

# Hybrid NVH Simulation for Electrical Vehicles II – Structural Model

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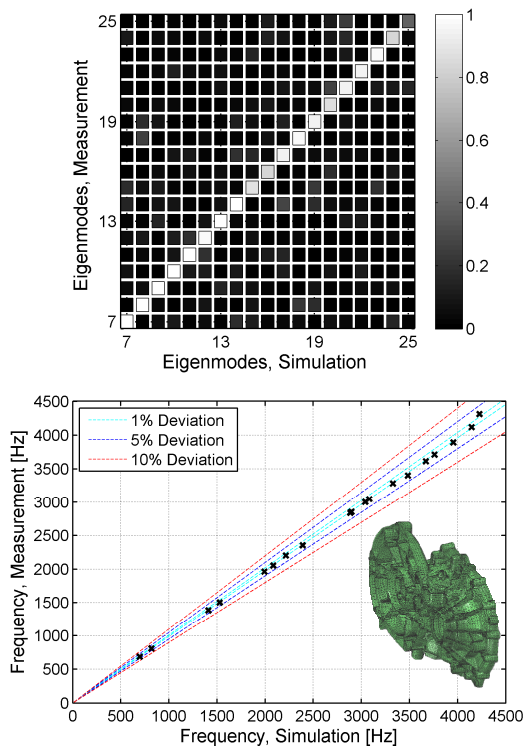
## Introduction

The FVA research project No.682 provides a fast, modifiable simulation tool starting with a model for the electrical drive train and resulting in a binaural auralization in the car cabin. The tool enables developers to freely change the properties of the electric drive components and listen to the resulting acoustics within a short time span.

For this purpose, a fully-coupled drive train simulation model has been developed for the calculation of surface velocities and forces. The goal is a valid high frequency (<5000Hz) Multi-Body-Simulation (MBS) model of the drive train which fulfills the requirements of the entire simulation method for a binaural auralization. Therefore, a possibility for implementation of electromagnetic forces is needed and the exporting of surface velocities and forces at specific points is necessary.

## Modeling and Validation

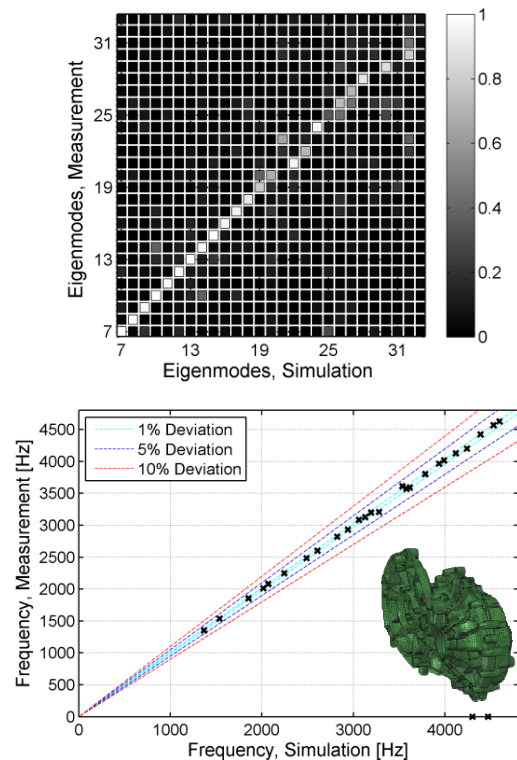
The drive train is a strongly coupled system and consists of shafts, bearings, fasteners, cooling fluid, and the housing. Due to the strong coupling of these parts, mode shapes are expected at higher frequencies, which are influenced by the elasticity of the specified elements. Thus, these parts are



**Figure 2:** Validation of a housing part: mode shapes (above) and eigenfrequencies (below)

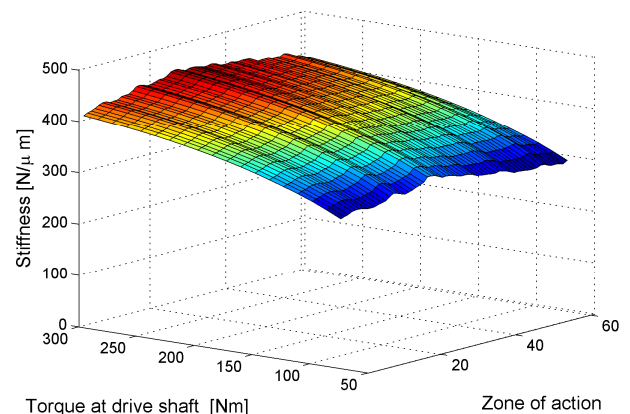
modeled using the Finite Element Method (FEM) and

validated by measurements in both components and assemblies. An exemplary result for a component is shown in Figure 2. The validation of the mode shapes is performed using the Modal Assurance Criterion (MAC) [EWI].



**Figure 3:** Validation of an assembly: mode shapes (above) and eigenfrequencies (below)

Even though the structure is very complex, the results are good up to a high frequency range. Same way assemblies are validated. For example the coupled gearbox parts shown in

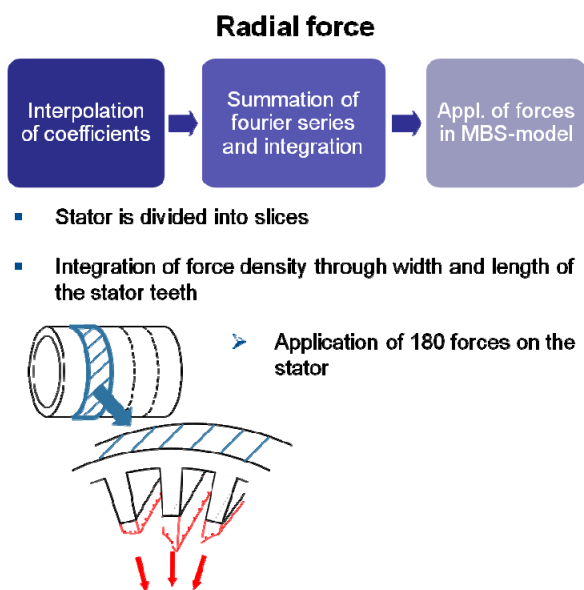


**Figure 1:** Example of a load-dependent tooth stiffness

Figure 3. These parts are coupled by a partial contact zone with infinite stiffness. To proof the validity of this modeling

strategy the comparison in Figure 3 is done. A lot of eigenfrequencies are very close together, therefore small deviations in frequency change the numbering order of the mode shapes. For this reason the MAC values close to one are not on the diagonal in Figure 3 (above), but overall a lot of mode shapes agree very well.

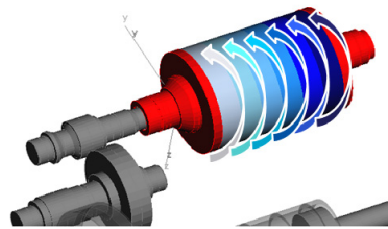
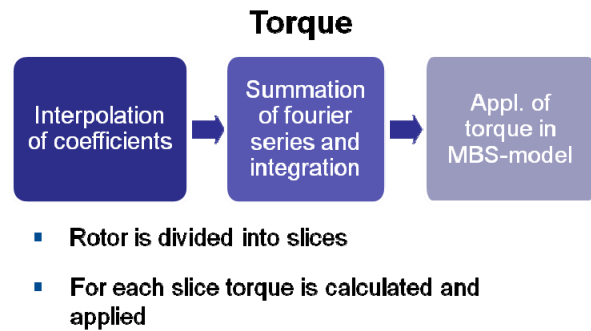
A special focus is the structural modeling of the stator with windings and the stator housing with cooling fluid. Along with the model building process, a method has been developed to parameterize a material model for orthotropic material behavior of the stator with windings [WEG]. Because of the lamination of the stator an isotropic material model is not recommended. The lamination combined with the windings lead to a description by non-uniform Young's moduli and shear moduli in different directions. Therefore mode shapes and eigenfrequencies are influenced. The resulting model is validated for a frequency range up to 3000Hz. Furthermore, it is evident that the cooling fluid has an important effect on the structural behavior of the system, and hence, the fluid is also implemented in the structural model. For the connection of the structural housing model to the elastic shafts, stiffness matrices are defined which contain the load-dependent stiffness values. For modeling the force excitation of gear stages, a User Force is used. The User Force MBS-Gear has been developed in the context of an FVA-Research project [D2S]. By using this User Force, the varying stiffness of the gear stages interacts with the dynamic behavior of the drive train. A load dependent characteristic is shown in Figure 1.



**Figure 4:** Application of electromagnetic force on elastic bodies

In addition, the implementation of radial forces and engine torque, produced by the electromagnetic field, is needed. The force and torque must be applied on the elastic bodies. For this purpose, another User Force has been programmed. The input for the User Force is given by a matrix calculated by the Institute of Electrical Machines [RIC]. The matrix contains coefficients for the Fourier series of the force density acting on the stator teeth. The force is calculated based on the rotor angle, and distributed along the

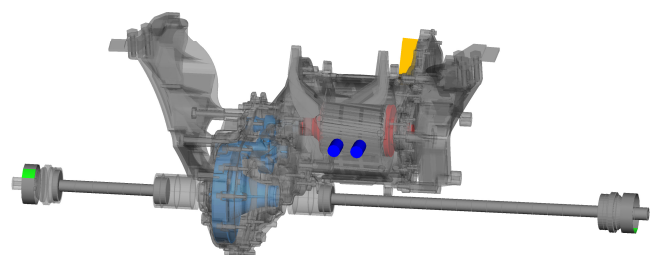
circumference of the stator. The general workaround of the User Force is explained in Figure 4.



**Figure 6:** Application engine torque on elastic bodies

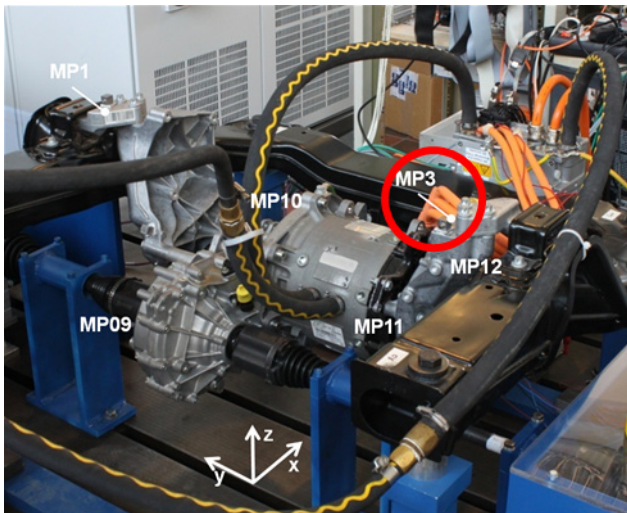
Analogous to the radial force, the torque is calculated and applied (Figure 6). The cyclic irregularity of the torque is considered as well.

All described parts and User Forces are brought together in a Simpack model in the Multi-Body environment. Beside the explained parts, additional elements like the support arms, the electrical connection, and the cooling connection are also implemented. The shown model satisfies the boundary conditions of the setup on the test rig at IEM (see Figure 7).



**Figure 5:** Drive Train in the Multi-Body Software Simpack

The elastic mounts between the entire drive train and the main frame of the car belong to the aforementioned boundary conditions of the model. The stiffness of elastomeric elements has a nonlinear characteristic and depends on the preload, amplitude, frequency, and temperature. Within this project, only the influence by preload is considered. By using modal analysis of the drive train on the test rig, the mode shapes and eigenfrequencies are derived. Parameters for the elastic mountings are determinable based on the given stiffness data for one

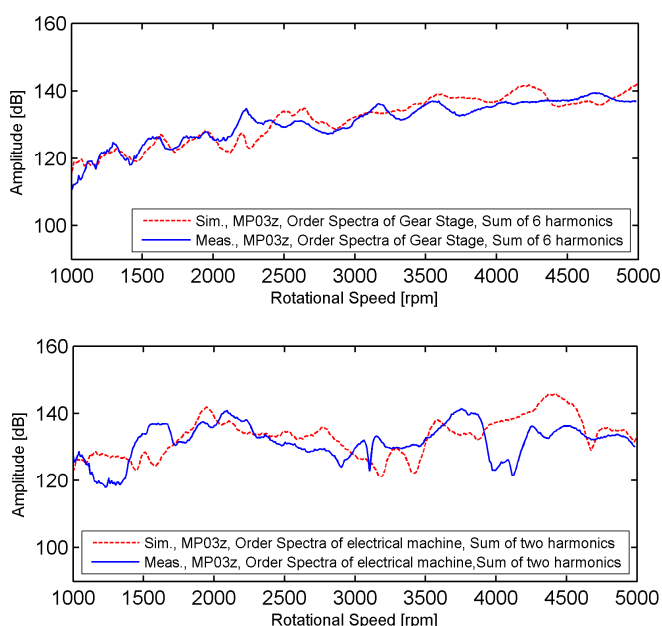


**Figure 7:** Drive train on bracing test rig at IEM

specific operating point and the knowledge about the vibration behavior of the system for different operating points.

The final validation of the entire system, mounted in the main frame, takes place in the frequency domain. Based on measurements of acceleration in time domain, order spectra are calculated. In general, the validation process is performed for each elastic mounting point (e.g. Measurement Points 1 and 3 (MP 1 and MP 3) in Figure 7, the second point is not visible in the picture).

Run-ups were carried out at different load conditions. In Figure 8 the comparison under full load condition is shown. For a comprehensible analysis of the different excitation mechanism (here tooth meshing and engine), the order spectra are performed for each subsystem. The dominant orders of each subsystem are then added and printed. For the case of the gear stage, the first six harmonics are added. In the event of the electrical machine, the first two harmonics are combined.



**Figure 8:** Comparison of measured and simulated order spectra (acceleration) at MP3

Results in Figure 8 show correlating effects. Hence, the main influences on the NVH-behavior of the entire system are described up to high frequency range. The model can be used for further investigations on a hybrid simulation method with the goal of a binaural auralization in the car cabin [KLE].

## Summary and Outlook

This work presents a validated model building process for a structural model of an electric drive train in the MBS environment. Housings and shafts are modeled in an elastic way and coupled to each other by stiffness matrices. The electromagnetic forces and torque are implemented and simulations in time domain are possible. The final validation of the entire system is done by comparison of order spectra of each excitation subsystem (for each gear stage and the electrical machine). Due to the simulation of elastic bodies the export of surface velocities is possible. Surface velocities are needed for the binaural auralization [KLE]. Further investigations for acoustical optimization of the entire system are shown in [FVA].

## Acknowledgment

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