Electric Drive Noise and Vibration Analysis

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Abstract

Next-generation vehicles will be electrically powered, which means that the internal combustion engine will no longer be the dominant noise source. Thus, crafting the acoustic experience inside the vehicle is of high importance to meet the quality expectations of consumers. One step towards understanding the overall electric vehicle acoustics is to investigate noise and vibration characteristics of the electric drive system. In addition, to meet the comfort and reliability standards, multi-domain analysis with linked simulations of the entire system are generally necessary. Further, for engineers to easily run design trade-off studies, parametric optimizations and ultimately arrive at an optimal design configuration, the holistic use of parametric models are essential. Using our coupled multiphysics simulation framework, we will demonstrate how the multi-domain analysis of an electric drivetrain is carried out by integrating structural, electromagnetic and multibody system simulations. Additionally, the framework places emphasis on automated model updates and process execution which dramatically reduces the time and effort to study numerous design alternatives.

1. Structural characterization

Modal analysis

The basis for the noise and vibration analysis is an elastic structural model of the electric drive system components. A finite element (FE) model of the stator, the interior permanent magnet synchronous machine (IPMSM) and the overall gearbox housing is used to characterize the dynamics of the structure. A modal analysis is performed and all natural frequencies in the frequency range of 0-10 kHz are extracted. Additionally, mode shapes corresponding to each of the natural frequencies are animated to visually confirm the existence of various characteristic spatial orders [1] of the stator.

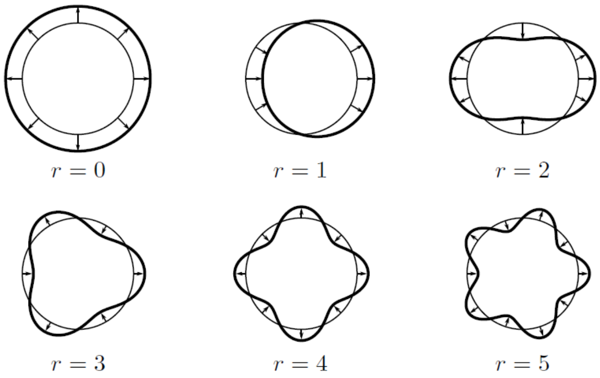


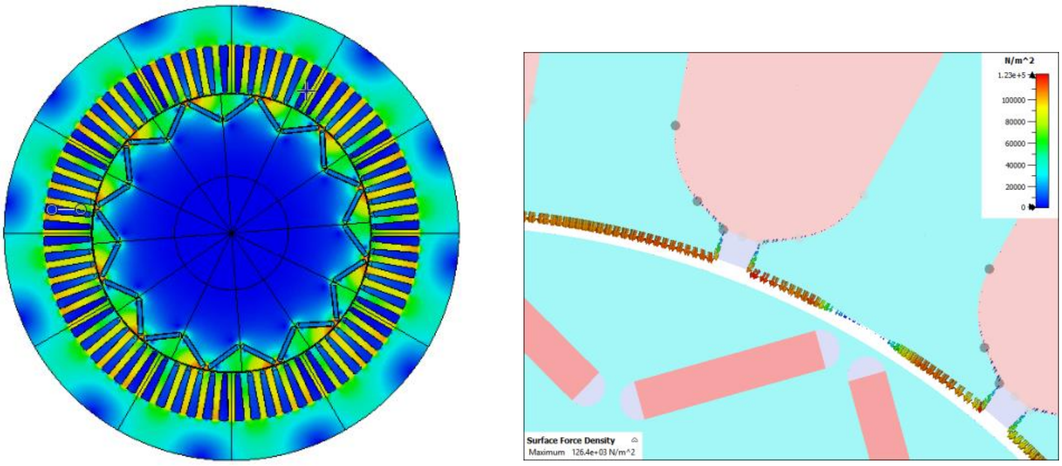
Fig 1. Illustration of Stator deformation for various spatial orders [1]

Substructuring

A reduced order model is obtained from the finite element model using the dynamic substructuring technique. The dynamic modes extracted during the modal analysis are used in the substructuring procedure. This model representation is important to describe the dynamic behaviour of the motor with relatively less degrees of freedom (in the order of few hundreds instead of few millions) and thereby achieving faster computations with negligible loss in accuracy.

2. Modelling Electromagnetic interaction

To examine the noise and vibration characteristics of the electric drive system, the structural model needs to be subjected to the electromagnetic force excitations. The dynamic response of the system can then be used to compute the surface velocities for further acoustic analysis.



a) *b)*

Fig 2. a) Magnetic flux density distribution and b) Force density distribution contour on the stator surface

Electromagnetic force calculation

In reference to [1], it is assumed that magnetic radial force density has the most significant influence on the stator vibration. The torque and radial force density distribution on the surface nodes of the stator are obtained from the finite element based electromagnetic simulation of 2-D cross-section of the motor geometry. The simulation is repeated for multiple operating points determined based on the sinusoidal peak phase current input and control angle of the rotor.

To better understand the influence of the electromagnetic forces on the overall acoustics, the radial force density distribution output is transformed from time to frequency domain and represented with respect to spatial and frequency orders. Based on the analytical relationship described in [2] between the radial force density, spatial order, frequency order and surface velocity, the most dominant order constellation is identified from the force density distribution grid and the corresponding operating point is investigated in detail to mitigate the resulting structural excitation force.

3. Multibody dynamics of Electric Drivetrain

Multibody simulation is the ideal tool to study noise and vibration phenomena of complex drive systems, because of the higher abstraction level that is used for the models. In contrast to finite element analysis, typical multibody simulation tools offer a large catalogue of application specific elements. Those elements are mostly based on analytical formulas and have the target to model a part of the system with exactly the required level of detail for avoiding unnecessary complexity and simulation effort.

Multibody models can integrate the mechanical properties of the flexible components with the typical non-linear excitation mechanisms, which enables to study the noise and vibration phenomena in electric drive systems more effectively. It has been shown [3] that these methods are successfully used for gearboxes at an established automotive manufacture.

Drivetrain components

To capture the high frequency noise in the acoustic range originating from the gear box (Gear whine), a fully flexible gear stage including its housing is modelled based on reduced order FE substructures representing the housing stiffness, gear body stiffness and tooth bending stiffness. The analytical Hertzian contact model accounts for the gear tooth excitations due to dynamic variations in the contact situation (transmission error) and stiffness. Flexible shafts are modelled using discretized beam elements with appropriate cross-section properties. The effect of varying cross-section of the shaft is also taken into consideration. Imbalance forces caused by eccentricity of the rotating parts as well as other inertial forces induced on different components are suitably included. The rolling bearings, which support the shafts relative to the housing, are also modeled using effective analytical methods based on ISO 16281:2008 which represents the bearing as non-linear coupled stiffness functions for all 6 degrees of freedom. The bearing model also includes backlash (clearance), which enables the multibody model to be also used for rattling analysis.

Multibody Simulation (MBS)

In order to assess the dynamic behavior of the electric drive, non-linear dynamic simulation of the complete electric drive assembly with the electric motor is performed. For covering the full operational range, a series of simulations at different machine speeds and torques are carried out.

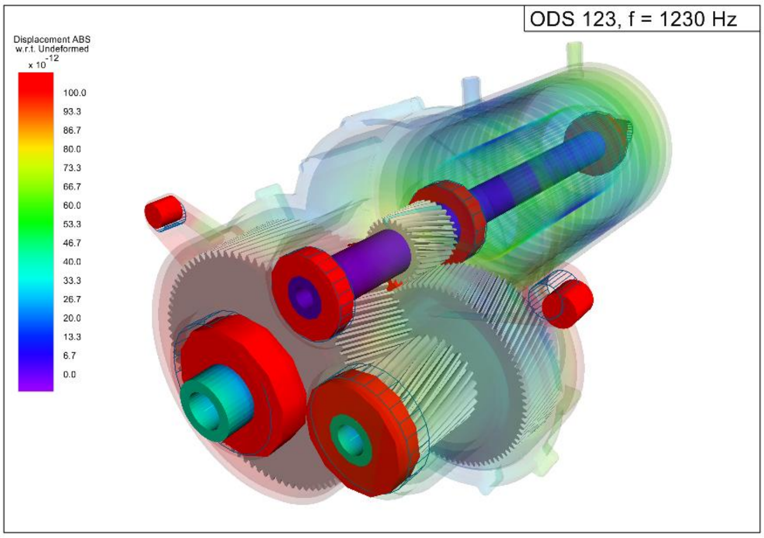


Fig 3. Operating Deflection Shape (ODS) of electric drive multibody system simulation

The responses, such as forces, velocities and accelerations at different locations in the model are studied using frequency domain plots (Waterfall / Campbell) and operating deflection shapes (ODS) of the assembly. Those results are used to characterize the behavior and compare with measurements.

4. Coupled multiphysics simulation framework

Coupling the above domain specific simulations is achieved through a data exchange logic to robustly communicate between the physics domains. The dataflow is executed in three stages.

Finite element substructure is used to derive a flexible body input which represents static and dynamic characteristics of the full FE model. This representation is further enhanced using additional residual modes to account for deformation due distributed surface loads on the structure.

The radial force density grid with respect to spatial and frequency order obtained as output from the Electromagnetic simulation is converted to a 3D input function with spatial and frequency orders as independent variables and force density as dependent value.

The flexible body input of the motor is integrated into the MBS model. To include the effects of electromagnetic forces on the structure, the equivalent nodal forces are computed on the fly from the 3D input function and applied on the elastic structure at each time step of the non-linear dynamic simulation.

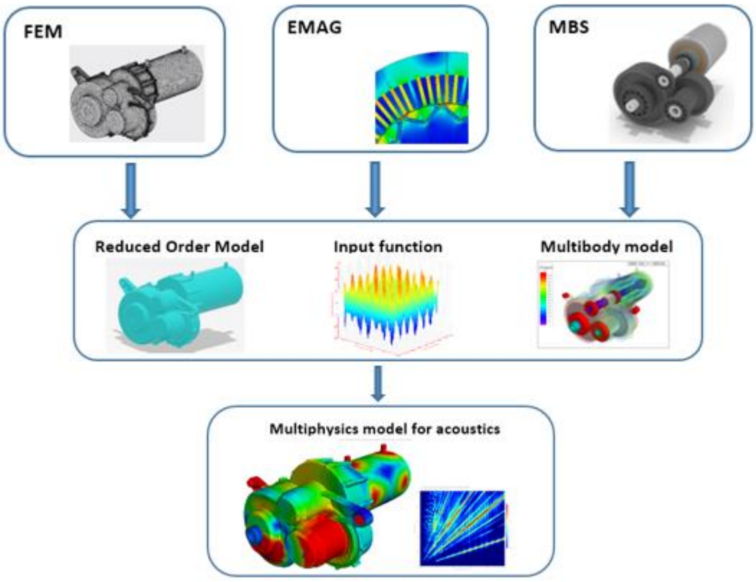


Fig 4. Multiphysics framework architecture.

Using **3D**EXPERIENCE platform, a vertical application is built to enable smooth data exchange between the simulations and to ensure consistent model configuration across domains. This integration framework facilitates robust coupling of different physics domains to account for phenomenon arising from multiphysics interactions. Additionally, the vertical application provides automated model update across simulations and possibility to perform parametric design of experiments on multi domain computations.

5. References

1. Aryanti Kusuma Putri et al (2015). Application of sinusoidal field pole in a permanent magnet synchronous machine to improve the acoustic behavior considering the MTPA and MTPV operation area, IEEE

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3. Alexander Neubauer et al (2014), Simpack user meeting 2014