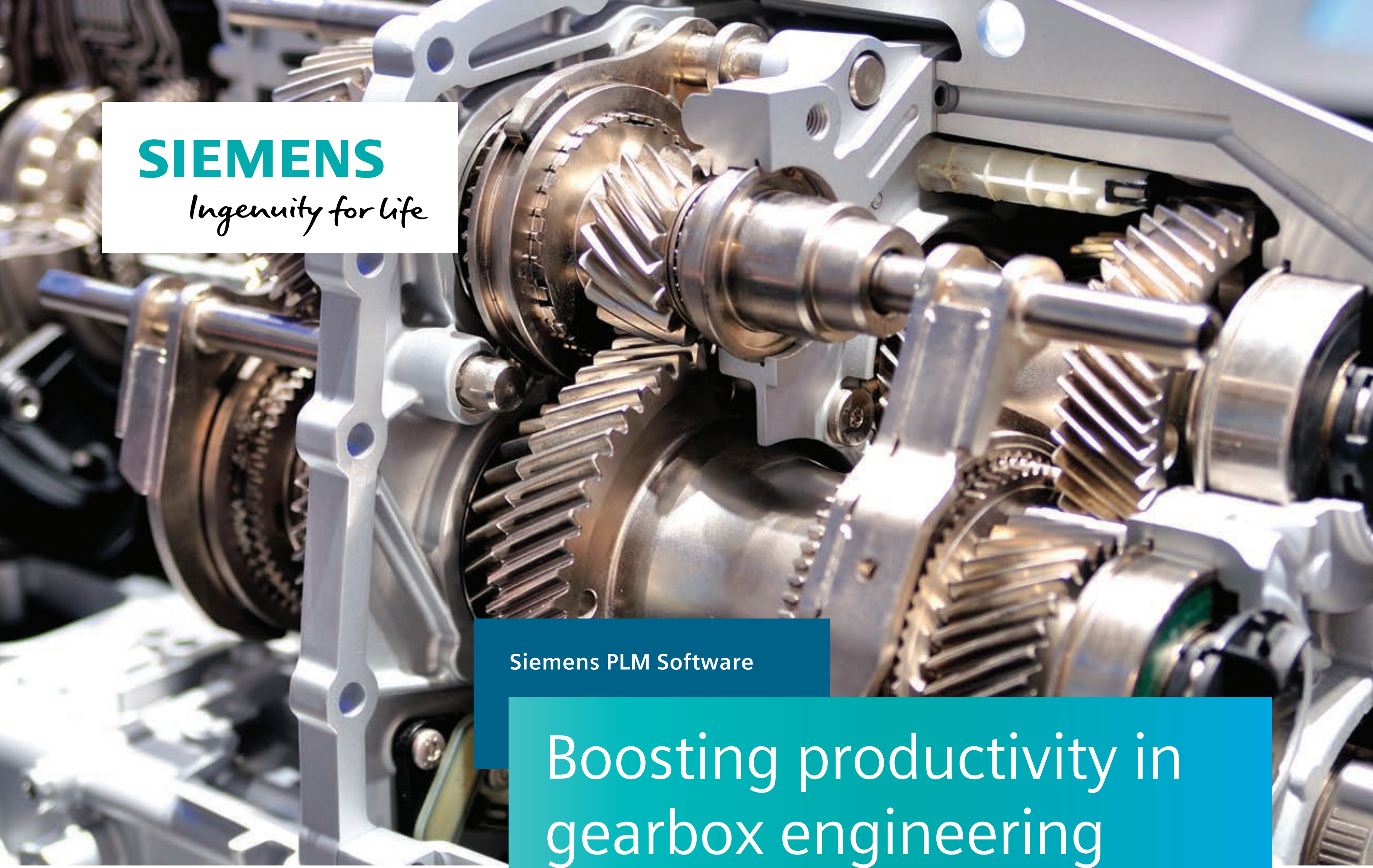


Siemens PLM Software

Boosting productivity in gearbox engineering

Introduction

Transmission engineers are familiar with the tedious process of modeling and parameterizing a gearbox in a multibody simulation environment. They typically need to spend up to several days for model preparation to then be able to numerically simulate the nonlinear dynamics to obtain system-level loads for noise, vibration and harshness (NVH), transient and durability analyses and to optimize the design for these attributes.

This paper introduces the Simcenter 3D Motion Transmission Builder: a vertical application that revolutionizes the user experience in setting up the multibody simulation model of the transmission while dramatically increasing productivity. The Simcenter 3D Transmission Builder enables engineers to progress from initial design to accurate simulations in a matter of an hour.

The multibody research team at Siemens PLM Software has invested considerable effort in revisiting the numerical approach to drivetrain simulation. The new solver architecture is designed to enable the user to perform dynamic multibody simulation according to three different levels of fidelity for gear contact according to the required computation time and desired level of predictive capacity: standard, analytical and advanced. This flexibility allows the design engineer to select the appropriate accuracy in the model for the performance engineering predictions of interest. This paper describes the capability using industrially relevant cases.

Contents

Executive summary

In recent years, substantial effort has been dedicated to analyzing transmissions at a system level to achieve better performance in terms of efficiency, noise and reliability. The main challenge is to capture the nonlinear system dynamics in a sufficiently detailed yet computationally efficient way. After designing the gear box, the design engineer needs to use multibody simulations to accurately predict the system behavior in view of NVH, transient, durability and other analyses. Until recently, building the multibody simulation models was a tedious and error-prone manual process. Modeling, parameterization and iterations for relatively complex models could take multiple days, even for an experienced user.

This paper introduces the Simcenter 3D Transmission Builder, a vertical application for efficiently creating multibody simulation models of full transmissions. The application brings in-depth, gearbox-specific ease-of-use into the multibody simulation process. The user maintains a thorough overview of the model structure, and can perform detailed analyses through simulations in Simcenter 3D Motion software, as part of the Simcenter™ portfolio from Siemens PLM Software. The Simcenter 3D Transmission Builder requires less user expertise, while significantly boosting productivity in setting up the multibody simulation model; many models can be created within an hour. The workflow is shown in figure 1.

Simcenter 3D Transmission Builder also provides interfacing with the new gear contact element. Several innovations to Simcenter 3D Motion are introduced in this paper. The contact detection method has been redesigned and validated against nonlinear finite element (FE) solvers to dynamically account for effects such as microgeometry modification, misalignments, tip contact, wedging and others. The advanced methods, based on a novel formulation and on the use of a new FE preprocessor developed in cooperation with the KU Leuven (Belgium) and the University of Calabria (Italy), have been extended to account for a wide range of flexibility-induced phenomena (lightweight gears, convective coupling effects, etc.). In addition, a novel method based on model order reduction (MOR) is adopted to efficiently analyze lightweight and ring gears in a dynamic multibody simulation environment.

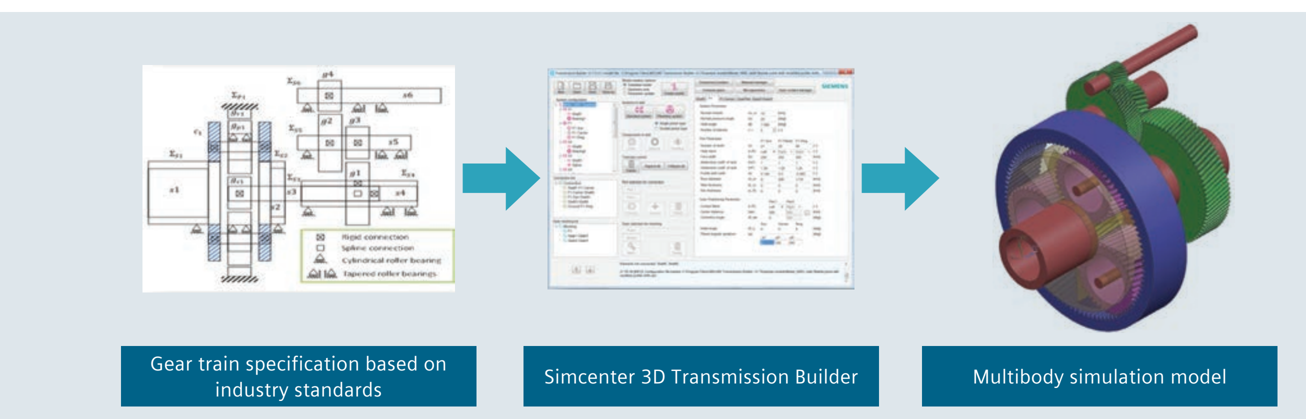


Figure 1: Workflow – based on gear design specifications, engineers can employ the Simcenter 3D Transmission Builder to quickly and accurately define the transmission layout and generate the multibody simulation model.

Background: gearbox design engineering

Due to increasing awareness of environmental concerns, industry is setting stringent targets for energy efficiency and emissions. Manufacturers are forced to improve their designs by balancing conflicting requirements between customers (increasing performance) and regulatory bodies (increasing efficiency). Mechanical transmissions are responsible for significant energy losses (6 to 8 percent of the total) in automotive and wind energy applications. Recent research studies[1, 2] document margins to significantly reduce transmission losses by 50 percent, revealing the potential for saving 9.3 million tons of CO_2 emissions in the automotive field, but do not consider the loss phenomena and their impact on crucial performance attributes such as durability and noise. The solution to this balance lies in the predictive capabilities with respect to system-level dynamics within the transmission design engineering process.

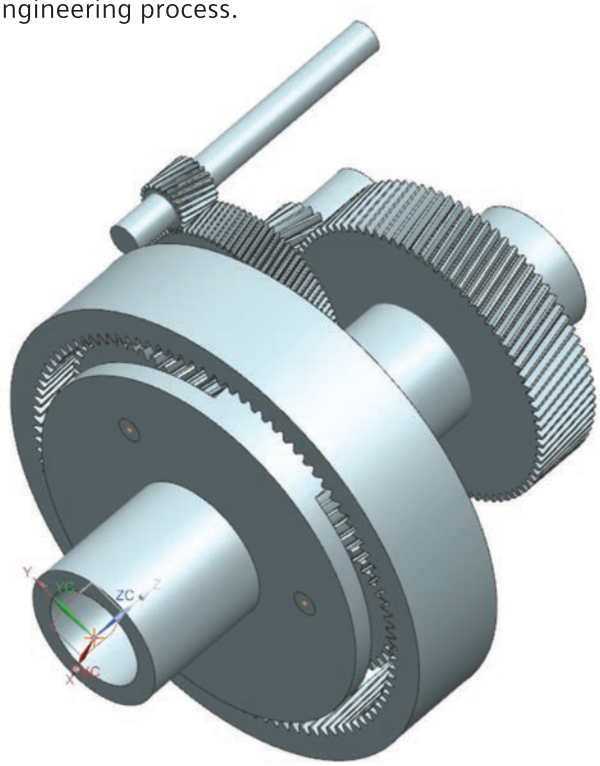


Figure 2: Transmission example – three-staged gearbox of a wind turbine with one planetary stage and two helical stages.

The basic components of a transmission system are gears, bearings, shafts and the supporting structure. These are all mutually connected and the supporting structure substantially affects bearing contacts and gear meshings affecting the transmission error. About 70 percent of energy losses happen in the gear train, and 30 percent in the bearings.

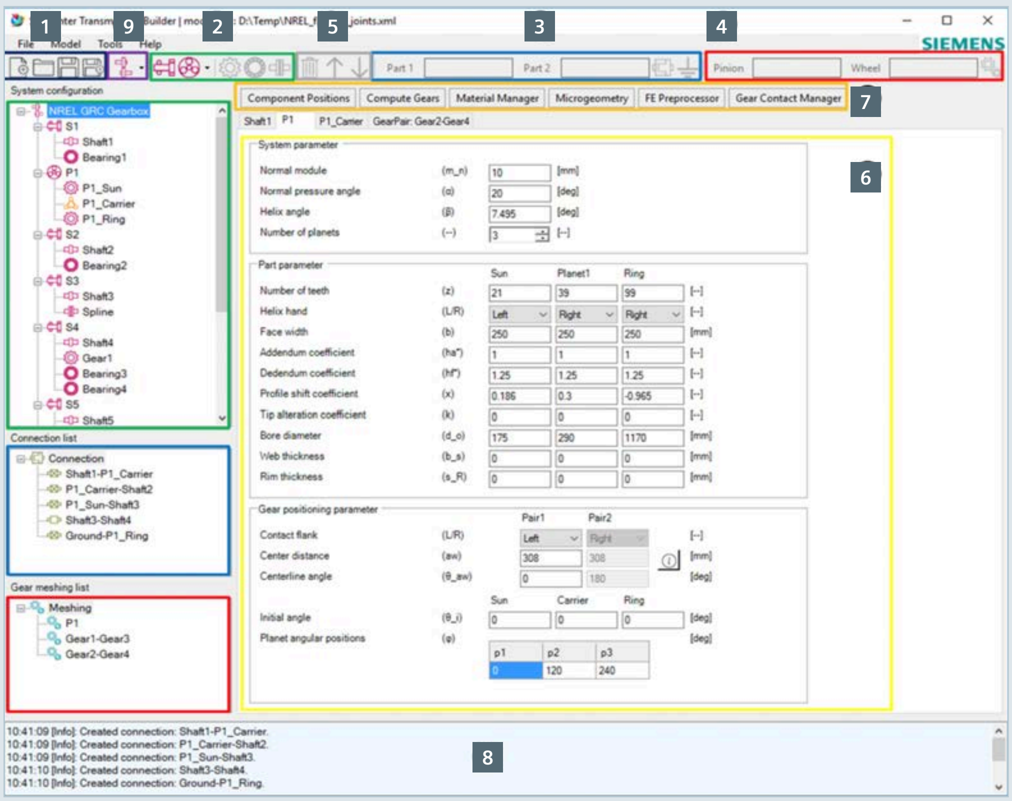
Gearboxes therefore present significant design engineering challenges in many applications, ranging from automotive (cars, trucks, buses) to wind turbines to helicopters. The primary challenge is to capture the nonlinear system dynamics in a sufficiently detailed yet computationally efficient manner. Designers of transmissions can choose from two software solution families to support their design and simulations. The first family is targeted at gearbox design and provides gearbox-specific know-how that can be used in the design process, but lacks certain simulation capabilities, especially with respect to system-level dynamics. The second family includes general-purpose multibody simulation tools (for example Simcenter 3D Motion), in which the drivetrain geometry must be created along with simulation-specific elements (joints, axis systems, bodies, force elements). Only in this environment can one obtain sufficiently accurate predictions in a feasible timeframe to predict nonlinear dynamics, noise and vibrations and durability performance. Until recently, building a full transmission model in a multibody simulation tool was a tedious and error-prone manual process. Modeling, parameterization and iterations to build fairly complex models could take up to multiple days for an experienced user. With the advances presented in this paper, design engineers can efficiently set up simulation models in the multibody simulation environment, and effectively predict and optimize their designs based on accurate simulations.

The gearbox shown in figure 2 is a gearbox that is used for 750 kW wind turbines as a speed increaser coupled with a generator. This model was created in a matter of minutes thanks to the ease of use of the Simcenter 3D Transmission Builder.

The Simcenter 3D Transmission Builder

The Simcenter 3D Transmission Builder provides an easy-to-use interface to build complex transmission systems in Simcenter 3D Motion. It facilitates the setup of the basic geometry and topology, which is directly linked to the solver and FE preprocessor, and performs automatic phasing. As such, the Simcenter 3D Transmission Builder dramatically decreases model creation time.

The main window layout of the Simcenter 3D Transmission Builder is shown in figure 3.



1. Main I/O: Initiate (new), save, save as, open system configuration files
2. System configuration: Add and manage systems and components
3. Connection: Define the connections between the components
4. Meshing: Define the meshing gear pairs
5. Control: Move or delete the added node of systems, connections or meshings in each tree view
6. Component specification: Manage the properties of the systems and components
7. Calculation: Calculate component positions in space and gear specifications, and manage material properties, microgeometry, FE preprocessor and gear contacts
8. Log window: Display user’s performed actions and warning/error messages
9. Link to Simcenter 3D Motion: Create/update the model in Simcenter 3D Motion

Figure 3: The main window layout of the Simcenter 3D Transmission Builder.

The Simcenter 3D Transmission Builder closely follows the workflow of the user in making decisions regarding the gearbox design and guides these decisions through analysis and simulation. The user begins with the transmission layout setup, arranging the shafts, gears, bearings, etc., and defining the gear meshing conditions for spur, helical and planetary gear systems. Thereafter, a gear geometry calculation compliant with the ISO 21771 standard[4] is performed, generating the gear geometry from the transmission design parameters according to the standard. The Simcenter 3D Transmission Builder then creates the 3D geometry models in Simcenter 3D Motion. Next, the gear microgeometry is created in a simple click (see figure 4) including profile and flank line modification or their combinations, as well as file creation for the gear contact model input.

The Simcenter 3D Transmission Builder can then be used to create the initial and boundary conditions such as component initial angles, automatic gear phasing, joints (bearings and coupling), constraints, etc. Finally, the gear contact manager enables interfacing with the gear contact model, so that the user is ready to solve the transmission system – typically in less than an hour.

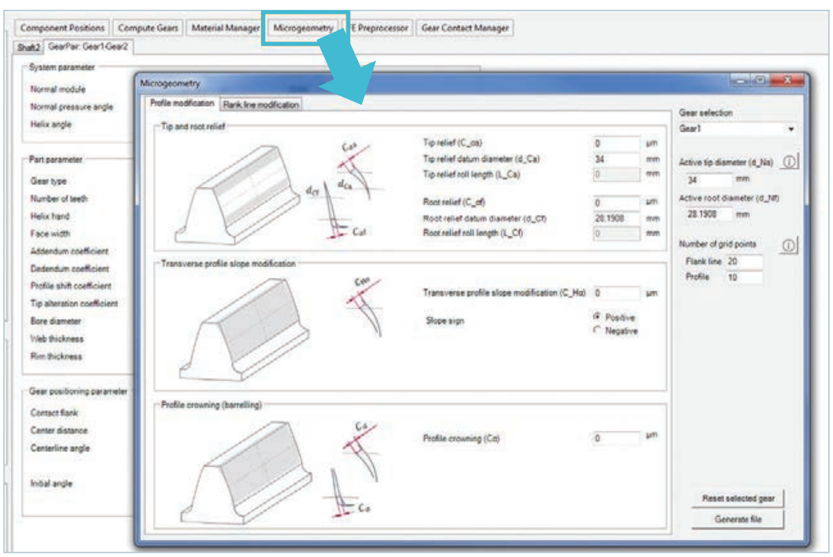


Figure 4: Microgeometry creation.

Solving the transmission system

The main tasks performed by the new gear contact element consist of detecting the contacts, computing the required deflections and translating the deflections into loads. Gear contact forces are accurately taken into account by the multibody solver to calculate the system-level loads, and hence the durability and NVH behavior. Figure 5 shows the most important geometrical effects that are dynamically captured by the new gear contact element.

Three classes of methods are enabled for translating the deflections into loads.

- Standard (based on ISO standards with optional user input)
- Analytical (ISO + Cai)
- Advanced (empirical or FE preprocessor)

These methods have been implemented in a modern object-oriented framework within the Simcenter 3D Motion solver, a general-purpose multibody software. Current efforts are focusing to extend its capabilities to include bearings, bevel and hypoid gears and spline connections within a similar framework.

The standard method

The standard method is intended for use when the global behavior of the drivetrain is important. The stiffness is constant and computed through ISO formulas[5]. The gear-pair meshing stiffness computed by this method is a qualitative approximation of the true stiffness of the analyzed gear pair; nonetheless, it can be of high value for resonance analysis and first design iterations of complex drivetrains, especially when the gear body flexibility is not of relevance. No microgeometry modification or tip contact is allowed, since no tooth-per-tooth contact is defined – only the global behavior of the contact pair is modeled. Misalignment is included in an averaged sense. The stiffness is not load-dependent, so the nonlinear stiffening effects with increasing load is not accounted for.

This simple method can be made more accurate when the contact stiffness and/or measured transmission error (TE) is known. The main advantages of this method are its ease of use and the high computation speed.

Contact modeling = detect contact ⇨ compute required deflection ⇨ translate deflections into loads						
What?	**In-plane relative translations**	**Axial relative translations**	**Rotational misalignment**	**Profile modifications/errors**	**Flank line modifications/ errors**	**Mesh phasing**
						
Relevant for?	Load-dependent backlash Frequency sidebands due to eccentricity	Gear rattle (helical gears)	System-level dynamics Gear whine Tooth loading ⇨ durability	Gear whine Frequency sidebands due to errors 'Ghost' noise	Gear whine Tooth loading ⇨ durability	Planetary transmissions Multiple meshing
Gear element	✓	✓	✓	✓	✓	✓

Figure 5: The gear contact element enables all aspects of contact detection that are relevant to predict system-level transmission behavior such as dynamics, noise and durability.

The analytical methods

The analytical methods can be used for several applications ranging from parametric studies on tooth finishing, misalignment, microgeometry, qualitative NVH studies on bulky gears (gear whine can be captured due to the stiffness variability that is implicit in the formulas) and dynamic validation of system-level phenomena. The method can be quantitatively accurate for gears that are bulky and when the gear internal dynamics (for example, in lightweight gears) are not of relevance.

This class of methods allows a significant step up as compared to the standard method. The stiffness function used combines the ISO tooth-pair stiffness[5] with specific formulas[6, 7] designed to provide the bending stiffness for the tooth-pair of spur and helical gears. The accuracy of the contact detection is drastically increased when using this method. In particular, the use of slicing and a novel contact detection technique developed for accurate dynamic misalignment analysis are seamlessly included in the method. Coulomb friction is also accounted for when requested. The slicing approach allows the user to select a number of slices in which the instantaneous axial overlap is divided. The contact detection is performed very efficiently for each slice within the gear contact pair, accounting for microgeometry, instantaneous misalignment and potential wedging.

As a rule of thumb, the number of slices should be increased if misalignment and microgeometry modifications are relevant to the analysis, but a number between 5 and 20 usually proves sufficient for most applications without significant effect on computational performance.

The advanced methods

With these novel methods the user can be even more accurate. Two advanced types of methods are implemented: Advanced empirical and Advanced FE preprocessor.

Advanced empirical

A well-known method in this class is proposed[8, 10] and implemented in the new gear contact element as the advanced empirical method. A series of tabulated bulk stiffness curves from coarse FE models of spur and helical gears was created[8] and are used to better account for body and tooth flexibility. The local contact compliance is taken into account thanks to the nonlinear analytical formula[9]. This method is developed for system-level simulation of gears where the tooth bending and nonlinear stiffening with respect to the load are important. The method is suggested for qualitative studies and sensitivity analysis related to gear whine when the gear-body flexibility starts to play a role, but not for lightweight or ring gears. The method also allows capture of effects such as stiffness variability along the involute profile and along the tooth width. For example, contact occurring at the side edge of a gear is “softer” as compared to contact at the gear center. The computational burden of the method is similar to the analytical one.

Advanced FE preprocessor

If lightweight gears, ring-gear flexibility and gear bulk deformation is of high importance, for example, causing side bands in the dynamic transmission error (DTE) due to holes in gear blanks, an even higher level of fidelity than in previous methods is required. This level of fidelity is provided by the advanced FE preprocessor method. The Siemens Research and Technology Development (RTD) team implemented this novel and unique method by combining the ideas coming from solid theoretical studies[8, 9, 10] and advanced numerical techniques originating from the model order reduction field[11, 12, 13]. The user can employ this advanced method in a straightforward way and let the algorithm work on the advanced numerics behind the scenes. The advanced FE preprocessor method exploits the power of the Simcenter Nastran® FE package with an FE preprocessing tool. This tool is linked with an easy-to-use interface and enables the creation of parametric FE meshes of spur and helical gears as well as the stiffness data that is needed for the computations within the multibody solver. The method is extremely powerful thanks to the coupling of FE-based tooth stiffness data that accounts for gear-body deflection in a very detailed way, including lightweight and ring gears and the nonlinear contact compliance. Convective coupling terms between slices and teeth are automatically accounted for. The method can be used to simulate every type of cylindrical gear: spur and helical, internal and external, including lightweight and highly deformable bodies. The use of MOR and its efficient implementation allow for a reduced memory usage and a computational burden that is orders of magnitude lower than other techniques that provide similar levels of detail. Depending on the underlying FE mesh and number of slices, the method will become computationally more expensive, but generally, a relatively coarse mesh and a limited number of slices allow for an optimal tradeoff between accuracy and computational performance.

Results

This section describes results and explores a few of the many capabilities of the new gear contact element. In particular, the effect of microgeometry modifications with increasing load and the dynamic analysis of a full wind turbine gearbox will be used to demonstrate the capabilities of the analytical approach; a validation test is used to showcase the potential of the advanced method.

Motion analytical method: profile modification analysis

It is important to design a gearbox such that the microgeometry modification is optimal for the operational conditions of the system; this can be accomplished with the analytical method. With the Simcenter 3D Transmission Builder, it is very easy to create a model of two identical helical gears and apply the desired microgeometry modification. In particular, the gears have 50 teeth, a normal module of 2.71 and a helix angle of 25.2 degrees. For microgeometry, a tip and root relief of maximum 10 μm and a lead crowning of 4 μm have been created and applied to both gears. In particular, microgeometry modifications are applied to achieve a minimum static transmission error (STE) at a desired nominal torque minimizing gear whine. It can be seen from figure 6 that the analytical method using only 8 slices is able to capture this effect very clearly. One of two gears is driven by a constant torque and the other gears resist with a viscous damping element in order to keep the speed constant to 10 rpm. Several torques are applied and the STE is shown in figure 6. At low torque the typical shape dictated by the imposed profile modification is captured; furthermore, the STE reaches a minimum at the rated torque of 20 Nm while further increasing at higher torques with the typical quasi-sinusoidal shape often reported for helical gears.

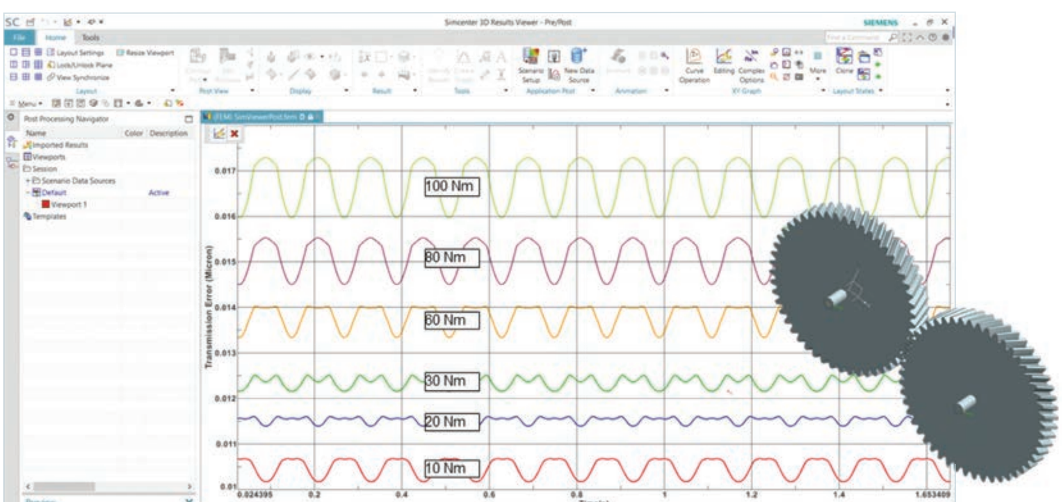


Figure 6: Quasi-static transmission error of helical gears with profile and lead modification with increasing load.

Motion analytical method: Dynamic analysis of full transmission

The gear force simulation enables gearbox analysts to assess the frequency content of the system dynamics response to the excitation coming from the gears. As a second example, a two-stage automotive transmission has been created using the Simcenter 3D Transmission Builder. The model is simulated in Simcenter 3D Motion with an input torque ramping up to 350 Nm. Over a simulation period of 20 seconds an output speed range between 0 and 2,500 RPM is simulated.

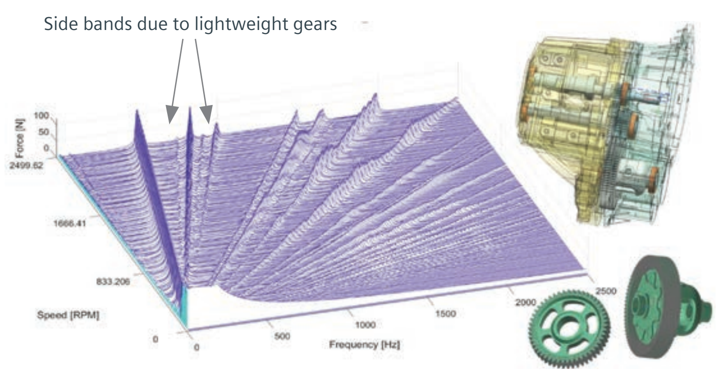


Figure 7: Bearing forces frequency spectrum derived from run-up simulation for a two-stage transmission.

Figure 7 shows the dynamic force response within one of the bearings. The results are postprocessed in a frequency domain to visualize the orders. The graph, as expected, presents the two main meshing orders and their multiple corresponding meshing frequencies of the two gear stages. Some smaller amplitude peaks are present at higher harmonics of these same orders.

As shown at the bottom of figure 7, the gears are designed with lightweighting holes. Using the Simcenter 3D Motion solver, it is now possible to assess the effect of thin rims and holes on the gear force excitation. This can be clearly seen in the typical sidebands shown in the waterfall diagram of figure 7 which propagates from the gear contact to the bearing reaction forces. This is further elaborated in the next section on method validation.

Within the Simcenter 3D environment the results from the transient multibody simulation can be seamlessly imported into the acoustics application. This enables an end-to-end workflow that is depicted in figure 8. With this process, the influence of a design change (e.g. microgeometry modification) can be analyzed on fundamental metrics like the sound pressure level in a microphone near the transmission housing.

In this way, the entire transfer path is covered: from the source (gear forces) via the transfer path (bearings and flexible housing structure) to the receiver (microphone array). Modifications in any of these subsystems can be easily analyzed in order to optimize a design and mitigate NVH phenomena like rattle and whine.

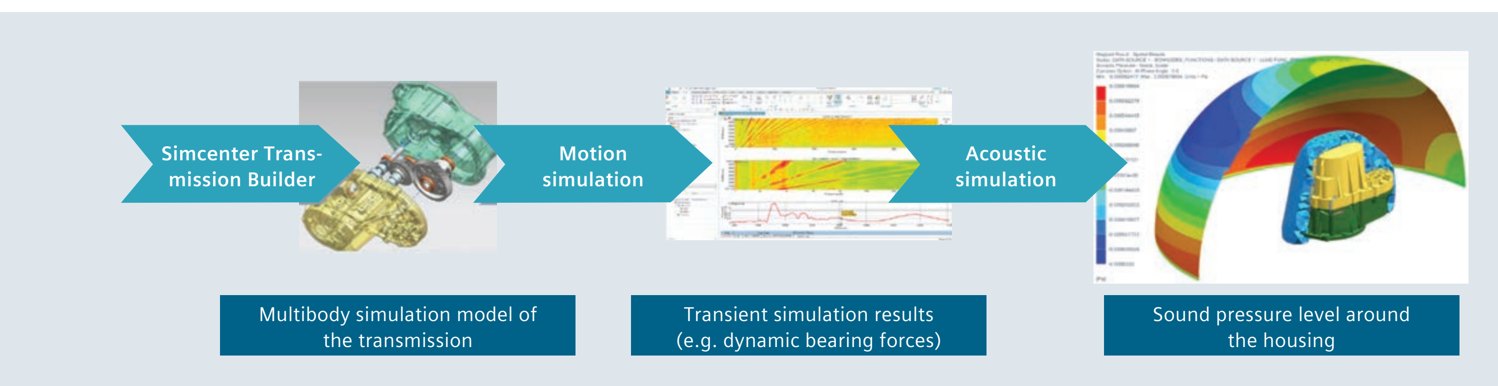


Figure 8: Typical workflow to assess acoustic radiation of a gearbox.

Motion advanced FE preprocessor: flexibility, friction and experimental validation

The in-depth correlation of an individual tooth contact with test data shows that it is crucial to take into account the effects of flexibility and friction in the simulation-based design of gears. This can be done with the new advanced FE preprocessor method, as shown in this third example. The Advanced FE preprocessor method and the underlying FE preprocessor have been developed by Siemens RTD together with the KU Leuven and the University of Calabria. Figure 9 shows the transmission error variation with increasing load of a pair of spur gears. These gears are physically mounted on an in-house gear test rig[14, 15] which is used for validation of the developed numerical models. The tested gears have 57 teeth, a normal module of 2.6 and a center distance of 150 mm. Both gears present a parabolic crowning modification of respectively 5 µm and 10 µm.

One of the gears is manufactured with three slotted holes, which introduce a significant reduction in stiffness of the gear rim structure. This leads to additional variations in the transmission error curves, depending on the positions of the teeth with respect to the holes.

The results in figure 9 show the transmission error over a full rotation, highlighting additional variations due to the rim design. With the new advanced FE preprocessor method, engineers are enabled to capture these complex phenomena in a seamless fashion, including the nontrivial coupling between gear flexibility, structural lightweighting, friction effects and microgeometry modification.

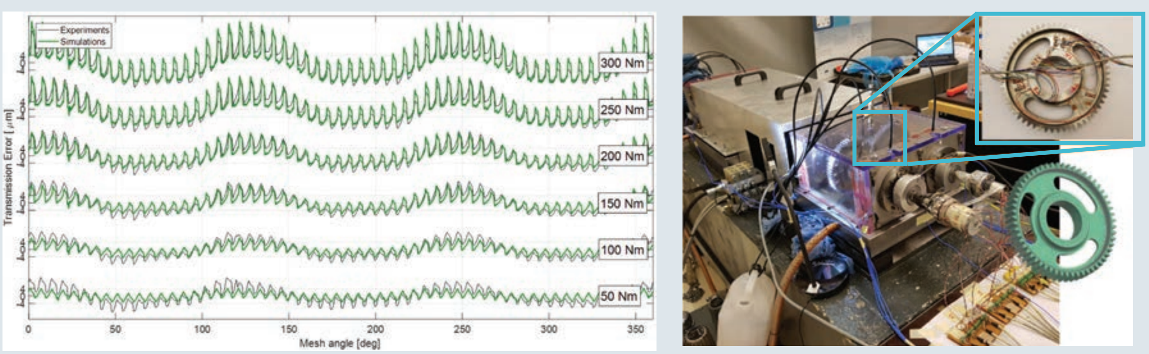


Figure 9: Experimental validation of transmission error against Simcenter 3D Motion – advanced FE preprocessor method – influence of microgeometry and friction with increasing load.

Conclusions

Siemens PLM Software has pioneered the next step in broader accessibility of simulation for gearbox design engineering. With the Simcenter 3D Motion Transmission Builder, the user can create models easily and thus increase productivity by choosing from a comprehensive set of contact methods to address the range of complexity found in industrial applications. Several industrially relevant results have been presented and discussed. It has been shown that the FE preprocessor can be used for mesh creation and the advanced FE preprocessor method has unprecedented features with respect to accuracy for output linked to NVH (gear whine, rattle) and durability analysis with a very good computational performance for the provided accuracy. Followup research and development is ongoing in the topic areas of bevel and hypoid gears, bearings, lubrication, spline and ring gear ovalization.

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