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Top-down Validation Framework for Efficient and Low Noise Electric Driven Vehicles with Shiftable Gearbox

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Summary

The shift towards e-mobility is resulting in new technological challenges. Due to that, new methods for a more efficient product development and a better product understanding are required. During the product development, activities of validation significantly contribute to generate knowledge of a system as well as to fulfill the characteristics customers expect. Based on existing top-down validation approaches this article discusses a Both-Ends-Against-the-Middle-approach. A physical-virtual coupled validation framework is presented. As an example, the development approach is introduced for the toothing validation layer of the powertrain of an electric driven vehicle with shiftable gearbox.

Keywords: electric drive, noise, gear, powertrain, simulation

1. Introduction

Facing todays challenges in electrical powertrain development, more often shiftable gearboxes are used due to the improved efficiency utilization [1, 2]. Finding the appropriate combination of motor and gearbox, different methods are available. The methods lead to an optimized powertrain topology in terms of efficiency [2, 3, 4] and considering the customers' requirements [1, 5]. Shiftable gearboxes also enable the use of lighter electric motors with higher maximum rotational speeds, which decreases the costs [1]. However, the increasing rotational speeds and the missing acoustic masking of the combustion engine lead to a more frequent occurrence and recognition of the gear noises by the driver. In particular, the tooth mesh and its behavior are a source for noises and require a holistic consideration through the development process. Therefore, several methods, for example, the optimization of the macro- and microgeometry of gears [6] or the reduction of the tonality of gear noises [7] are discussed. Available analytical models describe the influence of profile shifts on the mesh stiffness of spur gears [8]. In addition, the vibration and acoustic radiation of gearbox housings based on 3D-simulations as well as the influence of different gearbox macro designs on efficiency and vibration at high speeds have been discussed [9, 10]. Methods of generating acoustic optimized gears or efficiency optimized gearbox designs are known as shown above. However, a further holistic approach for the determination of the interaction between efficiency and noise behavior in the early stages of the product development is desired.

Validation is the main activity of the product development to generate knowledge and to fulfill the characteristics of the product customers expect [11]. By the use of mixed physical-virtual validation environments, early studies of the product behavior are possible [12]. The X-in-the-Loop framework (XiL) supports the validation activities and the development of validation environments, leading to a faster and more efficient product development [13, 14, 15]. Methods to create a physical validation environment, in particular for the acoustic analysis, are also known and exemplary described [16, 17].

XiL is used to validate product properties over a wide range of development stages without the need for a whole-system prototype. Considering validation as a multi-layer activity, the X stands for the system in question on the particular layer. Independently of the layer at which a system is validated, the consequent consideration of the user and its environment is a major part of the XiL framework. This can be shown particularly clearly in the validation of vehicles, since here the driver is in a close interaction with the system as well as the environment including the routes, weather conditions et cetera, see Figure 1. The first step is the definition of the unit under test and the specification of the rest-system properties required for the particular purpose of the test. The system is then divided into subsystems, which are either physical or virtual without losing the closed control loop shown in Figure 1.

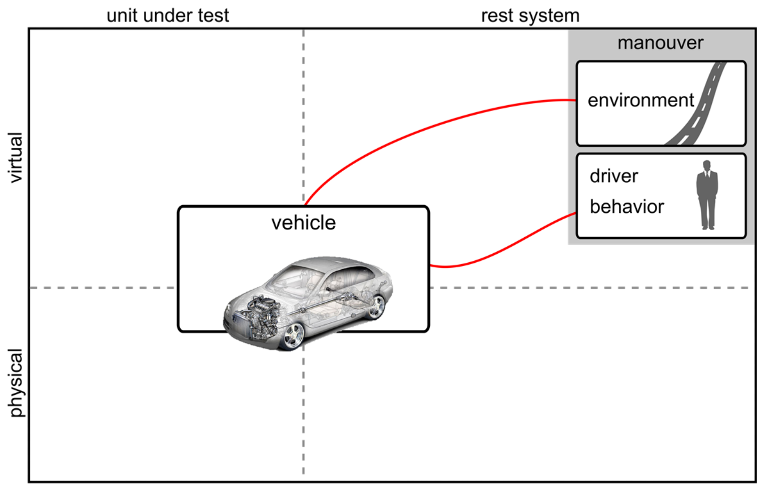

Figure 1: System layout, vehicle-in-the-Loop

By a combination of the approaches and frameworks shown above with meta models such as the V-Model [18], the integrated Product engineering Model (iPeM) [19] or the Munich Procedural Model (MPM) [20], a frontloading of activities can be realized. Considering XiL as the basis of a top-down planned validation, the established processes of Simultaneous Engineering and Concurrent Engineering can be combined to a new validation approach. That optimized top-down validation approach can lead to a simultaneous development of the physical as well as the virtual models in a Both-Ends-Against-the-Middle approach (BEATM) [21, 14].

Above all, there is the challenge of the development of, by physical tests validated, virtual models which enable the evaluation of acoustic quantities as well as the efficiency in early stages of the product development.

2. Top-Down Framework and Model Implementation

Based on the above introduced XiL framework and top-down validation approaches, the framework for all the project topics is set. Planning the validation from the top-level, leads here to a four-layer environment. The main focus by working on solutions for optimized powertrain units is still the whole vehicle with its real behavior in a real environment with a real driver. In particular the drivers sense for vibration and sound must be considered on all validation layers. Hence, on the top-level vehicle tests according to Figure 1 are planned.

Reducing the real vehicle by the chassis, the wheels, the side shafts and the battery is leading to the second validation layer (layer 2, see Figure 2). On that layer the motor-gearbox-unit represents the physical unit under test, the setup for a powertrain test rig is given. According to the XiL framework the cut off systems are part of the virtual rest system as well as the environment and the driver behavior, compare the system layout in Figure 2. The red lines indicate the interaction between the physical and the virtual domains, which leads to the need of proper sensors and actuators on the test rig as well as a real time capable simulation software. Reducing this system by the traction motor, leads to a gearbox test environment on the third validation layer which is not further discussed in that article. However, it is worth noticing that the interaction between all the validation layers is considered and is leading to the intended connection of the layers and the results. On the fourth validation layer the tooth mesh as the physical unit under test is left, all the other vehicle components are part of the virtual rest system.

By planning the validation in a top-down order, all the interfaces of the systems as well as the validation layers are set and can be appropriately realized. The implementation of the tests (both physical and virtual) is usually performed in a bottom-up order. Please see for further results on the process view the discussion of the extended validation approach in section 5.

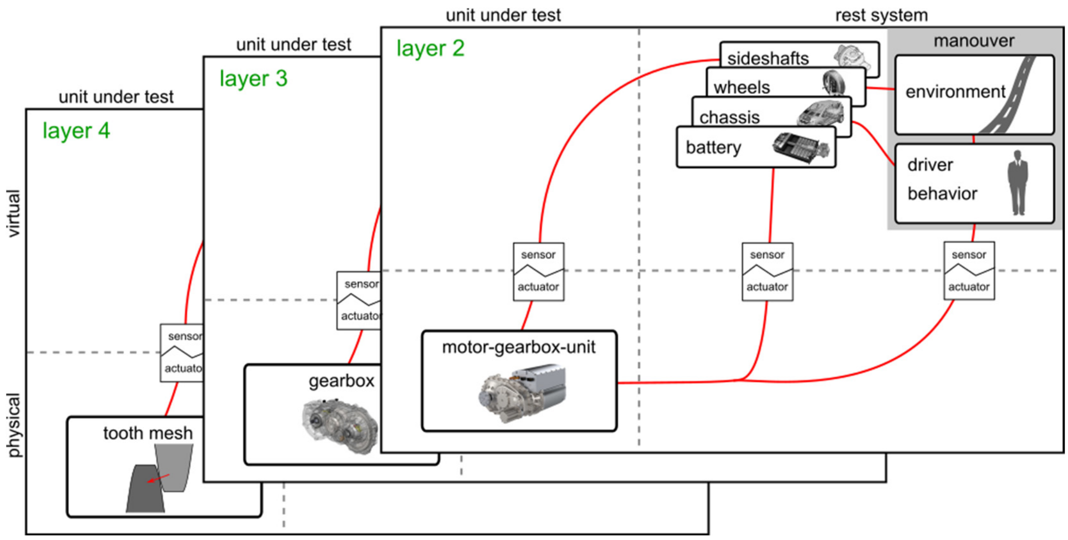

Figure 2: XiL system layout

The model implementation as described below (sections 3 and 4) is based on that system layout. Starting the implementation activities on the fourth validation layer, leads to a gear mesh study which objective is to gather results for optimized gears regarding sound emission and efficiency. The virtual domain of that layer is described in section 3, for the physical domain see section 4.

In addition to the above introduced framework, a model-based validation environment is established as shown in Figure 3. It shows the content of both the virtual and physical domains as well as the interfaces between them. The objective is to achieve validated models of the gear mesh. Therefore, the detailed toothing data is calculated by a professional gear calculation software by a project partner from industry. These parameters are used as input for the virtual domain as well as manufacturing parameters in the physical domain.

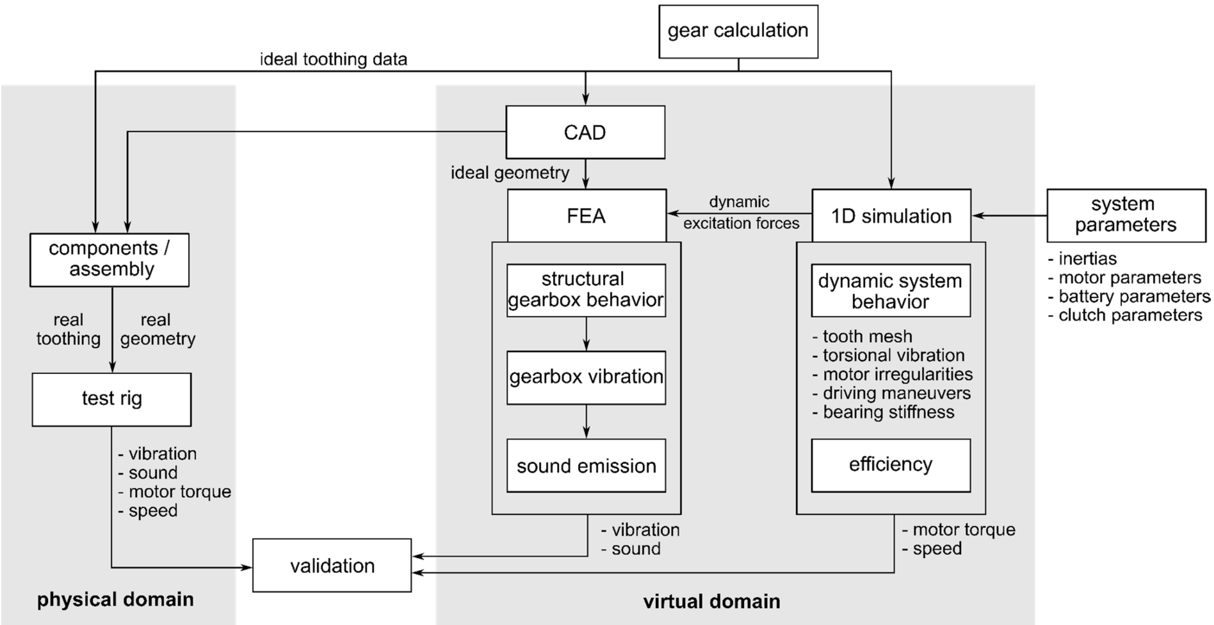

Figure 3: Model implementation

3. Virtual Model Implementation

To calculate the dynamic system behavior and the efficiency of the gear pair, a 1D simulation software is used. Subsequently, the dynamic excitation forces at the housing are passed on a Finite Element Analysis (FEA), where firstly the structural behavior of the ideal gearbox housing geometry is considered. By coupling the structural behavior and the excitation forces from the 1D simulation, the gearbox vibration and the sound emission (both air-borne and structure-borne) can be estimated. Those results are compared with the results from the physical domain.

The 1D simulation model contains the shafts (including their masses), ideal gears (including their masses, inertias and gearing parameters) and the bearings (including their stiffness and damping coefficients). Figure 4 shows an overview of the implemented system.

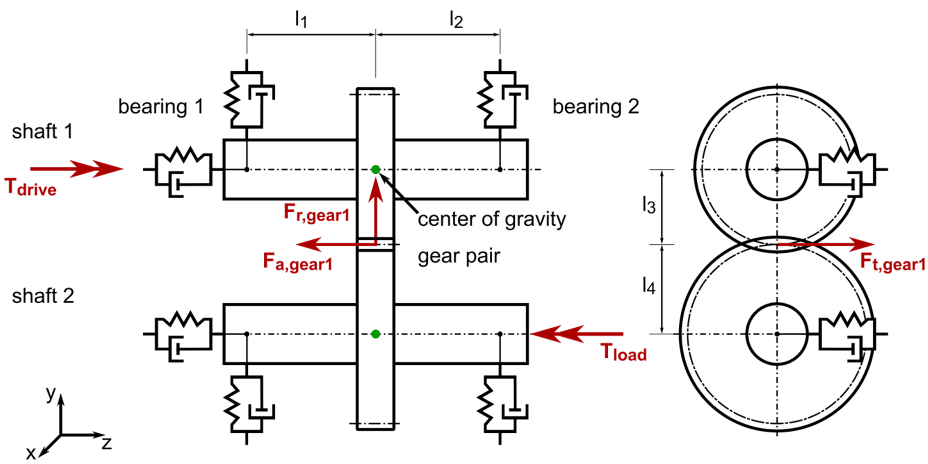

Figure 4: Gear system

The simulation model is divided into a rotational and a translational domain. In the rotational model an electric motor sets a drive torque. Therefore, a speed-torque-characteristic of a real electric motor is used. With the help of a simple control loop different load torques can be defined, depending on a desired speed. In between, a gear pair model calculates the transmission behavior of the gears, including the parameters from the gear calculation. Figure 5 shows a detail of the rotational system in the 1D simulation software.

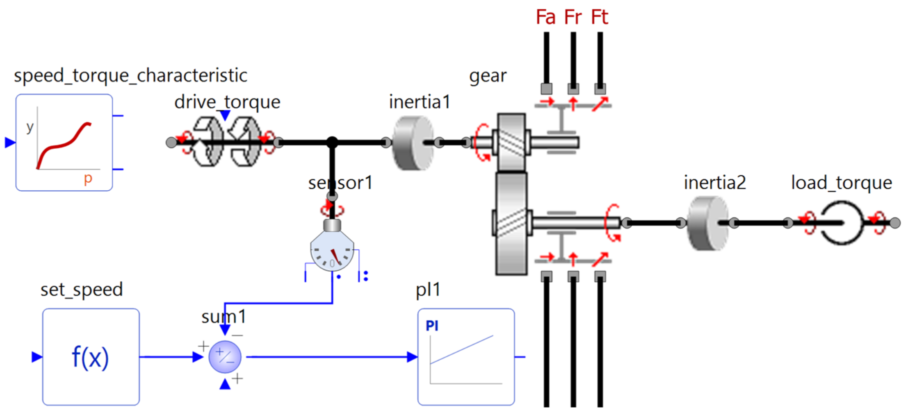

Figure 5: Rotational system in the simulation environment

The translational system is used for the calculation of the bearing reaction forces. Therefore, the tooth forces are provided by the gear pair model. Each shaft is represented by two translational models respecting the moment and force equilibrium. To calculate the bearing reaction forces at the gearbox housing in z- and y-direction the axial and radial tooth forces are used, see the coordinate system in Figure 4. The second translational model calculates the bearing reaction force in x-direction using the tangential tooth forces. The bearings itself are implemented by spring-damper-elements, for the consideration of the bearing stiffness and damping. A simulation model detail for gear shaft 1 is shown in Figure 6. The inner forces of the spring damper models represent the resulting forces in three directions and can be used for the following FE analyses.

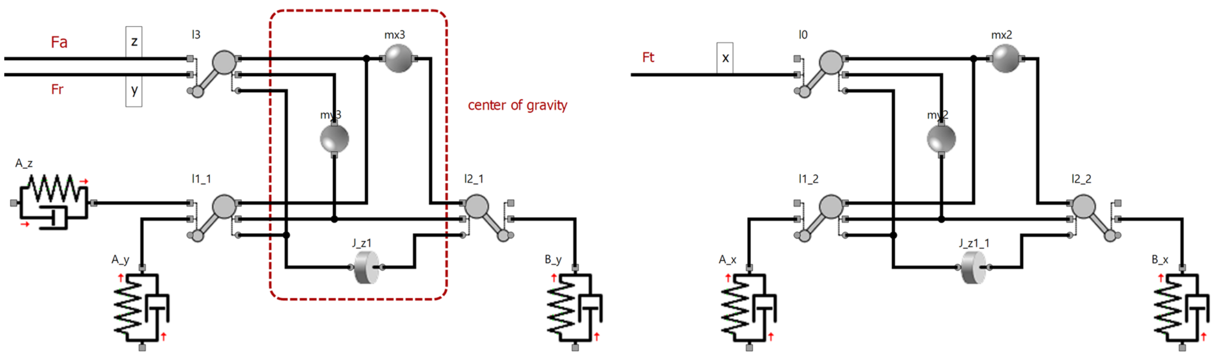

Figure 6: Translational systems for the calculation of the bearing forces in z- and y-direction (left) and x-direction (right)

To perform dynamic 3D FE analyses, the project schematic as shown in Figure 7 is set. The geometry block contains the solid domain (the gearbox housing) for structural analyses as well as the fluid domain (the acoustic region, air enclosing the gearbox housing) for the acoustic analysis. Based on a modal analysis for the determination of the eigenfrequencies and their shapes, a harmonic (frequency response) analysis with modal superposition is performed. As an input of the harmonic analysis, the dynamic bearing loads derived from the 1D simulation are used. The structural behavior calculated in the harmonic analysis is used as input for the acoustic analysis which estimates the acoustic parameters.

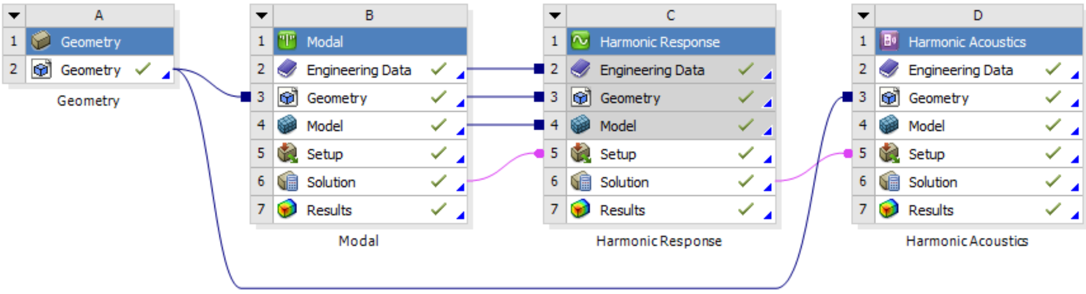

Figure 7: FEA project schematic

Figure 8 shows a result of the harmonic analysis. In the velocity amplitude spectrum (right) of a specific surface of the gearbox housing the eigenfrequencies are indicated by higher amplitude which are fed by the dynamic forces at the bearings. Figure 8, left exemplarily shows the deformation of the gearbox housing at a specific eigenfrequency. To predict the acoustic behavior of the system (in particular the air-borne sound emission), the acoustic analysis uses the results of the harmonic analysis.

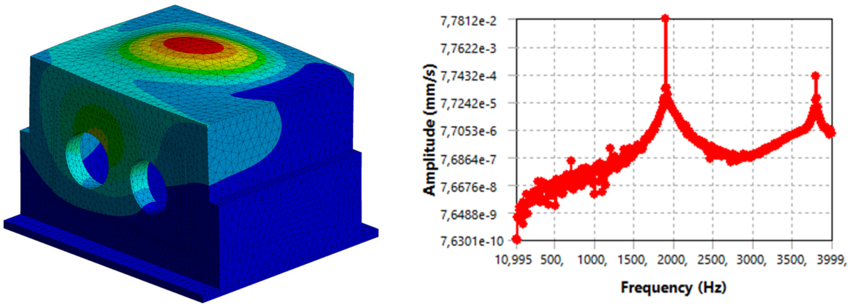

Figure 8: FEA deformation result of the harmonic analysis (left), velocity amplitude spectrum (right)

The acoustic analysis uses the fluid domain of the imported geometry. The load is applied by coupling the surface velocities calculated by the harmonic analysis to the interface surface of the fluid (air). Considering the acoustic coefficients of radiation, the sound parameters in the fluid region are calculated. Exemplarily, the sound pressure distribution within the fluid at a specific frequency is shown in Figure 9, left. The frequency spectrum (right) shows the sound pressure level at a specific point. These results can be used as a reference for physical tests, like structure-borne or air-borne sound measurements for validating the implemented virtual models (both 1D and 3D). Additionally, they can be used for further optimization loops of the gears and the housing.

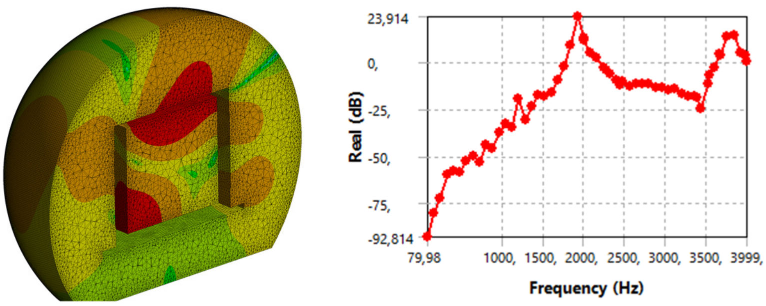

Figure 9: FEA sound pressure result (left), sound pressure spectrum (right)

4. Physical Validation Environment and Methods

To validate the results of the virtual models as described above, the physical domain is being developed according to Figure 3. The objective is to get validated virtual models of the gear mesh and the toothing parameters as well as information about the quality of the acoustic simulation. Since the parameter changes in the gears are in a micron range, a geometrically precise test rig is needed. Due to that and the high rotational speeds (up to 20.000 rpm) and high system frequencies (in particular from the gear mesh), sensors for torque, speed and sound pressure (structure-borne, air-borne) with highest accuracy are required. Figure 10 shows a rendering of the test rig. Like the simulation model described in the previous section, the test rig consists of a gear pair which is driven by two electric motors. Both are controlled by a real-time capable automatization software. By means of that, the feasibility of a rest system simulation according to section 2 is given.

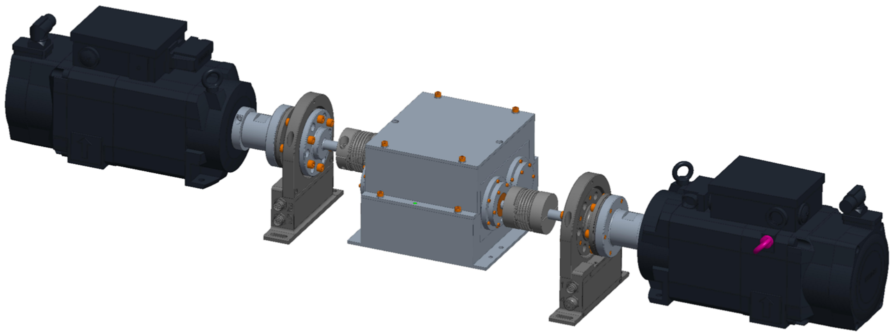

Figure 10: Physical validation environment

During the design process the bearing rollover frequencies as well as the torsional eigenfrequencies of the entire powertrain were considered. The gearbox housing has a determined structural behavior as described above. Thus, critical operating points and ideal positions for the placing of accelerometers are known. Due to the high influence of the concentricity to the vibration excitation, the gears are connected to the shaft by an optimized cone clamping sleeve. This ensures that the alignment of the gears after a replacement has the same quality.

According to the 3D simulation results, it is expected that the air-borne sound pressure level is pretty low. Therefore, the usability of the results must be checked. Appropriate software systems and data acquisition modules for the recording and processing of the data are already available. It is also possible to determine the efficiency of the gear pair enabled by the high precision speed and torque measurement data. This allows a combined analysis of efficiency and acoustics and the interaction between them.

To validate the simulation models which were implemented during the development of the test rig, physical testing has to be applied. For the validation of the calculated eigenfrequencies and their shapes of the gearbox housing an experimental modal analysis will be applied. Real experimental studies on the rollover frequencies of the bearings and the natural frequencies of the torsional vibrations will also be performed. In addition, the frequency response of the gear housing is measured at certain operating points (e.g. certain speed). Thereby, a statement can be made whether excessive frequency amplitudes occur at specific tooth meshing frequencies, due to the excitation of the natural frequencies of the gear housing. In addition, the acoustic simulation will be validated with real measurements. For this purpose, the same points as in the simulation are selected and the structure-borne sound is measured at this location. The required hardware for the physical analyses is available. This includes acceleration sensors for the modal analysis of the gearbox housing as well as high-resolution microphones and structure-borne sound sensors for the acoustic analysis. A dedicated analysis software is also available.

5. Extended Validation Approach

Obviously, there is an ongoing process of discussion and extension of the available validation approaches and frameworks. A Both-Ends-Against-the-Middle-approach (BEATM) introduced by the authors of this article is also available. The focus here is to make clear that validation is both a top-down and bottom-up activity.

The concept of the BEATM-approach is shown in Figure 11. Starting the product development process with planning the validation activities from the top to the bottom (from vehicle to gear pair, as described in section 2), the appropriate consideration of the rest system behavior at each validation layer is possible, compare the top-down planned activities shown in Figure 11. After that top-down planning of the activities the simultaneous development of virtual validation models as well as the physical validation environment is performed according to Figure 3 in section 2. The integration of the model itself is mostly a stand-alone activity without an interface to the validation layer. Hence, a bottom-up approach as shown in Figure 11 is performed. Depending on the time of the model implementation, not all the information required for this is available. Nevertheless, the idea of the result transferability from layer to layer must be considered. That just can be achieved by the validation of all (sub)models which are implemented. Consequently, it is possible to come to validated whole-system models by the combination of validated submodels although the model complexity is increasing from layer to layer and over the time of development.

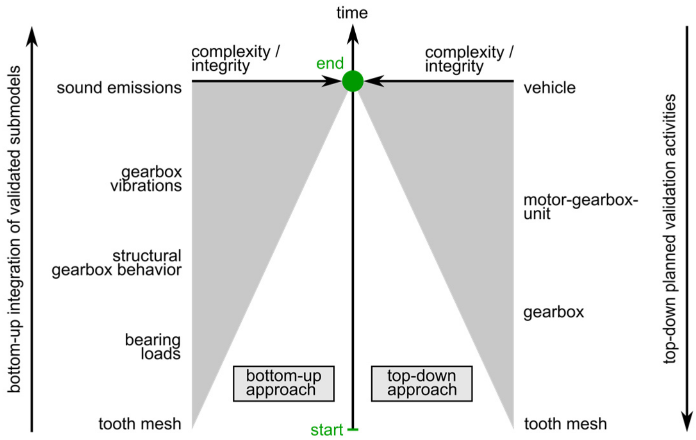

Figure 11: Both-Ends-Against-the-Middle-approach (BEATM)

By that, a real frontloading of validation activities in the product development process can be achieved. Working with these validated submodels guarantees, that there is an awareness for the customers' requirements over the entire development process, regardless of the validation layer on which is worked on. At the end all the implemented and physically validated models can be used for the development of further products with similar requirement. They can be transferred in a product development and reference process framework.

By the clarified combination of the bottom-up and top-down activities, existing validation approaches are extended. Thus, the contents of the virtual and physical domains meet at the end of the development and validation time line, meaning that both ends are striving to the middle. Compared with other process models, a better understanding of the product development is possible.

6. Conclusion

Based on available approaches and frameworks a physical-virtual coupled validation environment for noise and efficiency studies is introduced. Existing approaches are extended by a combination of bottom-up and top-down validation activities.

The virtual domain for a gear pair test is represented by 1D simulation models, which enable the estimation of the dynamic system behavior of a gear pair and the respective shafts, including the bearing behavior by stiffness and damping coefficients. By means of that, the reaction forces at the housing are calculated. Subsequently, a 3D FE analysis is performed, in which firstly the modal behavior is computed and secondly the frequency response is estimated, using the reaction forces from the 1D simulation as an input. Based on the results of the frequency response analysis, respectively the surface velocities at the gearbox housing, an estimation of the emitted air-borne as well as structure-borne sound can be made by an acoustic analysis.

Controlled by a real-time capable automatization software, a test rig including two electric motors will be representing the physical domain. Main objective of the test rig operation is the validation of the results from the 1D and 3D simulation models. The test rig behavior needs to be validated in the future, followed by the start of testing. Also, the extension of the virtual models regarding the efficiency is planned. Finally, the transferring of the Both-Ends-Against-the-Middle-approach (BEATM) into a reference process model is yet to be made.

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Presenter Biography

Steffen Jäger is Professor at the Furtwangen University since 2018 and is teaching in the fields of development and design methodology. After completing his doctorate in the Drive Technology Research Group at the Karlsruhe Institute of Technology (KIT), he worked in a spin-off he co-founded. The focus of his activities is the product development and validation of drive systems and their components