SZÉCHENYI ISTVÁN EGYETEM

MULTIDISZCIPLINÁRIS MŰSZAKI TUDOMÁNYI DOKTORI ISKOLA

Sipos Dávid

SIMULATION OF FULL VEHICLE ACOUSTICS IN MID-FREQUENCY RANGE

Doktori tézisek

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1. INTRODUCTION

The subjective comfort of vehicle passengers can be traced back to a series of factors, among which disturbing noises, vibrations and harsh, intrusive effects play a prominent role. The aforementioned effects are the same physical phenomena, they differ from each other only in the frequency range and in the way of human perception. The Noise, Vibration and Harshness (NVH) comfort features are not only one of the most important evaluation criteria of potential buyers but are closely related to travel safety as well since they can cause a feeling of discomfort and reduce the ability to concentrate. Buyers today prefer efficient, comfortable vehicles. Thus, car manufacturers have been investing huge efforts in product development to meet the often-conflicting conditions of customer demands. As an example, the interior noise can be reduced by adding noise insulators and damping materials, but the increased weight will affect the dynamics and the emissions or the energy consumption of the vehicle. As a result of these, the role of Virtual Prototyping (VP) and Computer Aided Engineering (CAE) methods is continuously increasing in the development process, enabling to achieve the desired vehicle characteristics and to evaluate various design options as quickly and cost-effectively as possible.

1.1. Characteristics of vehicle structures and noise sources

Thanks to advanced development methods, a modern vehicle features an integrated body and frame (unibody chassis) that provides lightweight design with adequate rigidity/stiffness. In such a structure, the entire car is a load-carrying unit, thus its specifics determine the dynamics, performance, comfort, safety, and many other characteristics of the vehicle. A wide range of materials is used, (see Figure 1) to maximize these characteristics while keeping the overall weight as low as possible. Due to the material diversity, several types of joining methods are used, as shown in Figure 2. These joining methods are extremely challenging to model in virtual prototypes, but they are decisive factors regarding the behavior of the complete model. In order to reduce the complexity of full-scale vehicle models, different model stages are distinguished. The least complex stage is called Body-in-White (BIW) that consists only of the chassis and the front and rear windshields. A Body-in-Blue (BIB) structure includes the front and rear doors, thus forming an enclosed internal cavity. The most complex stage is the Trimmed Body (TB) that includes all of the lining and trim elements in the passenger compartment, usually containing poro-elastic materials (PEM) such as foams, felts, etc. These materials contribute to noise reduction inside the cabin.

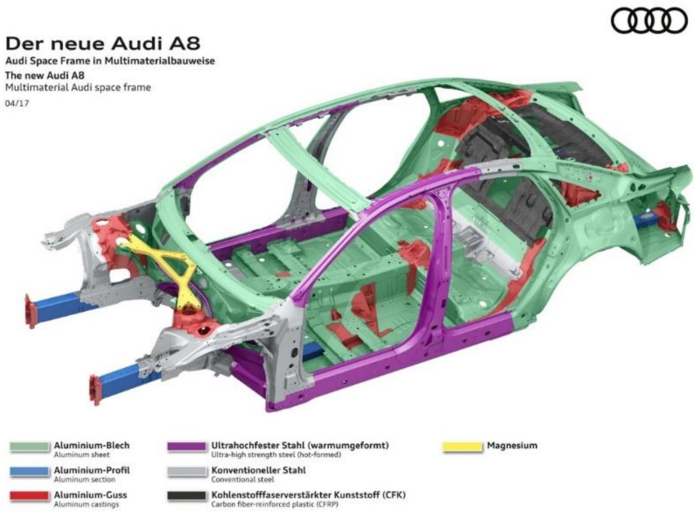

Figure 1. Multi-material vehicle chassis [1].

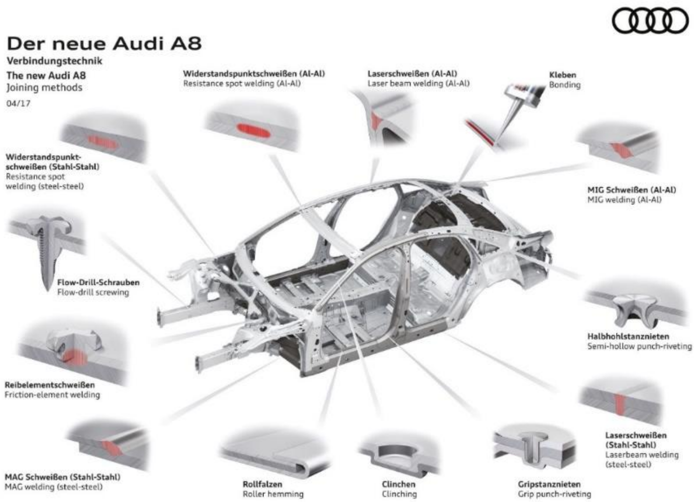

Figure 2. Joining methods in multi-material vehicle chassis [2].

There are two main sources from which noise could originate in a vehicle. Structure-borne noise is induced by the time-varying loads entering the chassis from the suspension and engine/motor mounts. The structure transfers these vibratory loads to the large, noise-radiating panels that in turn either excite the air in the cabin and generate noise or are perceived as vibrations by the passengers. Structure-borne noise generally falls within the low- and mid-frequency range (0-400 Hz and 400 – 1 000 Hz, respectively). Airborne noise, on the other hand, is typically induced by the pressure fluctuations in the surrounding air of the structure and is dominant in the high frequency range (above 1 000 Hz). These two distinct phenomena require different simulation tools for their prediction.

1.2. Methods and motivation

Several well-established CAE methods are available to assess the NVH characteristics of a vehicle in the early development phase depending on the frequency range to consider. Multibody Simulations (MBS) are typically used in the inaudible frequency range (below 20 Hz) for conducting motion analysis, to evaluate the comfort, safety, and dynamics of the vehicle. It is widely used for suspension design as well, which is a decisive factor in terms of rolling noise. Finite Element Analysis (FEA) is one of the most popular tools to solve complex engineering problems in various fields, including structural dynamics and acoustics. It uses Finite Element Method (FEM) to create a discretized mathematical model (mesh) of the model, in which connection points (nodes) the approximated solution of the displacement field is given by a set of algebraic equations. In dynamic analyses, at least 6-8 nodes per wavelength of the propagating waves are required to capture the vibrations of the model. In other words, the frequency range dictates the mesh density. Consequently, higher frequency simulations require finer mesh, which increases the computational requirements of the solution. However, there are other difficulties too in high frequency simulations that are challenging to solve by deterministic methods. These are the statistical nature of the frequency response, associated with the model uncertainty. With the increase of the frequency, the sensitivity to the model details, as well as the modal density of the structure increases. Thus, system level responses provided by energetic indicators would give more meaningful results. Statistical Energy Analysis (SEA) is the most widely used energetic approach in the high frequency range. In such analysis, the structure is subdivided into rather large panels and the spatially and frequency-averaged power balance of these is investigated. As Figure 3 shows, three distinct regions can be identified in the typical dynamic response of a model.

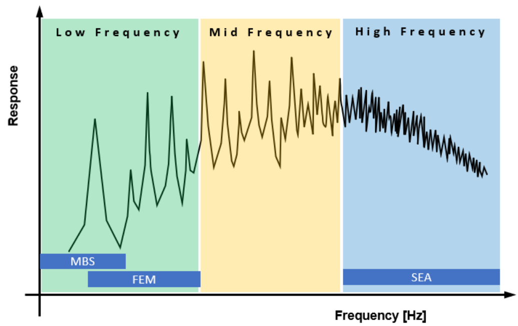

Figure 3. Typical dynamic response of a model and applicable methods.

Simulation methods, such as MBS and FEM cover the low frequency range where the response is deterministic and is driven by the global behavior of the model, typically below 400 Hz in the automotive industry. SEA is suitable at the other, high-frequency end of the spectrum (typically above 1 000 Hz), where the local behavior is dominant. However, in the transition zone, often called the “mid-frequency gap”, both methods reach their limitations, and their applicability is compromised. With the spread of electric vehicles, the need to develop a simulation tool able to provide comprehensive, broadband solution in the full frequency range is growing. This is because instead of an internal combustion engine, more disturbing noise sources (electric motor, inverter, etc.), emitting higher frequency excitations are installed in the vehicle. Therefore, the Dissertation aims to explore the limitations of state-of-the-art full vehicle acoustic simulation methods, as well as to enable the recently proposed Virtual SEA method to solve the “mid-frequency gap” problem. Various aspects of its capabilities, applicability and validity have been investigated and developed in the Dissertation.

The Dissertation is structured in the following way. First, a comprehensive literature review is provided in the field of full vehicle acoustic simulations with FEM and SEA, extraction of the SEA parameters, SEA sub-structuring and interior noise reduction. Based on this, the research gaps are identified, and the precise objectives of the Dissertation are formulated. After reviewing the theoretical background of the relevant numerical methods in detail, the solutions to the individual goals are discussed.

2. GOALS OF THE DISSERTATION

Based on the literate review and the identified research gaps, the main goal of the Dissertation is in general to assess and enable the Virtual SEA simulation method for the mid- and high frequency full vehicle acoustic simulations. The specific goals are:

1) To prove that the Virtual SEA approach is capable of considering the damping and coupling effects of different junction types through the proper finite element representation of the connection. In relation to this, the Dissertation aims to explore the influence of the finite element modeling parameters on the coupling and damping loss factors obtained via the virtual power injection method.
2) To demonstrate that the accuracy of the model depends on its sub-structuring and its compliance with the assumptions of SEA theory. Consequently, the goal is to propose a method that allows to create subsystems in a conscious and consistent way (instead of an ad-hoc, or experience-based approach) and provides the best possible subdivision of the model in terms of accuracy and SEA model validity point of view. To achieve this, a new method also needs to be proposed that allows the comparison of different subdivisions.
3) To perform a full vehicle trimmed body acoustic simulation in Virtual SEA, including an internal cavity as well as trim parts consisting of poro-elastic materials (PEM), and to validate these with experiments. This would provide validation of the specific approaches that enable the calculation of fluid-structure coupling and the consideration of the trim effects.
4) Last, the Dissertation aims to investigate how the energetic quantities computed during a Virtual SEA solution can be used for the NVH optimization of a vehicle chassis.

3. ASSESSMENT OF GOALS AND OUTLOOK

The main goal of the Dissertation was to enable the Virtual SEA approach to cover the mid- and high frequency vibro-acoustic simulations. Former studies already showed some of its key features that make it more effective than conventional simulation methods in certain cases. However, the Dissertation provides original contributions in achieving the goals that were defined in Chapter 3 of the Dissertation. First, it was shown in Chapter 5 that Virtual SEA is able to consider distinct types of junctions through the finite element representation of the connection, unlike analytical SEA. Various connection types were investigated by experimental and virtual power injection method and the results showed satisfactory agreement. The influence of the finite element modeling parameters was explored in a DOE, and the key factors, such as the thickness ratio of the connecting plates were identified with the help of response surfaces. Next, the validity of different SEA subdivisions was investigated in Chapter 6. It was proven that clustering methods lead to the best possible SEA models, thus providing better accuracy results than models built up based on intuition. In relation to this, a novel methodology was proposed that allows the comparison of different subdivisions. From several clustering techniques evaluated, the subsystem generation algorithm built into MSC Actran was proven to be the most effective method that facilitates reasonable and consistent model building and also saves resources. The following step of the enabling process was to create the vibro-acoustic Virtual SEA model of a full-scale, trimmed body vehicle. In this model, the fluid-structure coupling was realized by the SmEdA approach, and the effects of the trim bodies were considered by updating the affected damping and coupling loss factors, according to the analytical equivalent transfer admittance method. The results presented in Chapter 7 of the Dissertation confirm that Virtual SEA can be used for vehicle trimmed body simulations, with significantly less computational costs than finite element and reduced impedance methods. Consequently, Virtual SEA provides the transition of the low frequency finite element models to the mid- and high frequency range. The last goal of the Dissertation was to investigate how the energetic quantities computed during a Virtual SEA simulation can be used for optimization. It was found in Chapter 8 that the scalar field that distributes the subsystem energies between the subsystem nodes is proportional to the modal activity, thus it can be used to find the optimal distribution of damping layers on a vehicle chassis. The proposed method helped to save about 33% of the damping material used on the floor panel of a vehicle model while preserving the NVH performance. Furthermore, this was achieved by effectively no additional computation costs since the calculation of the scaling factor is part of a complete Virtual SEA simulation.

Future work could include the validation of other junction types that the Dissertation did not cover, such as bolted, riveted connections, in various angles, etc. For each junction type, a similar design of experiment could be used for exploring the effects of individual modeling parameters. Regarding the full vehicle simulations, the use of the automatic subsystem generation could result in even more accurate results. Once the placement of trim parts is considered during the subsystem generation, it can be used for trimmed body simulations as well. One could also explore the possibilities that other data mining methods such as Proper Orthogonal Decomposition (PDO), Machine Learning (ML), Artificial Intelligence (AI), etc. could offer to reduce the computational costs or improve the results of the subsystem generation process. Further studies could investigate how the presence of trim parts alters the extended solution of Virtual SEA, which would also require high-frequency measurements for the validations. The modeling method of the more complex-shaped trim bodies that cannot be described as a multilayered composite material needs to be worked out. One drawback of the Virtual SEA method is that the modal base needs to be recalculated for every single change in the model. Solving this could help the method to spread more quickly in the vehicle industry, where design cycles can be quite frequent. The Dissertation showed that the Virtual SEA method has immense potential to cover the mid- and high frequency range for full vehicle trimmed body acoustic simulations.

4. SUMMARY OF NEW SCIENTIFIC RESULTS

4.1. Thesis 1

In Chapter 5, I proved that the damping and coupling effects of various junction types can be accurately considered in Virtual SEA through the proper finite element representation of the connection. The most common junction types that can be found on a vehicle chassis structure have been validated by comparing experimental and virtual power injection method results for set of coupled plates. The effects of the finite element connection modeling parameters have been explored in a Design of Experiment, and I proved that the most influential ones are the geometrical properties, in particular, the thickness ratio of the connecting plates. The changes in the connecting element stiffness and the diameter of the connection point have less influence on the Virtual PIM results [II].

4.2. Thesis 2

In Chapter 6, I formulated a novel procedure to compare different subsystem divisions for the Virtual SEA approach. Based on this procedure, I proved that clustering algorithms are able to provide subsystem divisions that comply more with the assumptions of the SEA theory than the user-defined subsystems. The automatic subsystem generation feature implemented in MSC Actran has been proven to be superior to other clustering methods. I proved that ultimately, clustering-based subsystems lead to more accurate Virtual SEA models to be created in a more reasonable and consistent way, with less time spent on model building [I].

4.3. Thesis 3

In Chapter 7, I proved that Virtual SEA is capable of performing industrial-scaled, full vehicle trimmed body acoustic simulations in the mid-frequency range, with prediction accuracy comparable to finite element method, using:

- SmEdA approach, for the structure-fluid coupling,
- analytical equivalent transfer admittance method, for considering the damping, absorption, and insulation effect of multilayered, trim parts containing poro-elastic materials.

As such, I proved that Virtual SEA provides transition of the low frequency finite element models to the mid- and high frequency range [V].

4.4. Thesis 4

In Chapter 8, I formulated a novel methodology to determine the optimal location of damping pads on a vehicle chassis structure for a given frequency range. The methodology relies on the scaling factor of subsystem energy levels that distributes subsystem energies along the finite element nodes to retrieve local responses in MSC Actran's Virtual SEA module. I proved that this method enables to reduce to overall weight and coverage of damping layers on the vehicle chassis while preserving its NVH performance. An additional advantage is that the required scalar field is calculated during a Virtual SEA simulation, which means that the proposed method adds no extra computational cost to the overall solution [III].

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