BINAURAL „HYBRID“ MODEL FOR SIMULATION OF NOISE SHARES IN THE INTERIOR OF VEHICLES

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1. INTRODUCTION

Transportation vehicle development cycles must be reduced due to competitive reasons which require a reduction in time and costs. In the past, and still today, development processes in acoustic engineering consist of measurements, analyses, modifications and verification on prototypes in several loops. This procedure is time- and cost consuming. On the other hand the acoustic comfort needs to be targeted and designed for each typical driving condition in order to satisfy customers requirements. Validated numerical tools for vehicles acoustic design are still under development and will not be available to calculate each typical driving condition for several ten years. In the meantime "hybrid models" of acoustical behavior as presented can be used. These models will be based on a combination of measured and calculated data. They allow the definition of sound quality targets and modification design. Simulation and listening of the binaural acoustic responses at vehicles are based on the combination of known experimental data from previous vehicles and design modifications of components using experimental or numerical data basis.

Within the scope of the presented research project, designated AQUSTA (Improvement of the Structural Acoustic Quality of Transportation Vehicles Using Simulation Techniques of Binaural Analysis), several approaches have been developed, tried and tested, towards achieving the aurally-equivalent, binaural simulation of noise created in the interior of a vehicle by wind and engine. The presented model is based on measurements made with a vehicle or engine on a dedicated test rig. It includes the relevant transmission paths of the airborne and structure-borne sound components to the ears of a person sitting on driver's seat and takes into account triaxially vibrational excitation up to 2 kHz from the engine, engine stiffness and the reaction from the vehicle body. Airborne sound components are included at a limit frequency of 8.5 kHz. An extension to the complete audio frequency range is possible. The application of modified transmission elements, as realized in other calculation programs, or also through measurements allows objective and subjective predictions about expected vehicle interior sound quality on the one hand and the verification based on headphone monitoring on the other hand.

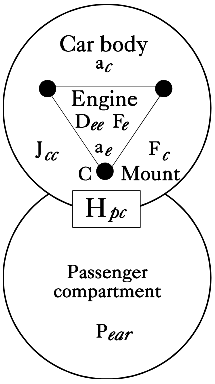
The presented model was evaluated for a low-cost front-wheel driven vehicle. Good results for the wind noise component can be demonstrated. For the engine noise components, the simulation model results are very much in the range of scatter resulting from comparative measurements at several vehicles of the same model [1]. Further improvement of the simulation can be expected by including noise components from drive train, wheel suspension and exhaust system.

2. MODEL DESCRIPTION

The complete binaural acoustic response recorded in a vehicle with the Artificial Head representing passenger's head can be mathematically defined as the sum of several mechanical and acoustical sources propagating waves which impact the head. The objective of the “hybrid model“ was to include a representation of equivalent mechanical and acoustical forces as well as structure-borne and airborne transfer paths. Two methods have been investigated to establish the model: The Direct Method and the Inverse Method. In a preliminary stage, it was necessary for the both methods to create a good physical model of the vehicle in order to define the best location of the point measurements used for an estimation of equivalent forces and transfer paths.

The Direct method is based on direct measurements of the forces in running conditions at the connecting points using a stiffness matrix approach for the mounts and a impedance matrix for the structure to be connected. Figure 1 provides an illustration of the model for an engine connected to the car body by three engine mounts.

Fig 1: Diagram of the Direct Method; engine connected to car-body by three mounts (**C**: Matrix of dynamic stiffness, **J**: Matrix of structure impedances, **H**: Matrix of transfer functions)



$$\begin{bmatrix} F_c \\ F_e \end{bmatrix} = \begin{bmatrix} C_{cc} & C_{ce} \\ C_{ec} & C_{ee} \end{bmatrix} \begin{bmatrix} a_c \\ a_e \end{bmatrix}$$

$$a_c = J_{cc} F_c$$
$$a_e = D_{ee} F_e$$
$$P_{ear} = H_{pc} F_c$$

$$P_{ear} = H_{pc} \left[I - C_{cc} J_{cc} \right]^{\#} C_{ce} a_e$$

The Inverse Method is based on simultaneous measurements of acceleration or sound pressure at several locations at the body structure or in air for running conditions. Then the transfer path matrix is used to determine the cross-spectrum matrix of the equivalent mechanical forces or acoustic forces.

In the simulation software the direct method was implemented [2].

3. SIMULATION METHODOLOGY

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

- Structure-borne transferpaths

Simulation modification of structure-borne paths was mainly focused on resilient mount modification. Several dedicated benches were developed to provide the engine mount matrix blox.

All transfer functions associated with matrix elements of $\mathbf{C}$'s, $\mathbf{J}_{cc}$ and $\mathbf{H}_{pc}$ were determined. A frequency range between 20 Hz and 2 kHz was covered with 1 Hz frequency resolution. To measure the matrix $\mathbf{C}$ elements (as given in fig. 1) a specially designed test-rig was used as shown in Fig. 2.

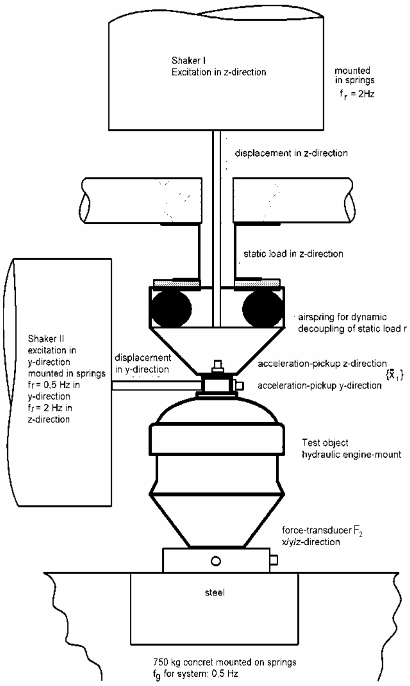


Fig. 2: Test rig for three-directional measurements of dynamic stiffness with static preload

Static load of engine mounts was added to be as close to that found in reality. Great care had to be given to reduce the nonlinearity as much as possible.

Direct listening of modification of structure-borne paths was developed and integrated into the system. The model may be used for stationary conditions and for engine speed variation. In the future, variable engine mount matrices must be included to consider a variation of load.

Measurements of $\mathbf{J}_{cc}$ matrix elements were carried out in a semi-anechoic chamber. They were determined between accelerometer and force sensor signals mounted at the engine-mount points of the car-body. The engine was dismounted during the measurements. Care had to be given for simulating the static load corresponding to the engine. In similar fashion, the matrix elements $\mathbf{H}_{pc}$ were determined between sound pressure signals picked up by the artificial head microphones and the excitation force signals [3].

Airborne transfer paths

Detailed research work was carried-out on airborne transfer path mechanisms in order to determine the contribution of each panel surrounding the cockpit for each airborne acoustic source.

Two methods to truncate the airborne path were developed and one of them was tested for the simulation of coincidence effect of lateral glasses. Evaluation measurements were carried-out in an aerodynamic wind tunnel with prototype modifications.

The binaural recordings and airborne transfer functions measurements were performed within the frequency range up to 8.5 kHz. Further details will be described in the following chapter.

4. AERODYNAMIC NOISE SIMULATION

Aerodynamic noise becomes dominant for the interior sound above a certain speed, the limit of which depends on the type of vehicles and environmental conditions. In the laboratory, the aerodynamic noise of a vehicle can be investigated in a wind tunnel under definable conditions. Under the experimentally verified hypothesis that different panels are incoherent sources for aerodynamic external noise, a masking procedure [4] was applied on the test vehicle in order to estimate transfer paths of different panels. Using this procedure as shown in Fig. 3, binaural recordings at the driver or co-driver position in the interior of the vehicle can be used for estimating noise transfer paths of different panels.

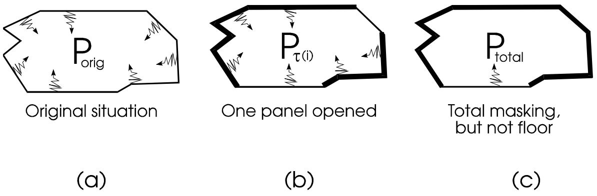


Fig. 3: Masking procedure for separating transfer paths of aerodynamic noise with removal of panel(s).

In the complex aerodynamic noise situation with transmission through all panels as shown in Fig. 3(a), the binaural sound signal P_{orig} is recorded. The masking procedure then is applied to each individual panel from the interior of the vehicle. The recording of $P_{T(i)}$ (Fig. 3(b)) is performed one after another for each panel under test. The rest signal of total masking P_{total} (Fig. 3(c)) has also to be recorded since the floor part of the vehicle can not be easily masked.

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

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

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

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

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

From experimental studies of wind tunnel recordings resulted that frequency components below a certain frequency do not show significant differences between individual panels. For this reason, a separation between these two frequency ranges is performed for the aerodynamic noise simulation as follows:

$$\begin{aligned} P_{simu}(t) = {} & P_{orig}(t) * h_{low}(t) + \\ & \sum_{i=1}^{m} h_{C(i)}(t) * \left[P_{orig}(t) * h_{high}(t) \right], \end{aligned} \tag{3}$$

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

Eq. (3) implies a useful simulation strategy when the difference between one panel currently used and another panel to be exchanged is characterized in terms of the transparency index. Here, the transparency index can be defined as ratio of the transmitted energy to the incident energy of a panel or structure. In effect, the difference can be used to construct a minimum-phase impulse response $h_{\tau(i)}(t)$, so that the simulation of exchanging n-th panel is straightforwardly performed using:

$$\begin{aligned} P_n(t) = {} & P_{orig}(t) * h_{low}(t) + \\ & h_{\tau(n)}(t) * h_{C(n)}(t) * \left[P_{orig}(t) * h_{high}(t) \right] + \\ & \sum_{i=1}^{n-1} h_{C(i)}(t) * \left[P_{orig}(t) * h_{high}(t) \right] + \\ & \sum_{i=n+1}^{m} h_{C(i)}(t) * \left[P_{orig}(t) * h_{high}(t) \right]. \end{aligned} \tag{4}$$

A physical modification of one or several panels can then be simulated in terms of FIR-filtering. The general concept of the simulation procedure is illustrated in Fig. 4.

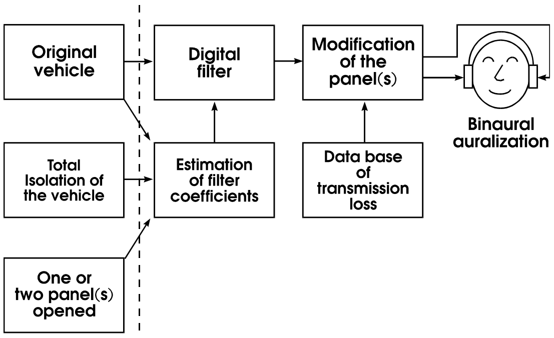


Fig. 4: Hybrid model for aerodynamic noise study in terms of binaural recording and simulation.

The simulation results were evaluated by measurements at a front-wheel driven car of the lower middle range. For the aerodynamic study the binaural recordings were conducted in a wind tunnel. The separating frequency of

$h_{low}(t)$, $h_{high}(t)$ in eqs. (3-4) for this vehicle is approximately 250 Hz. In order to demonstrate the agreement of binaural simulation results with binaural recordings in the original situation, a comparison between P_{simu} and P_{orig} in eq. (3) in terms of a 3rd-octave frequency analysis is illustrated in Fig. 5 for one experimental case. Extensive results from psychoacoustic A-B comparisons also confirmed satisfactory agreements between responses to $P_{orig}(t)$ and $P_{simu}(t)$ in eq. (3) and between recordings and simulations of individual panels in eq. (4).

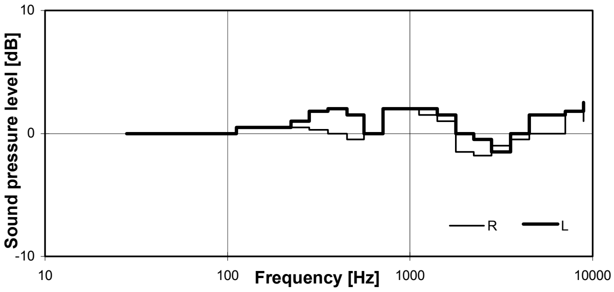


Fig. 5: Difference in level between the simulation results and the original binaural recording of aerodynamic noise.

5. SUMMARY

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

6. ACKNOWLEDGEMENT

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

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