Holistic Simulation of Gearboxes — System Simulation

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Introduction

Gearboxes are important assemblies within mechatronic systems. During the design phase of such systems it is essential to know the gearbox behavior under consideration of dynamic interactions with its environment. Holistic system simulation helps the engineer to understand this and to improve, adjust, or optimize gearboxes and their application.

This paper examines three applications with gear drives:

- Noise development in a planetary gear system
- Interactions between a gearset and an electric drive
- Thermal behavior of an actively cooled gearset

The examples demonstrate how systems models can be created and analyzed using the possibilities in *SimulationX* in order to understand, improve, or predict system behavior.

Reduction of Operational Noise by Optimization of Teeth Numbers

Modern powertrains of electric drive cars are driven by small machines with high speeds, e.g. — up to more than 10,000 rpm. These machines are coupled to planetary gearboxes with high transmission ratios, which can lead to high noise contrary to current comfort requirements. Identifying potential natural frequencies in gearsets is critical as part of the design process to ensure a long lifetime of the mechanical components and reduce operational noise. In this paper we present the comparison of four design variants of a planetary gear set with four planets.

Four design variants are discussed, which can be mostly described by changes in two design parameters:

Table 1 Design variants of a planetary gear

Type	# Teeth Ring	# Teeth Planet	# Teeth Sun	Normal Modulus	Helix Angle	Contact Ratio	
						R-P	S-P
Var. 1A	92	19	52	1.55	18.6	2.8	2.9
Var. 1B	90	19	50	1.55	18.6	2.8	2.9
Var. 2A	108	24	60	1.25	23.0	3.4	3.7
Var. 2B	106	24	58	1.25	23.0	3.4	3.7

The type-A variants use a 4x-symmetry of the sun gear, whereas the type-B variants use a 2×2-symmetry. Thus variants A and B differ in the contact phase angle at the planet-sun contact with 0° and 90°, respectively. The type-1 and type-2 variants differ in the geometry, including number-of-teeth-per-planet; the normal modulus; the helix angle; and the total contact ratio. The task is to find the variant that ensures the lowest operational noise.

In general, a simulation model is built to accomplish a particular analysis task; here we can work with a 1-D rotational system (Fig. 1).

Pre-defined, *Modelica*-based model elements representing inertias, loads, stiffness or detailed tooth contacts (gear pair meshings) of the planetary make it easy to create large, detailed models. Please refer also to References 1and 2, where you can find a detailed description of the planetary gearbox model components, including all necessary fundamentals.

Depending on the analysis task, it is also possible to represent the planetary as a three-dimensional, multi-body system (MBS) that offers the representation of up to six-degrees-of-freedom for each component. MBS enables the

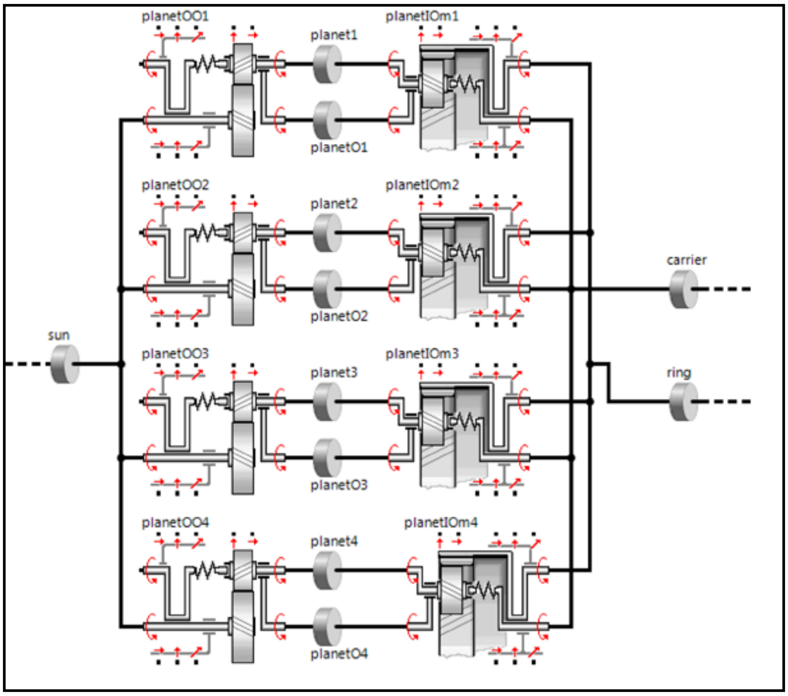

Figure 1 Diagram view of a planetary gearbox with four planets as a 1-D rotational system in SimulationX.

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analysis of spatial interactions and provides an intuitive graphical feedback (animation) of the parameters and behavior, including the mode shape analysis of natural frequencies. Figure 2 shows the diagram as well as the 3-D view of the corresponding MBS model of our planetary gearbox.

The simulation model was used to determine the natural frequencies as well as the reduction in torque magnitude for each variant, compared to the reference concept. A steady-state analysis was performed on the variant models for planet speeds from 0 to 4,500 rpm and excitation frequencies from 0 to 15,000 Hz. Fast Fourier transformations (FFT, order analysis) of the time-domain results, displayed as Campbell diagrams, show big differences between the variants — especially 1A and 2B, in the range of 4,300 Hz (Fig. 3).

The simulation demonstrated that variant 2B is the best modified design, compared to the reference concept variant 1A. Using variant 2B, it is possible to reduce the torque at the sun gear at the primary natural frequency from 3.81 Nm to 1.23 Nm, i.e. — a reduction of 68%.

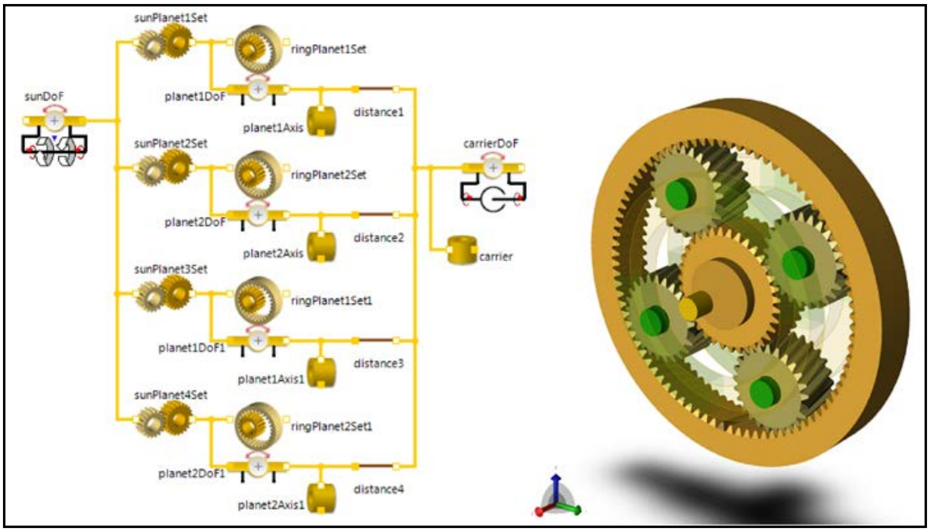

Figure 2 Diagram and 3-D view of a planetary gearbox with four planets as MBS in *SimulationX*.

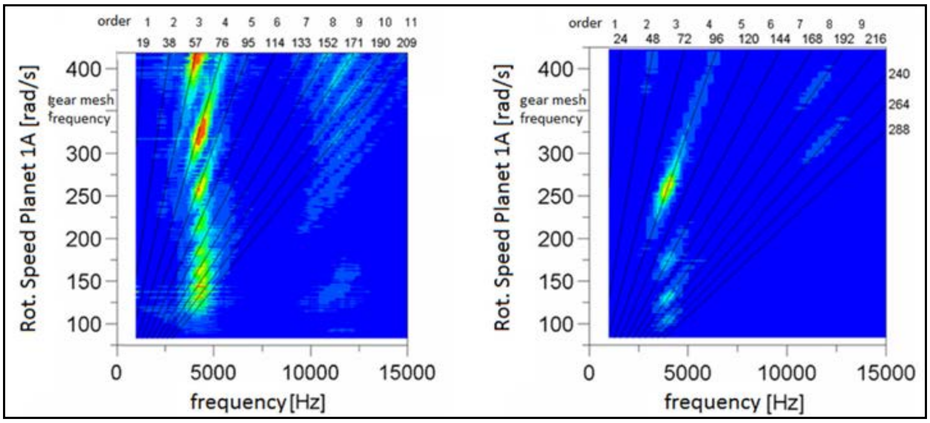

Figure 3 Campbell diagram for order analysis and resonance investigation (ITI-ORD by ESI ITI GmbH).

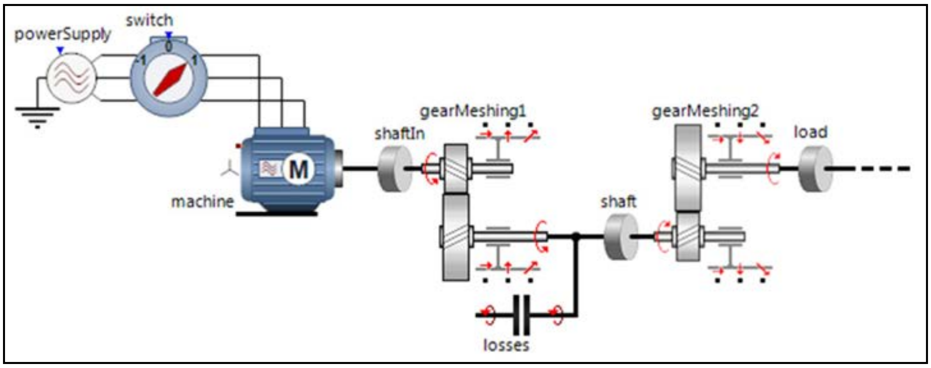

Figure 4 Model of an electric-driven work machine in SimulationX.

Influence of Electrical Grid Disturbances on Gears

Disturbances in the electrical grid influence the system behavior of electrically driven machines or generators (e.g., wind energy plants (WEP)) and therefore its lifespan.

Reference 3 describes the analysis and identification of such grid disturbances and their influence on bearing loads in a WEP. In many cases it is impractical if not impossible to switch generators off during incidents or faults in the electrical grid; official guidelines and standards define permissible grid fluctuations and voltage drops for electrical power customers and suppliers (e.g., EN50160).

When designing the mechanical system, it is important to analyze the influences of grid disturbances such as symmetric or asymmetric short circuits and the corresponding voltage drops. Figure 4 shows the model of the drive of a machine with a geared motor. There are two gear pairs between machine and load. The machine drives a speed-dependent load. Each gear pair meshing element represents a constant mean gear meshing spring stiffness and its rotating backlash.

During steady-state operation at 116 rpm load speed a (3-pole) short circuit occurs between 10 and 10.1 s; high peaks of the tooth contact forces can be seen in Figure 5. The maximum values are up to 4 times higher than the mean load.

This example shows how important it is to consider realistic interactions with other (e.g., electrical) systems using physical models when designing the mechanical system. In contrast, generic assumptions tend to result in over-dimensioned systems.

Temperature Analyses of Gearsets

The system shown in the model (Fig. 4) is cooled by an oil cooling system for which another task must be solved, i.e. — what happens when the cooling system drops out, and how much time do we have to stop the system automatically to avoid oil flaming or teeth damage as a result of overheating?

Figure 6 shows the detail of an extended model of the work machine drive. It contains a hydraulic and pneumatic model of the oil cooling circuit as well as a thermal model to represent the heat transfer from the gear pair meshings to the cooling oil. For these kinds of long-term analyses it is quite accurate to work with mean gear mesh stiffnesses and only low-frequency excitations. We assume a gear meshing efficiency of 95%.

Figure 7 shows the main results of the simulation: during normal steady-state operation the oil sump temperature is approx. 95°C. At 5 minutes the oil cooling system is disrupted and the oil temperature quickly increases. After approximately 80 seconds the limit temperature of the oil is reached. Beyond this point we can expect damage to the gears or the gearbox because of decreasing viscosity and loss of lubrication of the oil film between the teeth contacts. Furthermore, after 2.5 minutes the oil's flashpoint is reached.

Based on these results we can design a control system that shuts down the machine automatically (in this case within approx. 60 seconds) to avoid damage. It is indeed possible to test such an emergency shutdown on a virtual system.

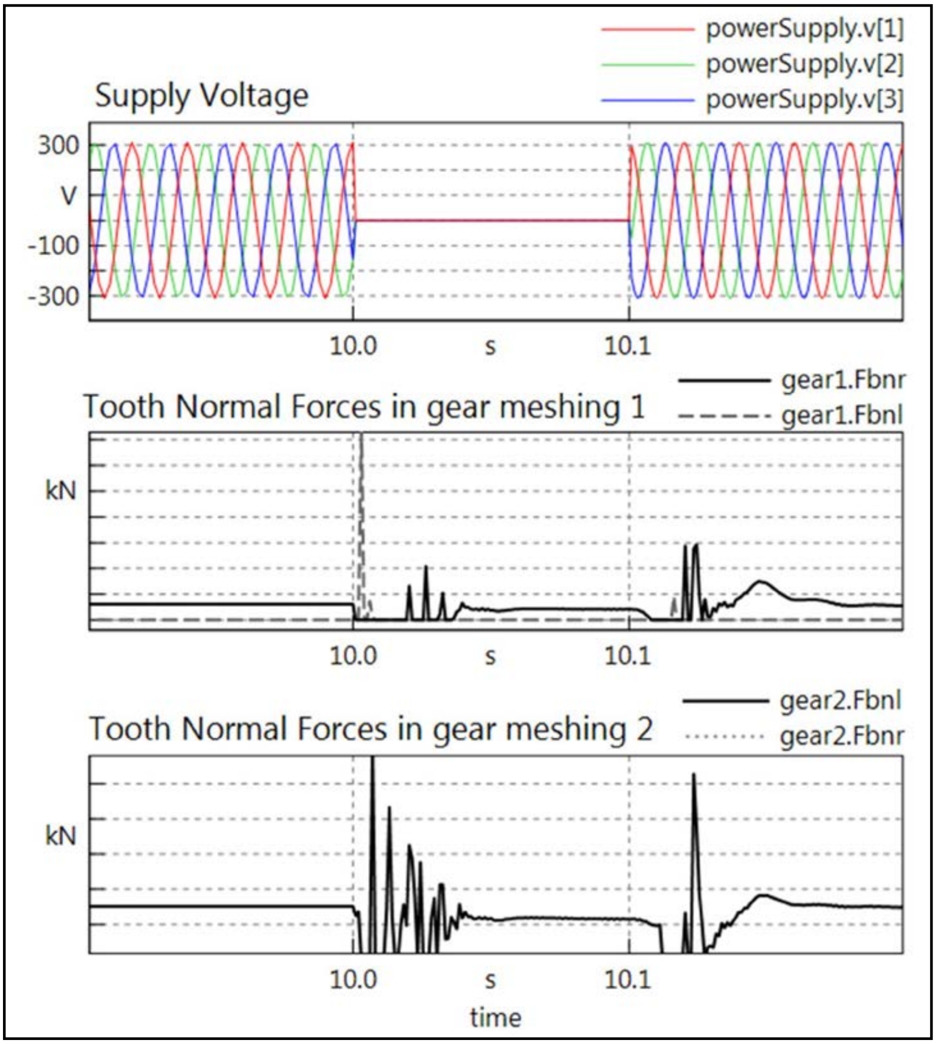

Figure 5 Top — supply voltage with short circuit breakdown; Middle, Bottom — tooth contact normal forces of gear 1 and gear 2 each for both flanks.

Outlook — WindTwin Project: New Ways of Monitoring the Maintenance Condition of Wind Turbines Using Virtual Plants

Research has shown that preventive maintenance of wind turbines costs 25% less than reactive maintenance, and that predictive maintenance costs 47% less. Also, there is a need to increase wind turbine reliability to 99.5% (Ref. 3), which can be achieved by developing new data analytics techniques, processing, and visualization for effective operations and maintenance.

The upcoming WindTwin project aims to revolutionize the monitoring and maintenance of wind turbines — both onshore and offshore — by developing an innovative digital platform that will virtualize the WPP (wind power plant) using a digital twin of the wind turbine behavior and operation. These virtual plants — or hybrid twins — will combine the mathematical models describing the physics of the turbine's operation with sensor data collected and processed from real assets during real-world operations. For example, condition monitoring will be applied on the gearbox, and sensors will be placed on the real wind turbine asset; the data being collected will be processed and transferred to the hybrid twin, continuously resulting in a close to real digital twin of the wind turbine showing real-time performance. These virtual models will allow wind farm operators to predict failure and plan maintenance — thus reducing both maintenance costs and downtime.

Summary

- The holistic system simulation of gearboxes in every field of application helps us to analyze and understand the complete system behavior.
- Several examples demonstrate that it is important to take physical interactions from different sub-systems into account, e.g. — mechanics, electronics, thermal, hydraulics and control.
- All experiments (modeling, result analysis, etc.) were done completely in *SimulationX*.
- Intuitive, application-oriented model libraries for representing all sorts of systems make it possible to quickly create and parameterize system simulation models. Options in the component models enable switching between various degrees of calculation detail according to what type of analysis task needs to be done.
- Furthermore, the object-oriented modeling language *Modelica* enables the modeler to extend existing library elements or create new library elements based on new requirements. (*Note*: the paper cited in Reference 5 summarizes the advantages of modeling using *Modelica* in comparison to other technologies.)
- Also possible is the coupling or integration of sub-models from other simulation platforms via the functional mock-up interface (FMI). This technology also makes it possible to integrate *SimulationX* models into other environments.
- Thus system simulation is the most important tool in the layout, improvement and analysis of systems, and a decisive part of *CAE* (computer-aided engineering) development process of machines with gearboxes. **PTE**

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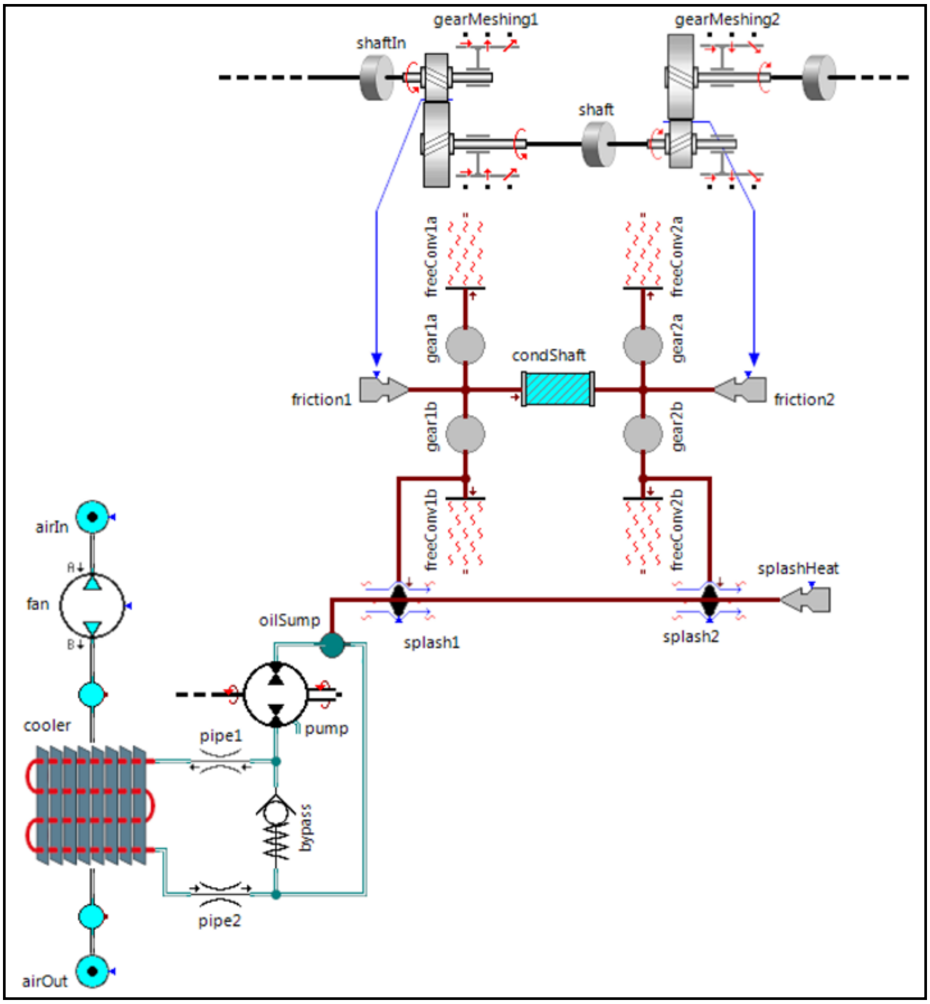

Figure 6 Model of a machine with detailed sub-models of gear oil exchange and heat transfer from teeth to oil in *SimulationX*.

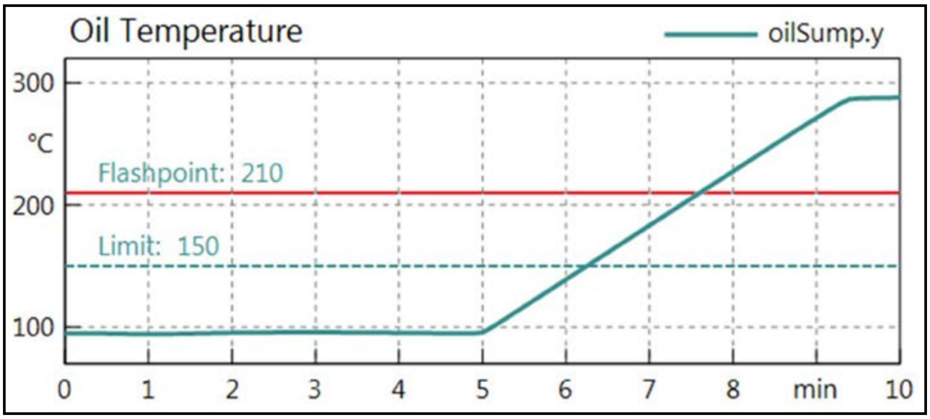

Figure 7 Model of a work machine with detailed sub-models of gear oil exchange and heat transfer from teeth to oil in *SimulationX*.