Advantages of Prediction Techniques up to 1 kHz for the Vehicle Development Process

Hans H. Priebsch
Acoustic Competence Center mbH, ACC Graz
Austria
Christoph Fankhauser
MAGNA STEYR Fahrzeugtechnik AG & CoKG
Graz, Austria

sound in motion

2nd Styrian Noise, Vibration & Harshness Congress

Acoustic Optimisation in the Vehicle Development Process of the Future
New Demands – New Solutions

2003

Abstract

In the whole automotive industry, numerical simulation is appraised to have a high potential for reducing time and cost of the development process and increasing the quality of the product. Present activities focus on augmenting prediction tasks from the beginning of the development of a new car on one hand and enhancing simulation models and methodologies for high precision results on the other. For this target the paper describes latest developments and applications of different simulation methodologies. Their qualification for specific aims in the acoustic development of vehicles is discussed. The examples described in the paper focus on expectable result quality and assessment possibilities of the methods considering their specific capacity in the frequency range.

1. Introduction

The targets in the acoustic development of modern vehicles are conditioned by both, the requirements of the market and the legislation. While legislation reacts on environmental impacts of increasing traffic on the people living in cities or near motorways, interior sound is focused on brand identification and on comfort requirements of people driving the car. These demands represent a strong technical challenge and cause increasing effort for acoustic measures in the vehicles on one hand while the development time is already reduced to a competitive basis of about 28 months on the other.

To fulfil development targets under these conflicting demands, numerical simulation has been introduced for acoustic package development. Today, engineers use numerical simulation as a powerful tool for convincing predictions. Nevertheless, an effective benefit for the vehicle development process can only be gained if these methodologies are used starting from the early development phase. The targets are an optimum concept design of the acoustic package with reference to the main criteria of cost, weight and acoustic comfort as well as an accurate monitoring of the delivered quantities from component suppliers.
There are simulation tools existing, but their specific applicability in the acoustic development plays a mayor role. Finite Element Method (FEM) can be applied for the calculation of interior noise and is especially useful for hotspot analyses of metal sheets examining the sensitivity for the noise excitation sources [1, 2, 3]. With Statistical Energy Analysis (SEA) efficient models for vibro-acoustic transfer paths of the entire vehicle have been developed and validated by measurements at noise attenuation test stands and in the vehicle. Both methods FEM and SEA have their big advantages but still limitations, too.

In this field of application, the paper describes latest developments at ACC Graz. It is focused on enhanced models and application methodology of both FEM and SEA with respect to the needs of the development process. Furthermore, it presents possibilities of a new simulation method. The work in ACC is carried out in co-operation with the industrial partners MAGNA STEYR and AVL List GmbH.

2. Interdependence of vehicle development and acoustic simulation

2.1. Vehicle acoustic development

To gain significant profit from simulation, numerical models are required in the design concept phase of the development process, already, long before any hardware prototype is available. Therefore, co-ordination between available data, required models and assessment request of the different development stages has to be traced from the concept phase throughout to the concept refining. This interdependence of vehicle development process and numerical simulation requirements involves an effective management of design data.

Fig. 1 shows an example for a development process for vehicle acoustics as it is presently established at MAGNA STEYR. It can be seen that the emphasis of the simulation is placed at the project start. Here in the concept phase, the biggest economisation potential exists. On one hand, conclusions from acoustic simulations enable an unerring trim design, on the other hand the sub-project vehicle acoustics can be initiated months earlier.

The matrix in Fig. 2 gives an overview about typical tasks for simulation, benchmark and experimental work in the acoustics development. The exciation is required as a simulation input and will also be analysed at the prototype by measurement. Simulation may use other simulation results or measured results of components as an input to the vehicle model. The transfer through the structure is evaluated with FEM and SEA for the above mentioned reasons. Also airborne sources are used in FEM or SEA, depending on the frequency range. The measuring techniques are used in the prototype phase to evaluate the simulated results. Appropriate calculation models are required for each step. As described in [1], crash models can be used as a basis for FEM models for the vibro-acoustic calculation of vehicles, but they have to be adapted to the specific requirements, e.g. spot welding dynamics. Models for SEA analyses have to be generated based on existing data from similar vehicles and are applied to give design trends. For the models of new parts the hybrid SEA procedure provides a possibility to enhance the model quality.

2.2. Holistic approach

To simulate the interior noise of a vehicle all parts relevant for the noise generation and vibration transfer to the passenger cabin have to be included in the calculation model. The acoustics engineer is put in the position to study all the noise and vibration phenomena of a frequency domain with one single model. This holistic approach has considerable advantages for vehicle acoustics, because interactions of different vehicle areas are represented within the model.
This type of models of the entire vehicle has to include models for the engine, the exhaust system, the chassis, the car body, the trim and the passenger cavity. Fig. 3 shows an example for the FEM model of a sports car aiming at numerical simulation of the interior noise up to 250 Hz.

2.3. Frequency range

Results and acoustic design assessment for vehicles are required in the entire audible frequency range, beginning with vibration investigations in the low, harshness aspects in the mid and acoustic analyses in the higher frequency ranges.
Regarding simulation methods, the specification of low and high frequency varies according to the design characteristics (mass and stiffness distributions), with the modal density of a structure respectively. For the vehicle in general the relevant frequency ranges can be set as shown in Fig. 4.
The method of Multi-Body Dynamics (MBD) is used in the low frequency range. In general, MBD tools provide rigid elements (bodies) connected by contacts (joints). The joints are characterised by properties of damping, elasticity, friction, etc. The application limit of MBD is given by the first bending modes of the parts (25 - 40 Hz).

Recently developed and validated enhanced FEM models of trimmed vehicle bodies proved their utility for assessing the transfer behaviour for excitations to the interior noise up to 250 Hz despite the high modal density in this range [4]. By this means the frequency domain of ignition order of conventional engines can be covered. More than 700 modes of car body, trim and cavity have to be represented by such models having more than 1 Million degrees of freedom (DoF). Above 250 to 300 Hz FEM faces two problems because of the high modal density: the significantly increasing number of DoF for a correct representation of the natural modes and the impossibility to resolve single modes from measured results for the validation.
As a method based on energy flows, SEA is ideal for high frequency analyses. Natural modes are no more relevant, although a minimum modal density is required [7]. Therefore, a problem associated with predicting internal car noise with SEA is that the passenger car cabin has very few modes, particularly at low frequency. Thus, the lower limit for SEA is at about 350 Hz for vehicle structures and at about 600 Hz for car cabins according to their different characteristics in modal density.
As a result of the modal densities the mid frequency “gap” occurs with simulation as shown in Fig. 4 and is still of concern in the industrial applications.

3. Simulation Techniques for Vehicle Acoustics

3.1. FEM for interior noise prediction

FEM had been successfully introduced and used in the development process for durability, comfort and crash analyses before it was introduced for acoustic ones. Today, FEM is a widely accepted tool for the numerical simulation of the steady-state behaviour of coupled structural-acoustic systems. As an advantage, FEM exhibits almost no restrictions to the complexity of geometries of parts and structures. As described above, FEM is limited to the low frequency range due to the enormous grow of model size with increasing frequency. And this occurs specifically with models comprising the entire vehicle because the model of the trimmed body has to be augmented by the models of the noise excitation source for the calculation of absolute interior noise levels. Focusing on combustion and mechanical noise sources and excluding wind noise the following parts have to be added to the trimmed vehicle body, Fig. 3: The power train including engine, gear box and mountings, the exhaust system including mountings and the chassis considering the excitation boundary of the road surface. In this model the number of DoF increases significantly up to about 3 Millions.

Thus, a reduction of the vehicle model size is a requirement for handling reasons (model size, CPU time). Sub-structuring techniques are well known for linear structures. But in the vehicle excitation non-linear effects are to be considered. Therefore in ACC, a specific approach has been introduced. It is described for the noise excitation from the power unit (engine and gear box) as follows: In the first step, the excitation at the mounts is calculated considering a relevant model of the power unit and the condensated structure matrices of the trimmed body, Fig. 5. The power unit excitation is simulated by means of the software AVL EXCITE [5]. Besides FEM models of engine block and gear box housing the model comprises all moving parts of the crank train. The displacements at power train mounts shown in Fig. 5 result from the non-linear forced vibration simulation of the engine at 4000 rpm and full load. Furthermore, results of contact forces at the mountings of the power unit can be obtained. In the second step, the forced vibration analyses of the entire vehicle due to the dynamic forces in the mounting is calculated (e.g. Fx, Fy, Fz for the left front engine mount in Fig. 5).

This procedure considers the principles of dynamically correct separation of structure areas. It also allows the insertion of measured data as excitation to the vehicle (e.g. from engine run up). It can be applied for the structure borne excitations via chassis and exhaust system, too. Further details for the chassis simulation are described in [6].

In Fig. 6 the results of interior noise calculated due to the excitation at the mounts of the exhaust system are plotted. The different types of mounts for catalyst and mufflers are shown and are included as FEM models. The exhaust system is modelled by FEM, too, considering effects of changing pipe wall thickness (due to manufacturing), and the specific characteristics of the non-linear flex-element. The exhaust system is excited by the second order of the 4 cylinder engine during engine run up (900 to 6000 rpm, 2 min). The vibrating of the engine in its mounts can be derived from measurement or simulation. The increase of the forces in the mounts near 200 Hz could be correlated to a natural mode of the exhaust system resulting in increased vibration of the structure, too, Fig. 7. The pressure distributions in two positions in the car cabin indicate differences of the interior noise for driver and front-seat passenger.

To estimate the amount of vehicle floor excitation caused by the radiation of the vibrating surface of the exhaust system a calculation is carried out by means of boundary elements. The boundary conditions of road surface, vehicle floor and actual distances between mufflers and tunnel are considered. To allow for correct wave propagation underneath the car the lower part of the vehicle surface is also considered in the model. Fig. 7 shows the distribution of the surface vibration velocities at the exhaust system due to vibration excitation of the engine on one hand and the pressure distribution at vehicle floor due to surface radiation of the exhaust systems on the other. Again, the excitation is due to the second order of engine run up at 200 Hz for a passenger car. The red spots in the positions of catalyst and first muffler mark local maximum pressure of 110 dB and underline an acoustic effect of the tunnel. The effect on interior noise can be compared for both excitations (structure borne and air borne). For this car and at 200 Hz the contributions of both excitations have about the same level.

3.2 SEA for advanced applications

Although, the basics of Statistical Energy Analysis (SEA) were published in the early 1960`s, already, the first applications of this technique to the automotive development are relatively recent [7]. Today, SEA is used for several applications for both part and full vehicle models in the higher frequency range up to 5 kHz. For example the sound package efficiency is evaluated through transfer functions. The transfer functions give a measure for the fraction of acoustic energy approaching the passengers ear through certain transfer paths. Thus, SEA models of high quality can give a clear picture of complex acoustic processes.

An example of calculated results for a recent application is given in Fig. 8. The aim is to clarify at the third octave band, whether noise radiated by the gearbox is transferred via structure or air paths at a level recognisable in the car cabin. In a first step, the sub-structure underneath cavity is exposed to the radiated power measured at the gearbox. Assessing the resulting A-weighted sound pressure level inside the cabin in the second step, the air borne noise can be identified as the relevant transfer path, Fig. 9. Thus, it is proven indirectly that structure isolation at gearbox mounts is sufficient.

Actual areas of interest with SEA are to develop standards for modelling in terms of characteristics for specific materials and the coupling of sub-structures, internal loss factors (ILF) and coupling loss factors (CLF) respectively. Furthermore, the experimental effort for the determination of SEA parameters is still very high. Hundreds of transfer functions have to be measured and evaluated. Finally, the need of experiments hinders a predictive assessment in the development in case of significant design modifications.

To eliminate these disadvantages a hybrid method is applied [7, 8]. Hybrid SEA employs FEM for structure parts and simulates the experiment for determining loss factors by means of response functions from calculated forced vibration analyses. Thus, SEA is used to interpret FEM results at high frequencies employing mean values in frequency and space domains. Fig. 10 shows the simulated vibration pattern of a car front area at 2500 Hz, excited with unit force at the firewall. 7 sub-structures had been defined in advance and checked by the Smith Criterion (weak coupling condition). To post-process FEM results to the experimental SEA tool, a interface between FEM and SEA tools had been programmed. Thus, the post-processing from 25 excitation points and 80 response points at the vehicle parts can be carried out very fast. The quality of the results for ILF and CLF distributions from hybrid SEA depends very much on the correct modelling of the dissipative characteristics of the sub-structures in the FEM model. Usually, material damping values used in FEM lead to correct ILF and CFL results. The quality of the results obtained by calculation is proven by the comparison with measured ones in Fig. 11. Plotting all loss factors for a certain frequency band in one matrix gives a first impression of possible energy flow and coupling conditions. Fig. 12 shows the matrix of loss factors for 6 sub-areas of the car front in the 1250 Hz third octave band. Each element represents one CLF between different sub-areas. The ILF values occur in the diagonal. The Smith Criterion is fulfilled because the diagonal elements are much higher than the others. The value of this methodology for predictive design decisions is obvious and will drive its further development.

3.3 WBT - a promising alternative

As described above, there is a simulation gap between FEM in the lower frequency range and SEA in the higher frequency range due to their application restrictions. Therefore, alternative methods and solutions have been investigated and the Wave Based Technique (WBT) was found to be the most promising methodology. WBT was introduced by Desmet [9]. Based on the theory described there, the pre-conditions for a first 3-dimensional (3D) implementation to be applied for common acoustic domains was performed in ACC in collaboration with the Kath. University of Leuven (KUL) [10]. The solution of WBT is based on the indirect Trefftz method approach. It exhibits better convergence properties than the FEM with respect to the model size. This allows accurate predictions at higher frequencies compared to FEM [11].

A special (rigid) car cavity, called Sound Brick, was build at ACC to validate the method free of undefined effects from fluid-structure interaction up to 1 kHz. An internal loud speaker generats the noise for exciting the cavity. Fig. 13 shows results of measurement at a microphone position, of FEM (considering maximum element length of 10 cm) and WBT. The advantage of WBT can be observed very clearly. With increasing frequency the correlation between measured results and WBT is much better than with FEM. This is shown in the two zooms in frequency range in Fig. 13. The number of elements required in a WBT model is not depending on the model size, but on the model geometry. E.g. the Sound Brick consists of one WBT element only. For the geometry shape of a car cabin the required WBT element distribution is shown in Fig. 14. Compared to FEM, still, the number of elements is reduced significantly.
Despite of these very promising results a disadvantage for WBT may occur with high geometrical complexity, which can reduce the computational efficiency. Therefore, the coupling of the two methods FEM and WBT was already investigated in 2D in order to benefit from advantages of both the high convergence rate (WBT) and the wide application range of FEM [11]. The extension for relevant 3D application is part of ongoing work in the collaboration between KUL and ACC. A central aspect is, that WBT is not restricted to the simulation frequency gap but offers promising properties in the whole frequency range.

4. Conclusion

An effective benefit from numerical simulation techniques for the vehicle development process can only be gained if these methodologies are used starting from the early development phase. Especially, in the concept phase, the biggest potential for efficiency improvement with simulation exists. Simulation techniques such as FEM and SEA are well introduced for specific development targets, already. Nevertheless, for extended and efficient applications enhanced simulation procedures and new methods are required.

The application examples presented show:

- The problem of interior noise simulation up to 250 Hz with large models (entire vehicle) and structure borne excitations can be solved by a dynamically correct separation of structure parts.
- The hybrid SEA approach reduces the experimental effort and gives high quality results.
- Wave Based Technique is a promising tool to close the existing simulation frequency gap. Combining advantages of FEM and WBT can extend the application flexibility.

5. Acknowledgements

The work described above was funded by the Austrian Federal Ministry of Economy and Labor in context of Industrial Competence Centers, the Federal State of Styria, the Styrian Development Agency and the City of Graz. Moreover, the authors thank all members of the MAGNA STEYR, AVL List GmbH and ACC for their contributions to the presented results, specifically DI. E. Böhler, Mag. F. Diwoky, Mag. DI. I. Hauer and Dr. A. Hepberger.

6. References

[1] H.H. Priebsch, I. Hauer, H. Fellner, G. Polt, F. Brandl, Numerical Simulation of Vehicle Interior Noise up to 250 Hz, Proc. of Styrian NVH Congress, Graz 2001

[2] C. Fankhauser, B. Kastreuz, H.H. Priebsch, K. Jalics, I. Hauer, A. Glettler, Development of Vehicle Trim by means of FEM and SEA, DAGA'03, Aachen, 2003

[3] B. Kastreuz, H. Macher, C. Fankhauser, K. Karaca: Ein hybrider messtechnisch-simulatorischer Ansatz zur gezielten Körperschalldämpfung in Fahrzeugen" (Design of Car Body Damping Layers by a Hybrid Measuring and Simulation Approach", VDI Tagung: "Mess- u. Versuchstechnik in der Fahrzeugentwicklung" VDI-Berichte 1755, Würzburg, 2003

[4] H. Fellner, I. Hauer, H.H. Priebsch, G. Polt, F. Brandl, Numerical Simulation of Trim in the Vehicle Interior, ATZ 7-8, Vol. 104, 2002

[5] H.H. Priebsch, H. Herbst, G. Offner, M. Spouch, Numerical Simulation and Verification of Mechanical Noise Generation in Combustion Engines, 27th ISMA Conference, Leuven, 2002

[6] H.A. Macher, C. Fankhauser, Conflicting Demands in the Development of Vehicle Chassis, 2nd Styrian NVH Congress, Graz, 2003 (to be published)

[7] N. Lalor, The Application of SEA to the Reduction of Passenger Car Interior Noise, University of Southampton, 1994

[8] L. Hermanns, G. Fortunato, G. Dalben,: The Use of FEM to predict SEA loss factor models, Euronoise, Patra, 2001

[9] W. Desmet, A wave based prediction technique for coupled vibro-acoustic analysis, PhD Thesis, K.U. Leuven, division PMA, 1998

[10] A. Hepberger, H.-H. Priebsch, W. Desmet, Bas van Hal, Bert Pluymers Application of the deterministic wave based prediction technique for the steady state response of a car cavity up to 1kHz, Proc. of ISMA Conference Leuven, 2002

[11] B. van Hal, W. Desmet, D. Vanderpitte, P. Sas, A coupled Finite Element - Wave Based Approach for the Steady-State Dynamic Analysis of Coupled Structural-Acoustic Systems, 5th World Congress on Computational Mechanics, Vienna, 2002

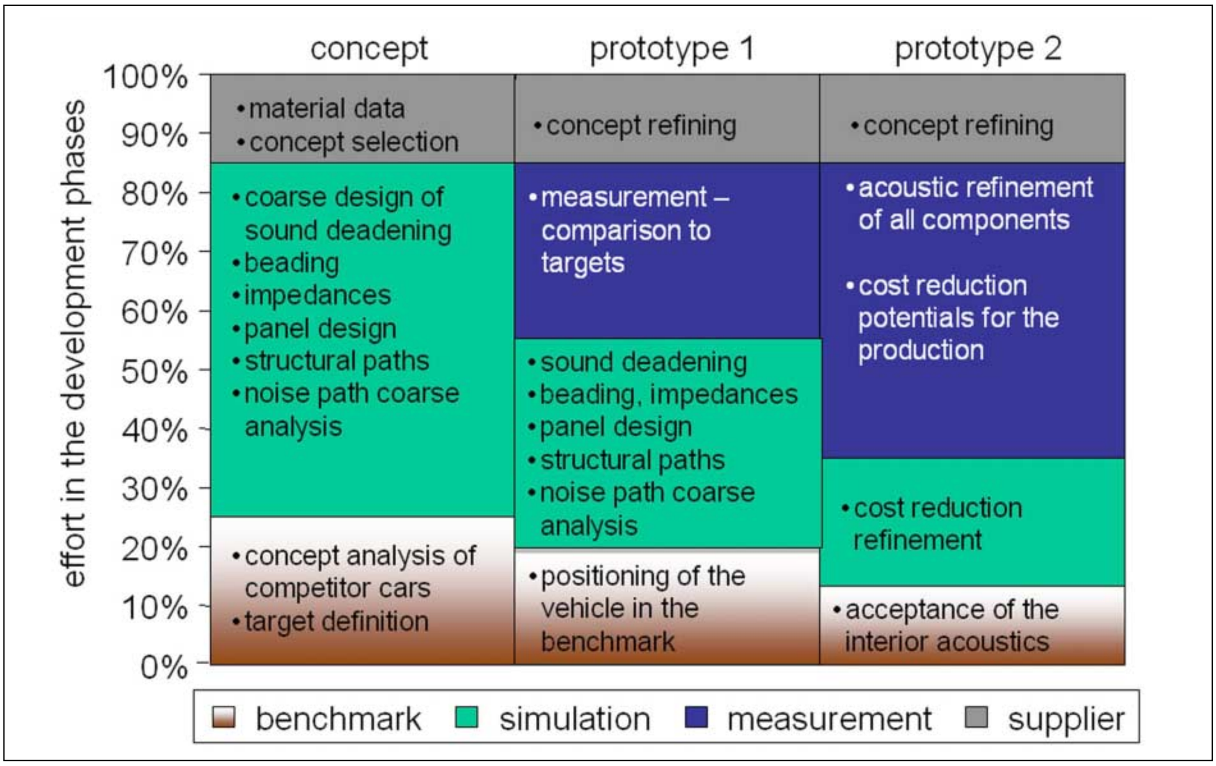

Figure 1: Example for the development process for vehicle acoustics

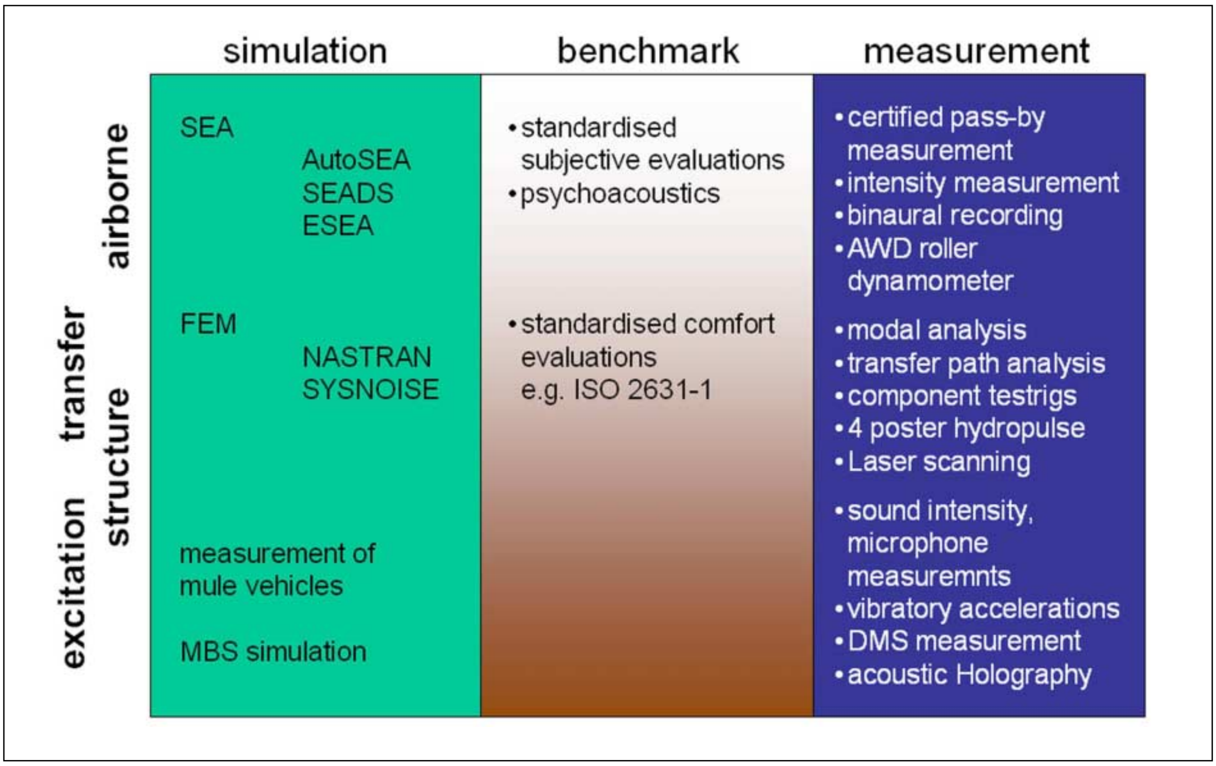

Figure 2: Matrix of typical tasks for simulation, benchmark and measurement in the acoustic development process

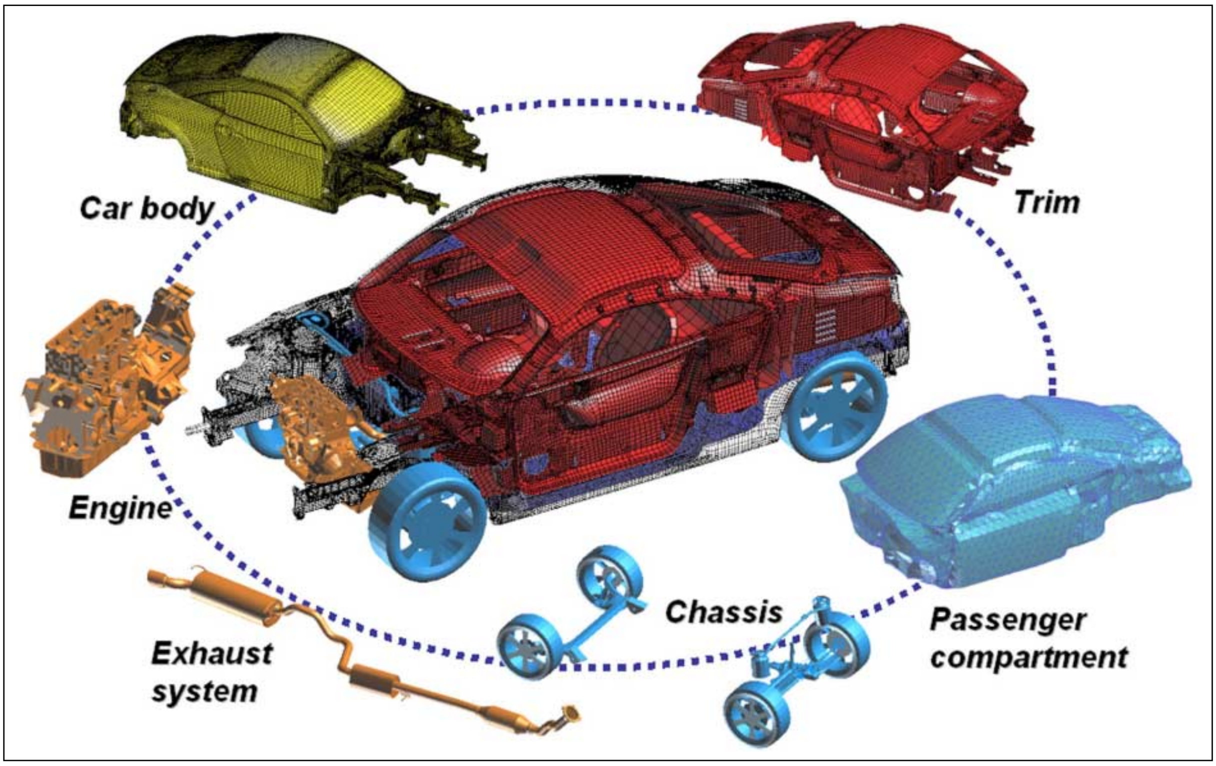

Figure 3: Holistic approach for vehicle simulation: Model of the vehicle parts required for the interior noise simulation considering excitations from power unit, exhaust system and road

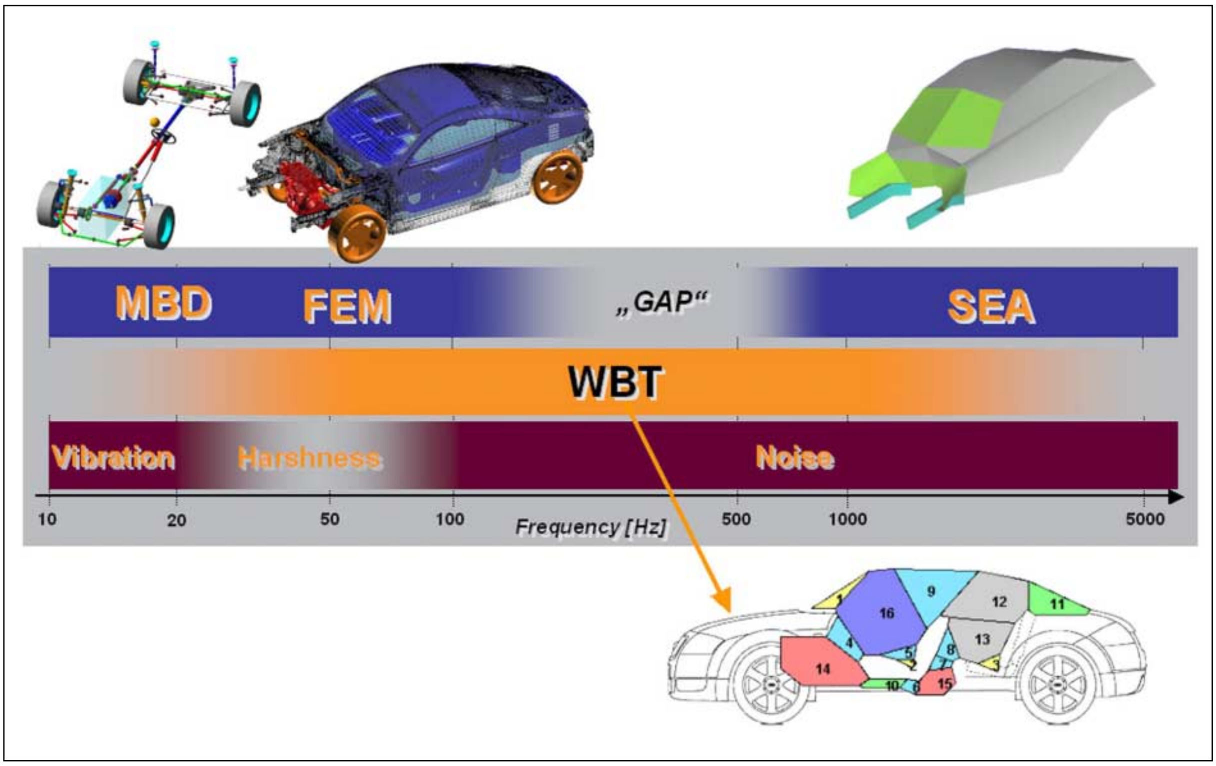

Figure 4: The frequency dependence of simulation methodologies

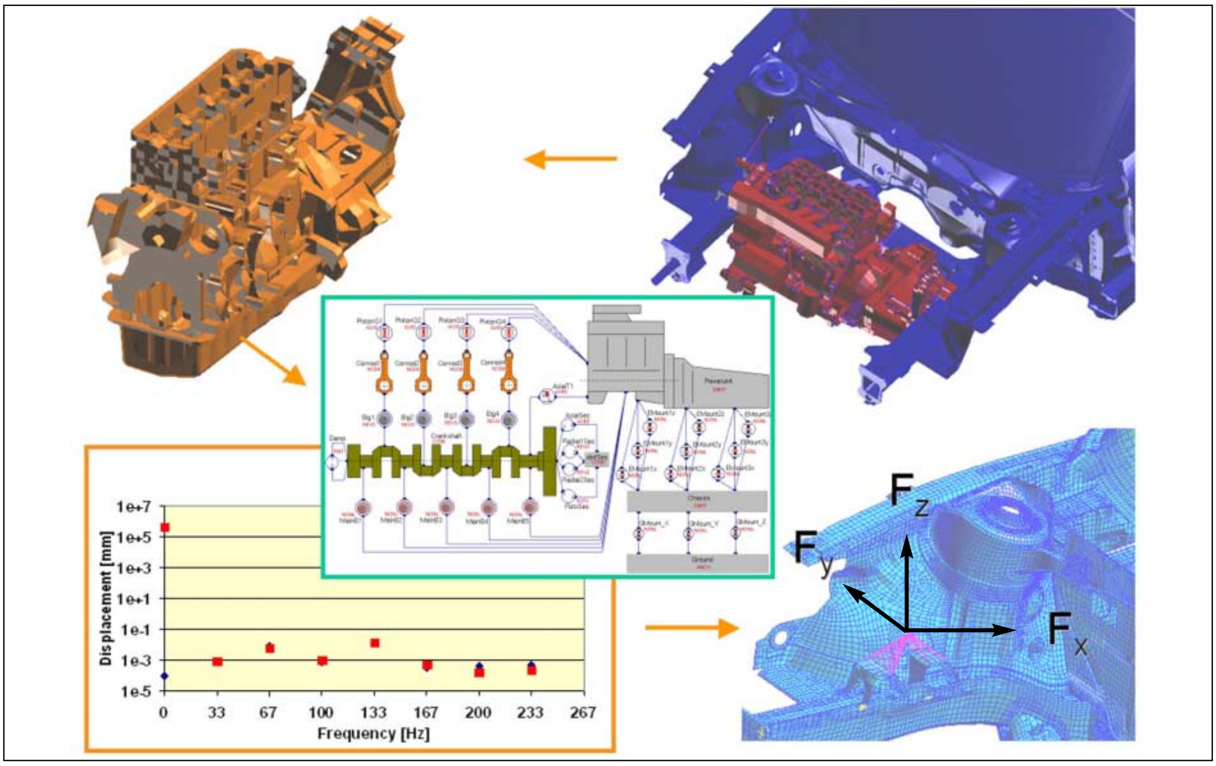

Figure 5: Reduction of vehicle model size considering dynamic boundary conditions from engine excitation, calculated displacements at engine mounts due to forced vibrations of the engine at 4000 rpm and full load

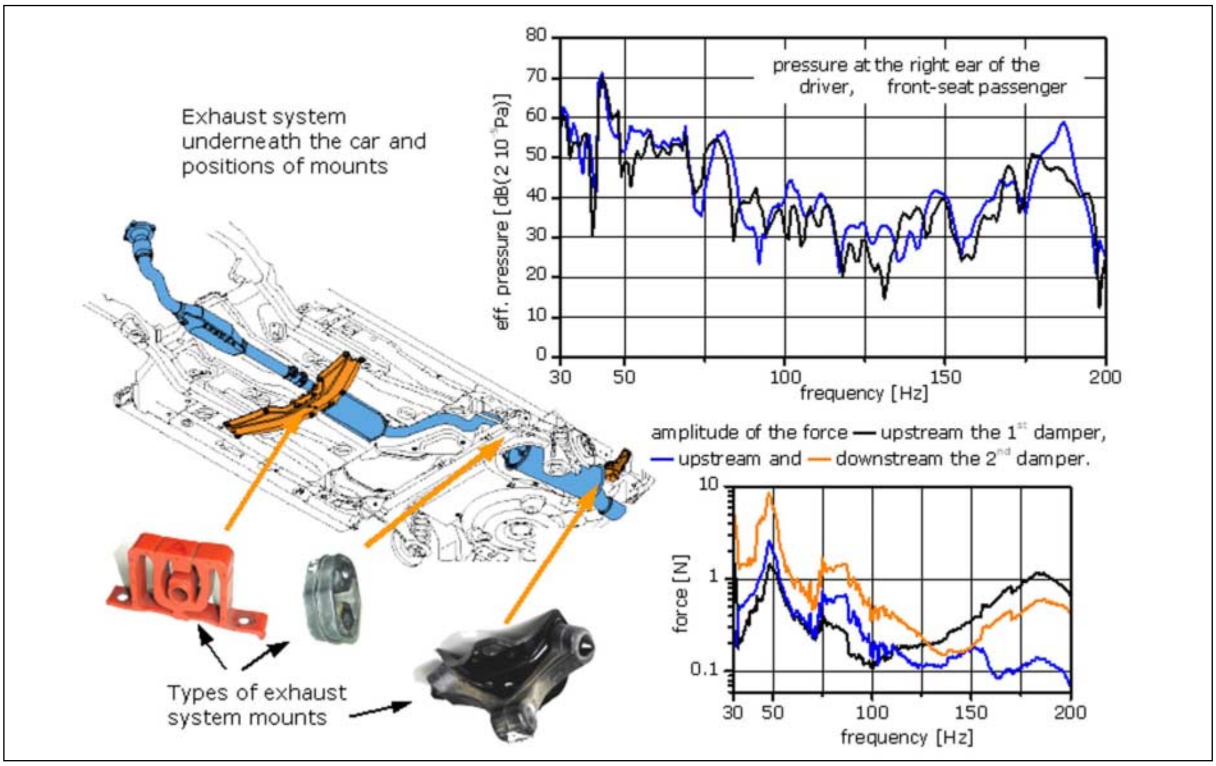

Figure 6: Interior noise caused by the vibration excitation of the exhaust system via the elastomer mounts, second engine order due to engine run up (900 to 6000 rpm, 2 min)

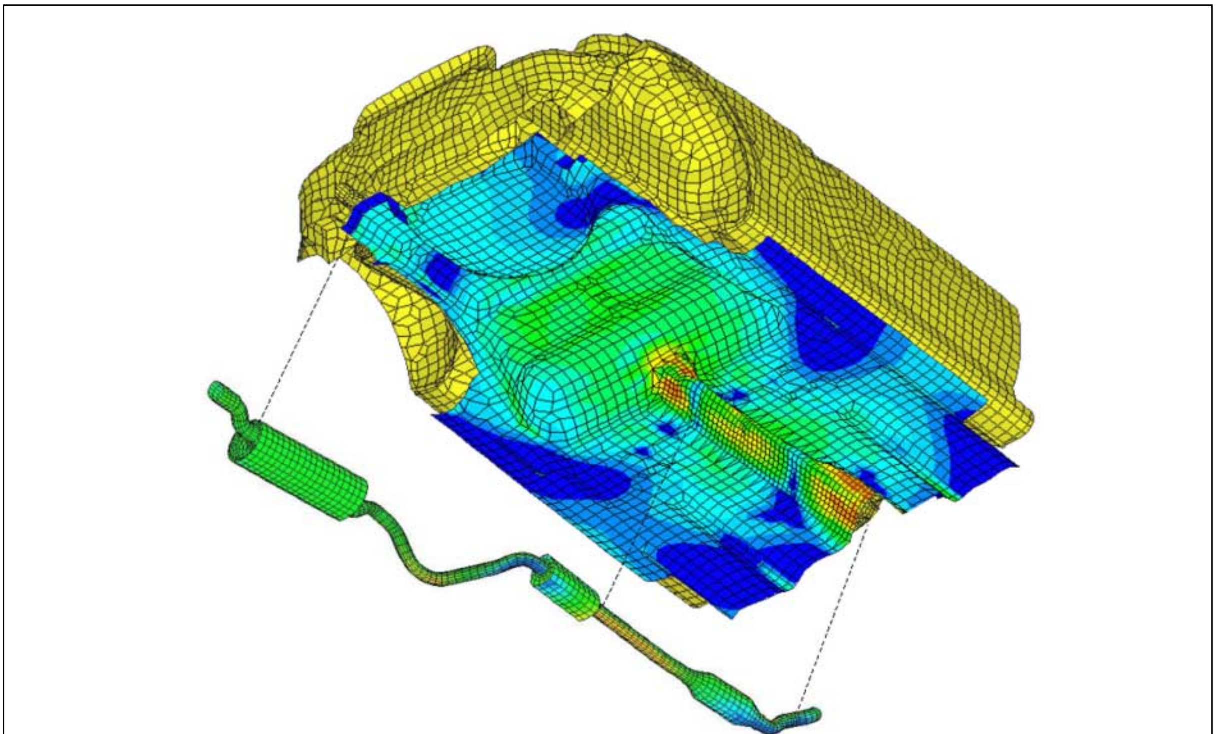

Figure 7: Distribution of surface vibration velocity at the exhaust system due to vibration excitation of the engine and pressure distribution underneath car due to surface radiation of the exhaust system at 200 Hz. Excitation is due to second engine order during engine run up (900 to 6000 rpm, 2 min). Red spots show local maximum pressure of 110 dB.

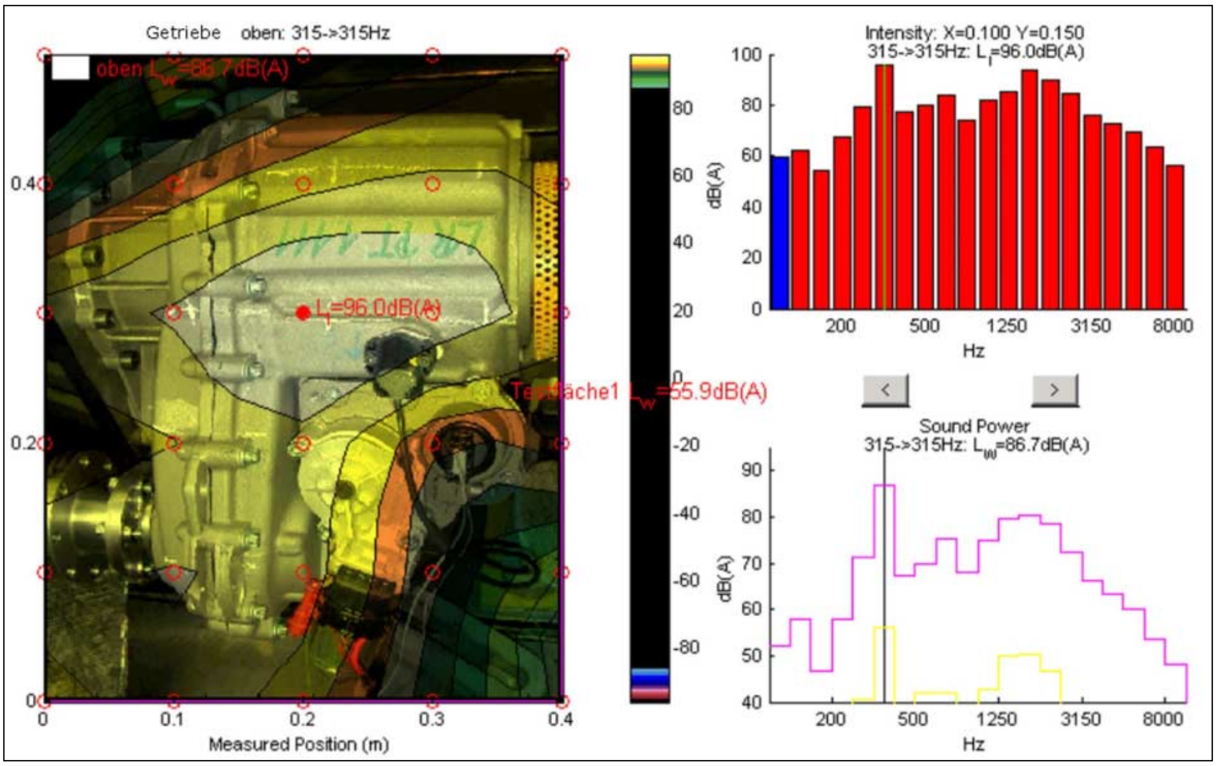

Figure 8: Sound pressure level of a gearbox underneath vehicle, relevant intensity and sound power distribution in frequency range

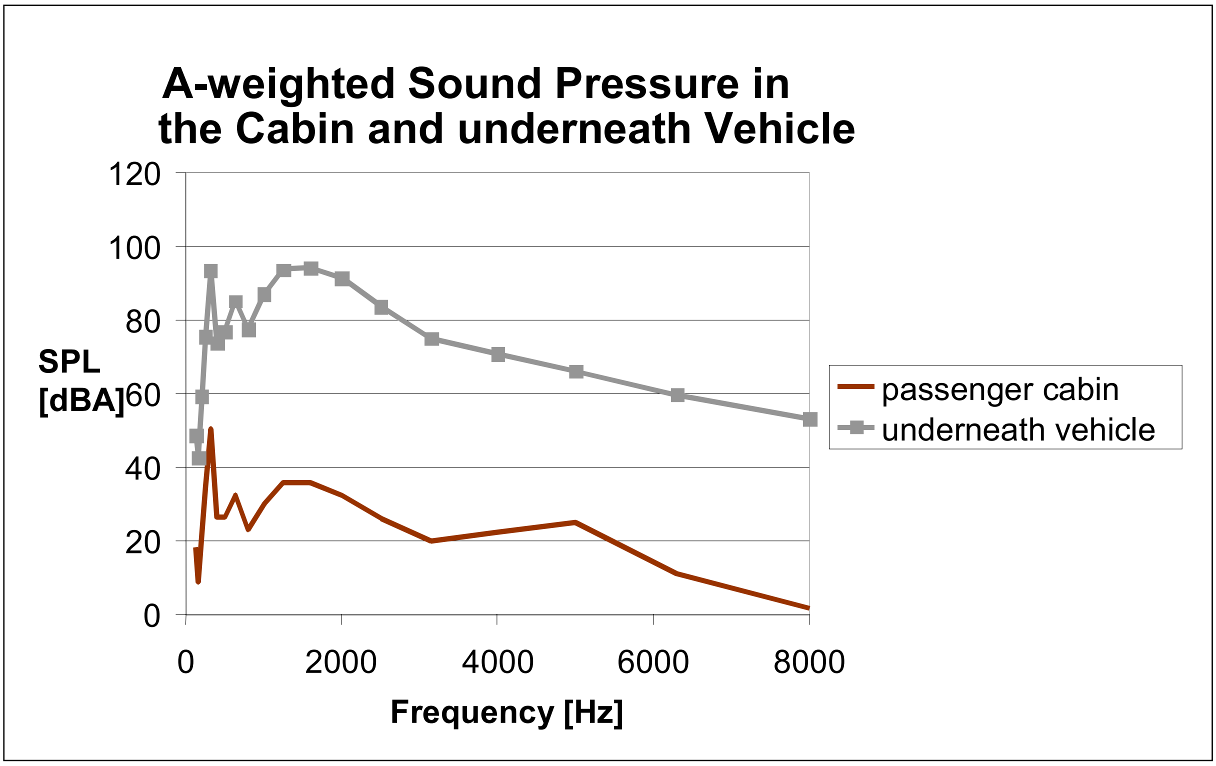

Figure 9: Sound pressure level underneath the vehicle and in the passenger cabin due to noise radiation of the gearbox as shown in fig. 8. Integral noise level in the car is 58 dB(A)

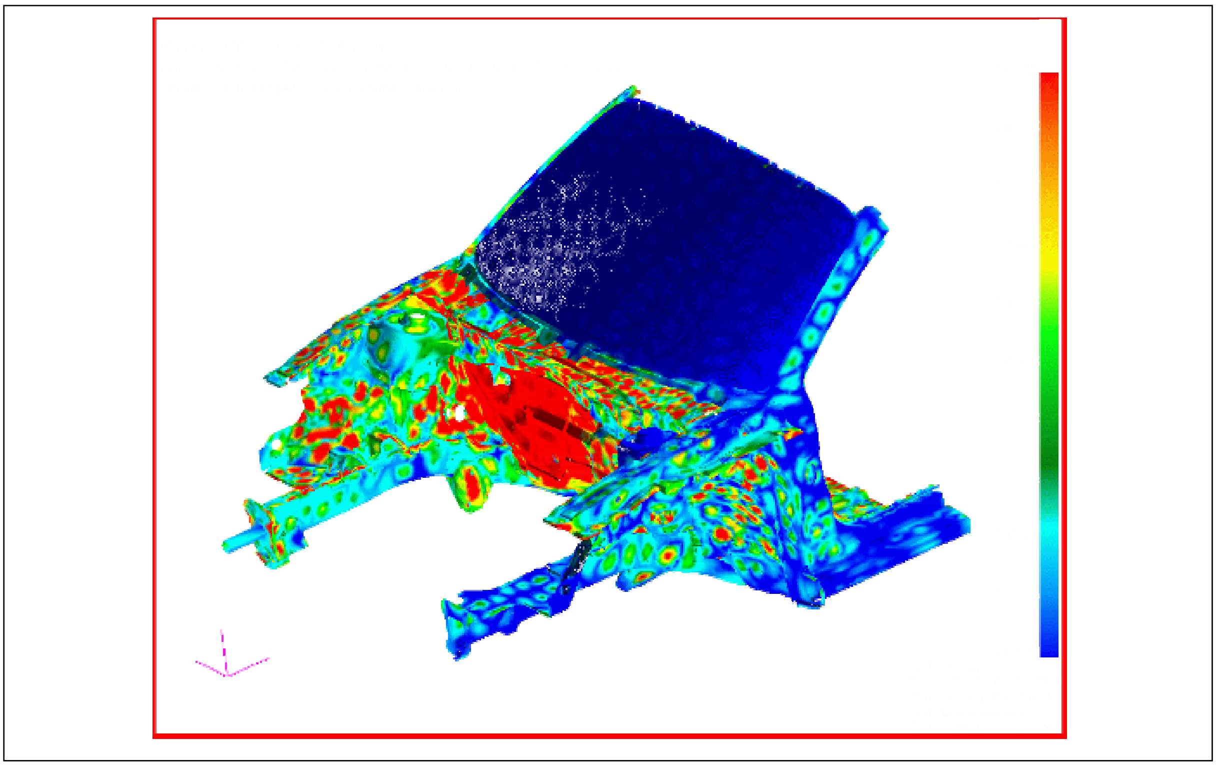

Figure 10: Example of hybrid SEA at vehicle front, vibration pattern at 2500 Hz due to unit force excitation at fire wall

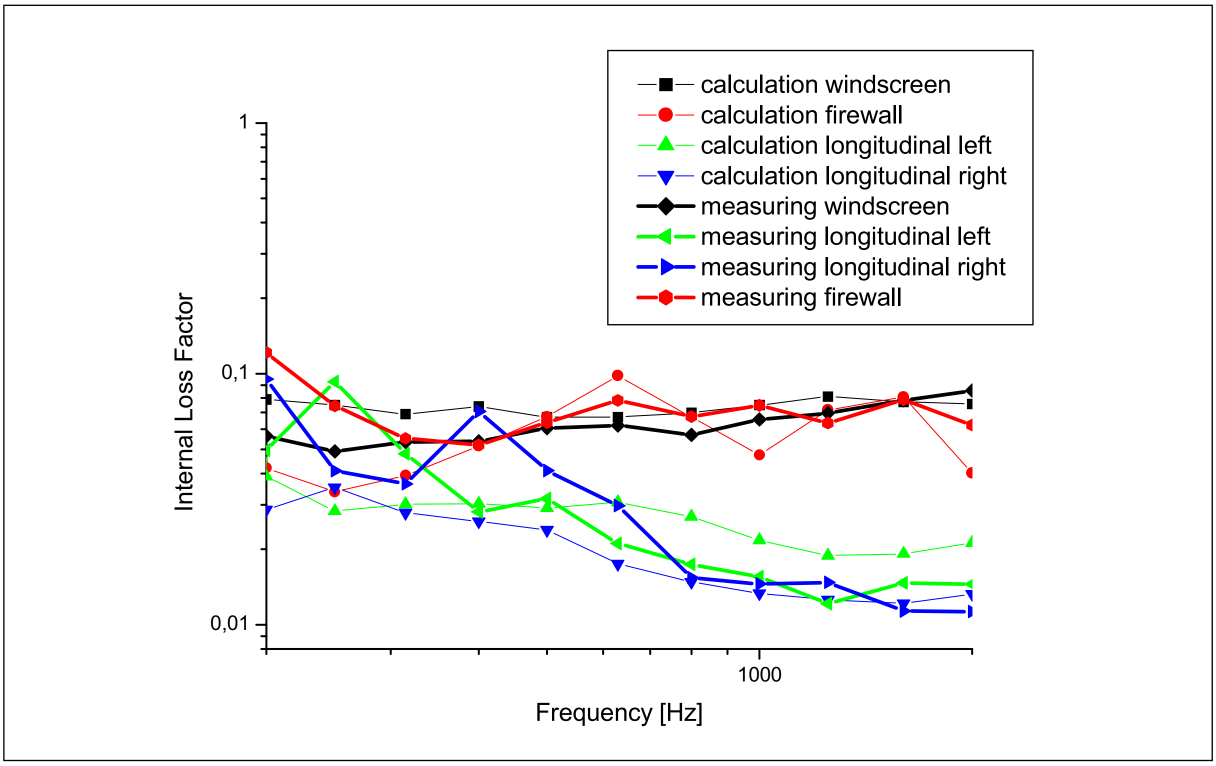

Figure 11: Comparison of measured and calculated internal loss factors for the car front.

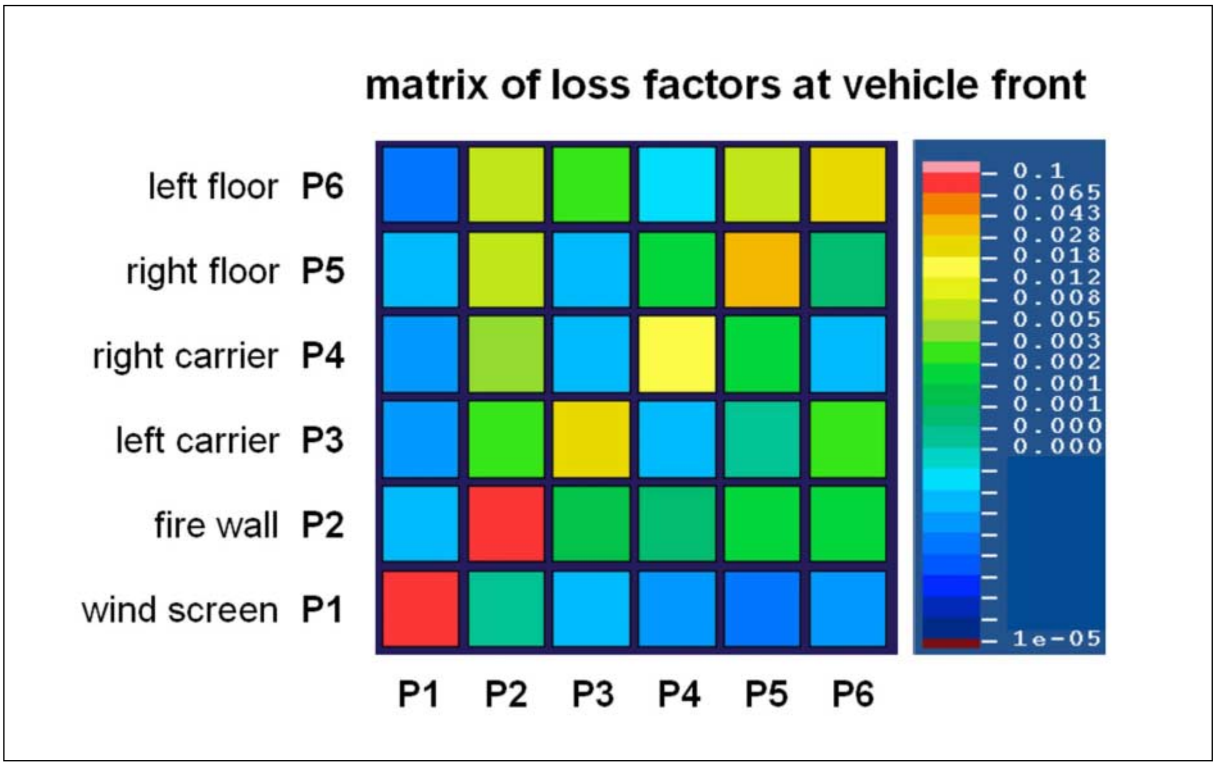

Figure 12: Matrix of calculated loss factors at 1250 Hz for a car front: Each element shows the coupling loss factor between two sub-areas Pi and the internal loss factors in the diagonal.

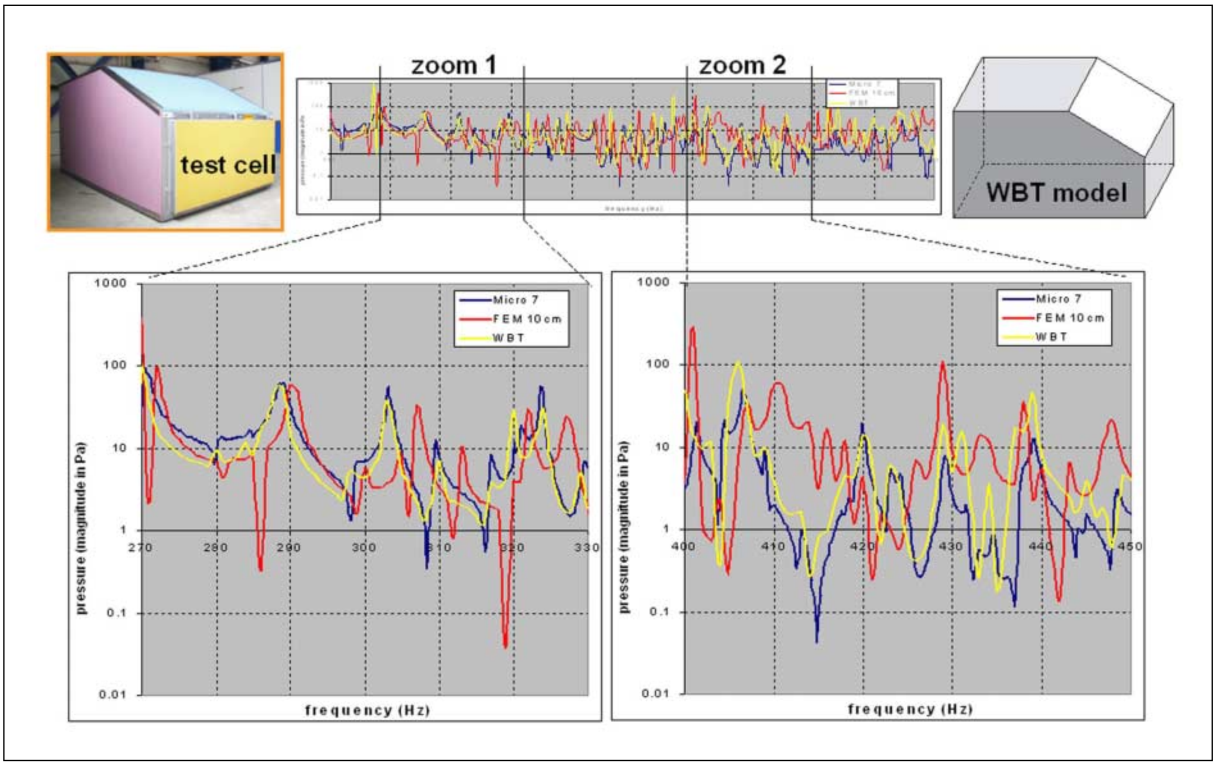

Figure 13: Validation of Wave Based Technique (WBT) using a test cavity made of concrete (Sound Brick), zoom of results comparing microphone measurement (micro 7), FEM (max. element length 10 cm) and WBT

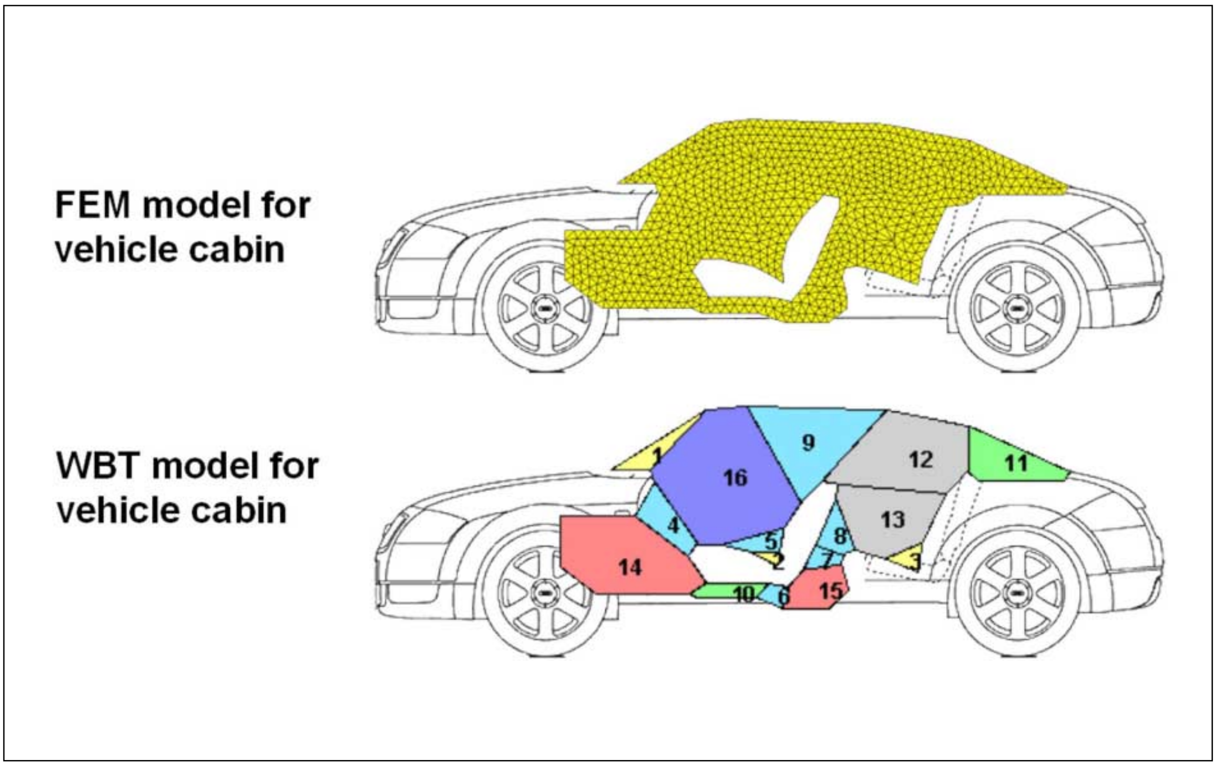

Figure 14: Ongoing development WBT for interior noise prediction of vehicles in collaboration with PMA KU Leuven