: Comparison of the measured reference signal with the synthesized signal at the driver's position inside the cabin

The described BTPA/BTPS technology has become well-known over the last decades. The challenge is the correct adaptation of each transfer function concerning effects like crosstalk, etc.

SUB-STRUCTURING TECHNIQUES FOR THE BTPA/BTPS

An especially important methodology improvement for structure-borne transfer paths 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. This requirement is fulfilled for most engine mounts. If one component is modified, the simulation only needs to be performed for the modified substructure rather than for the entire transfer path [3].

This method allows the use of engine test-rig measurements or FEA simulations for simulating structure-borne contributions in cars without installing the separately-measured or simulated parts, like mounts, in 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, FEA- and vehicle data is possible.

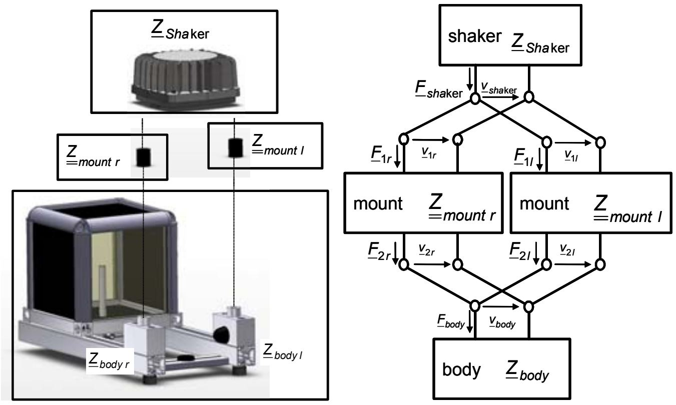

Fig. 5: Modeling the vehicle simulator using four-poles

Fig. 5 shows how the vehicle simulator can be divided into four-pole parameters. Each mount can be described as a four-pole connected to a source (shaker) and a load impedance (body).

TEST-RIG MEASUREMENTS

All four-pole parameters of the mounts can be determined using a test rig. Therefore the mounts are clamped, dependent on the shape of the mount, with one single input and output between a dynamometer and an excitation source, a shaker. Additionally, a static preload can be applied to the mount. As an input signal a sweep for the frequency range of interest is used.

The acceleration/velocity and force at both terminals of the mount can be measured. To calculate all four-pole parameters with the system of equations

$$\begin{pmatrix} \underline{F}_1 \\ \underline{F}_2 \end{pmatrix} = \begin{pmatrix} \underline{Z}_{11} & \underline{Z}_{12} \\ \underline{Z}_{21} & \underline{Z}_{22} \end{pmatrix} \begin{pmatrix} \underline{v}_1 \\ \underline{v}_2 \end{pmatrix} \qquad (1)$$

two operating conditions are necessary to determine all four variables Z_{11}, Z_{12}, Z_{21} and Z_{22}. In the case of test-rig measurements, it is possible to measure the mount upside-down to achieve these two conditions.

FEA CALCULATIONS

To calculate the four-pole parameters of rubber mounts with the help of FEA several requirements must be considered. In a first assumption the material of rubber can be approximated to be linear-elastic in the low frequency range up to 500 Hz. With this assumption the material data like the Young's-modulus, the density and the Poisson's ratio must be determined.

Calculation of Young's modulus

With a linear elastic approach the Young's modulus of the rubber mount can be determined by the deflection at a given maximum pressure delivered by the manufacturer. It is very important when modeling, that the geometrical boundary conditions like the connection threads or thread holes are made carefully and the weight of the model corresponds to the actual weight. By creating an assembly with three parts, head clamping plate, rubber mount, and the base plate, one can take into account the different materials rubber and steel. With this method a good approximation can be achieved which later can be adapted to the real measurements.

Calculation of four-pole parameters with FEA

The four-pole parameters of a mount are calculated with the FEA method: To determine the force and deformation/velocity at both terminals of the mount, reference nodes must be created. These reference nodes are connected to all nodes that touch the interface between mount and body, with rigid weightless elements. The clamping of the reference node at the body side is ideally stiff (infinite mechanical impedance). An additional adapting mass is generated at the reference node at the engine side. A standardized input load of 1 N is placed at this reference node (Fig. 6).

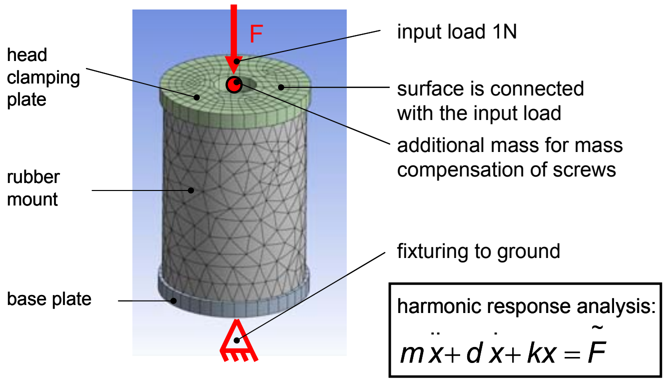

Fig. 6: FEA simulation

By means of a harmonic response analysis the reaction forces $F_R = -F_2$ at the clamped node and the deformation x_1 at the input node can be calculated in the frequency domain, likewise the reaction moments and the twist angles at the input in all directions in space. Due to the defined boundary conditions, the input force is identical to the input load of 1 N. Of course there is no deformation at the clamped node due to the fact that this node is rigid. The four-pole parameters Z_{11} and Z_{12} can be calculated as (*f*: frequency)

$$\underline{Z}_{11} = \frac{\underline{F}_1}{\underline{v}_1} = \frac{1}{\underline{v}_1} = \frac{1}{\underline{x}_1 j2\pi f} \qquad \underline{Z}_{12} = \frac{\underline{F}_2}{\underline{v}_1} = \frac{\underline{F}_2}{\underline{x}_1 j2\pi f} \tag{2}$$

By turning the mount upside-down and exchanging the clamped node and the load input node, the parameters Z_{22} and Z_{21} can be calculated. The transfer impedances Z_{21} and Z_{12} are identical for reciprocal systems. In the vehicle simulator both mounts are symmetrical in the x-y-plane which allows calculating the four-pole parameters in just one measurement ($Z_{11} = Z_{22}$).

Adapting FEA calculations based on test-rig measurements

Due to some smaller FE-modelling errors there are some small variations between the FEA and test-rig measurements. These errors are caused by missing additional masses like screw nuts, clamping parts etc. or by an inaccurate Young's modulus value.

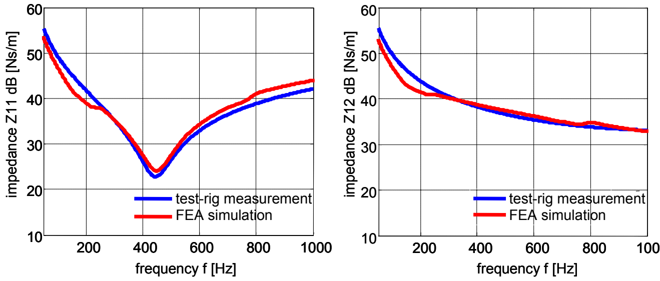

Fig. 7: Comparison of the four-pole parameters Z_{11} and Z_{12} based on test-rig measurements and FEA calculations

A fitting algorithm allows for adapting the Young's modulus, the damping coefficient and the additional mass. As a result the adapted FEA-calculated four-pole parameters are given. Fig. 7 shows the comparison between the results achieved with test-rig measurements and with FEA simulations.

Calculation of four-pole parameters without adaptation

Based on the adapted FEA calculation in z-direction all parameters and boundary conditions of the FEA-model are corrected. Just by changing the direction of the input load, the reaction forces and deformations affected by this new boundary condition can be recalculated. Due to the symmetry of the mount the input and output impedances of the x- and y-direction are the same and therefore also each corresponding four-pole parameter.

INTEGRATION OF THE FOUR-POLE PARAMETERS INTO THE BTPS MODEL

CHARACTERIZING THE TRANSFER IMPEDANCE UNDER FINITE LOAD CONDITION

Up to this point it has been described how the transfer functions work against infinite rigid impedances like a mount attached to the ground. On the other hand, if the mount is coupled to any kind of load impedance this impedance must be known and taken into account for the calculation. For example in a car the load impedance Z_{body} can be determined by performing an impact hammer measurement at the body side of the engine mount. All necessary load impedances can be determined, measuring in all three directions in space.

The values achieved from the load impedance Z_{body} measurements can now be combined with the calculated four-pole parameters from the FEA simulation and the test-rig results to calculate the transfer function

$$\frac{\underline{F}_2}{\underline{v}_1} = \frac{\underline{Z}_{21}}{1+\frac{\underline{Z}_{22}}{\underline{Z}_{body}}}. \tag{3}$$

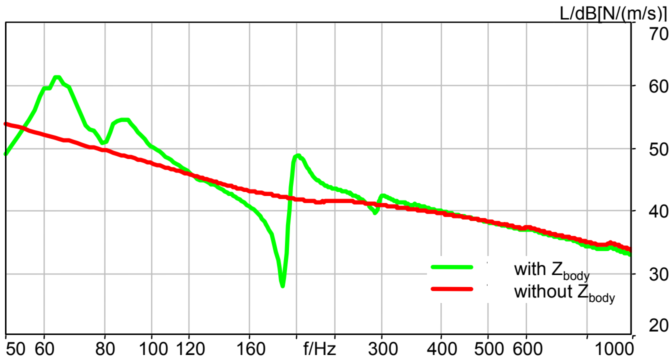

Fig. 8: Transfer impedance with and without considering the load impedance Z_{body}

The need of considering the load impedance in the calculation is shown in Fig. 8. The transfer impedance from equation (3) is compared to the mount transfer function Z_{12}.

With the transfer function calculated in equation (3), the mount transfer function a_{body}/a_{engine} and the apparent mass F_{body}/a_{body} can be replaced in our synthesis for the structure-borne transfer path.

Due to these sub-structuring techniques it is possible to combine test-rig measurements, FEA simulations and impact measurements in the car to calculate the structure-borne path from the engine to the driver's ear inside the cabin (Fig. 9).

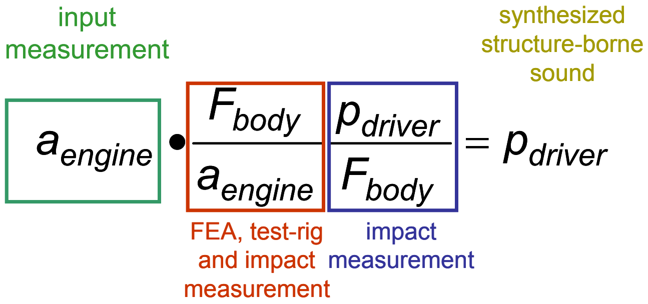

Fig. 9: Structure-borne transfer path with combined FEA and test-rig measurements

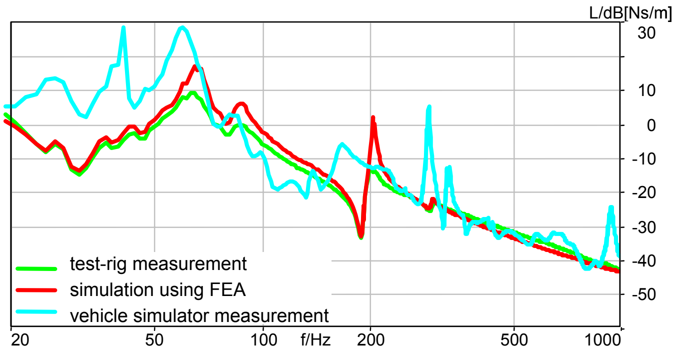

Fig. 10: Transfer impedance F_{body}/v_{engine} obtained using test-rig measurements, FEA simulations and vehicle simulator measurements

Fig. 10 shows the transfer impedance calculated with equation (3). The four-pole parameter Z_{22} and Z_{21} are obtained from two different approaches: first using test-rig measurements and second using FEA simulations. Both results are shown together with results from impact measurements at the vehicle simulator.

DESCRIPTION OF THE SOURCE

The procedure described above has shown how to calculate virtually the four-pole parameters of an existing engine mount, with test-rig or with FEA measurements. The main advantage is the virtual exchange of different mounts, without having to do any installations in the car. To be able to do this, one further aspect must be taken into account. The characteristics of the excitation source are affected by the engine-mount-chassis fixture or the engine impedance.

If an engine is fixed to an infinite mass (without damping elements), there will be no acceleration but a large dynamic reaction force. Otherwise, if an engine is mounted to an infinite soft mount there are nearly no dynamic forces but high accelerations. Due to this fact it is important to know the impedance and the source strength of the engine in order to characterize the whole system.

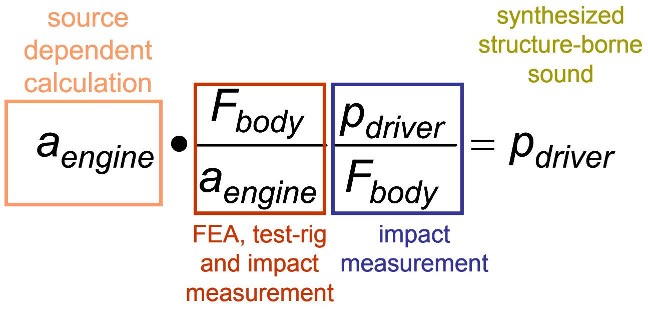

Fig. 11: Structure-borne transfer path using predicted excitation signals based on engine accelerations on a test rig and four-pole parameters (FEA or test-rig measurements) as well as impact measurements (to determine load and source impedance)

By integrating the source characterization into the BTPA/BTPS model it is possible to create a synthesized sound at the driver's position without having an input measurement of the real car. Only engine test-rig measurements are needed. The engine acceleration can be predicted based on the engine source characteristics, the calculated four-pole parameters and the body impedance (**Fig. 11**). The source characterization is the subject of current research and has been shown to be very promising.

VALIDATION

The use of a sub-structuring technique based on four-pole parameters (from FEA simulations or test-rig measurements) for the BTPA/BTPS model has been described above. This method is an extension to the standard BTPA/BTPS methodology which allows integrating virtual modifications to an existing BTPS model.

With the help of the vehicle simulator many calculations, FEA simulations and combinations of both, have been examined. The main focus was to describe different structure-borne transfer paths by using four-pole parameters. The four-pole parameters were determined for each engine mount in z-direction on a test rig. These measurements can also be done by FEA simulations, which then, however, must be adapted to the test-rig measurements (Fig. 7). With an adapted FEA model it is easy to obtain all moments and forces in all directions in space without time-consuming measurements.

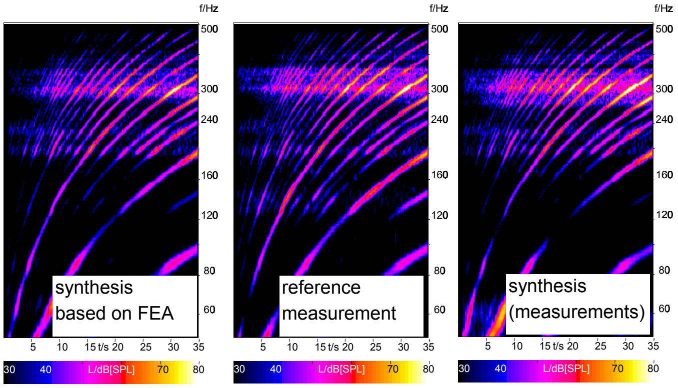

Fig. 12: Spectrograms of the total structure-borne noise based on FEA simulations (left) and vehicle simulator measurements (right) compared to the reference signal (centre).

Fig. 12 represents spectrograms of the structure-borne noise, based on three different methods. On the left side, one can see the synthesis determined via the FEA-calculations and the input impedance of the body together with the acoustical transfer function, as described in Fig. 9. On the right side, the synthesis is exclusively calculated with data obtained from impact measurements at the vehicle simulator. This represents the established BTPA/BTPS method, as described in Fig. 2, with no virtual elements. Both syntheses add all the contributions of the transfer paths, calculated for both mounts of the vehicle simulator in all three directions in space.

These two above-described syntheses are compared to the measurement in the cabin with the reference microphone (centre of Fig. 12). When examining the results of the syntheses one can detect some visible and also audible deviations from the reference, which however are small enough to be neglected.

Finally, a BTPA/BTPS model was created, not only with the structure-borne transfer paths (both engine mounts in three directions in space) but also with the airborne transfer path. The synthesized structure-borne transfer paths were created by using sub-structuring techniques based on FEA four-pole calculations. The result is illustrated in Fig. 13.

Fig. 13: Spectra of the measured reference signal and a synthesis achieved by FEA-calculations, considering both structure-borne and airborne contributions.

CONCLUSION

It has been shown that the traditional BTPA/BTPS methodology can be extended using four-pole parameters not only from test-rig measurements but also from FEA simulations.

Via this method it is possible to design or to modify existing parts such as mounts with respect to acoustics. For the prediction of the effects due to structural modifications, an adequate source characterization is needed. The characterization of the structure-borne source is a part of recent research work, whose results will be published in the near future.

ACKNOWLEDGMENT

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