

DIGITAL INDUSTRIES SOFTWARE

Boosting productivity in gearbox engineering

Efficiently and effectively build and simulate multibody simulation models

Executive summary

Gearbox design engineers typically spent several days preparing a parameterized model before they could numerically simulate the nonlinear dynamics to obtain transient system-level loads for noise, vibration and harshness (NVH), conduct durability analyses and optimize the design for these attributes.

Simcenter™ 3D Motion Transmission Builder software is a vertical application that revolutionizes the user experience in setting up the multibody simulation model of the transmission and dramatically increases productivity. Using Transmission Builder enables engineers to progress from initial design to accurate simulations in as little as one hour.

Time-domain multibody simulation can meet the required accuracy to predict system-level loads and NVH performance to replace physical prototype testing. This white paper describes this capability using an industry-relevant case.

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Introduction

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 non-linear system dynamics in a sufficiently detailed, yet computationally efficient way. After designing the gearbox, the design engineer needs to use multibody simulations to accurately predict the system's behavior for NVH, transient, durability and other analyses. Until recently, building the multibody simulation models was a tedious and error-prone manual process. For an experienced user, it can take days to conduct modeling, parameterization and iterations for relatively complex models.

Using Transmission Builder provides an in-depth, gearbox-specific, easy-to-use multibody simulation process. By conducting simulations in Simcenter 3D Motion, the user can perform detailed analyses while maintaining a thorough overview of the model structure. Simcenter is part of the Siemens Xcelerator business platform of software, hardware and services. Using Transmission Builder requires less expertise while significantly boosting productivity when setting up the multibody simulation model. As a result, many models can be created in an hour. The workflow is shown in figure 1.

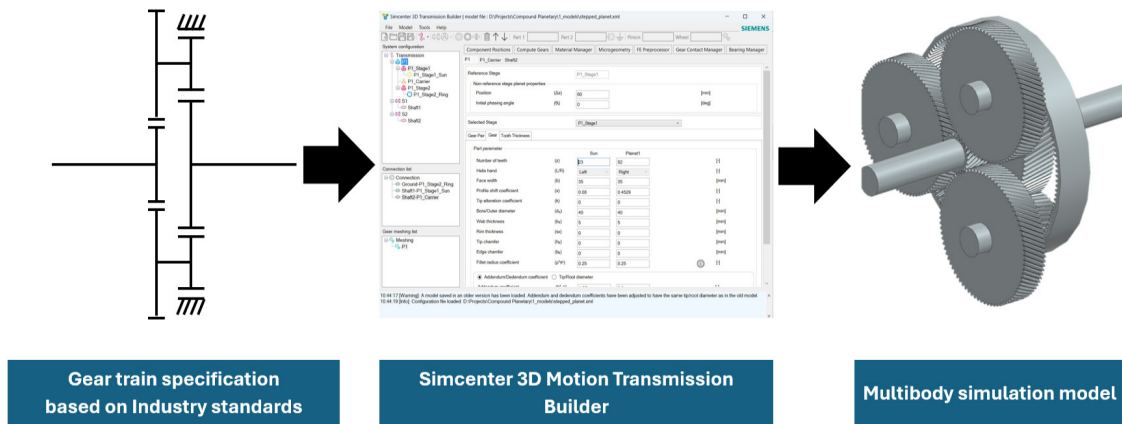


Figure 1. With the workflow based on gear design specifications, engineers can employ the Transmission Builder to quickly and accurately define the transmission layout and generate the multibody simulation model.

Transmission Builder also provides easy access to different levels of fidelity for gear and bearing analysis. Several innovations to Simcenter 3D Motion are introduced in this paper. The contact detection method has been 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) has been adopted to efficiently analyze lightweight and ring gears in a dynamic multibody simulation environment.

1 Gearbox design engineering

Due to increasing awareness of environmental concerns, the industry is setting stringent targets for energy efficiency, emissions and noise regulations. 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 document significantly reduced transmission losses of 50 percent, revealing the potential to save 9.3 million tons of carbon dioxide (CO₂) emissions in the automotive field, but these studies do not consider the impact on crucial performance attributes such as durability and noise.^{1,2} The solution to this riddle lies in using predictive capabilities for system-level dynamics in the transmission design engineering process.

The basic components of a transmission system are gears, bearings, shafts and the supporting structure. These are mutually connected, and the supporting structure substantially affects the contact of bearings and gear meshing through several types of misalignments that affect the transmission error. About 70 percent of energy loss happens in the gear train, and 30 percent in the bearings.

Therefore, gearboxes present significant design engineering challenges in many applications, ranging from automotive (cars, trucks, buses) to wind turbines and helicopters. The primary challenge is to capture the nonlinear system dynamics in a sufficiently detailed, yet computationally efficient way. Designers of transmissions can choose from two software solution families to support their design and simulation. The first family is targeted at transmission-centric computer-aided engineering (CAE) tools (such as Romax, KISSsoft, Masta, etc.),

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 you obtain sufficiently accurate predictions in a feasible amount of time to predict nonlinear dynamics, noise

and vibration, and durability performance. Until recently, building a full transmission model in a multibody simulation tool was a tedious and error-prone manual process. It could take days of modeling, parameterization and iterations to build complex models for an experienced user. With the advances presented in this white 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.

2 The Simcenter 3D Motion Transmission Builder

Using 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 mesh phasing. As such, using Transmission Builder dramatically decreases the time it takes to create a model.

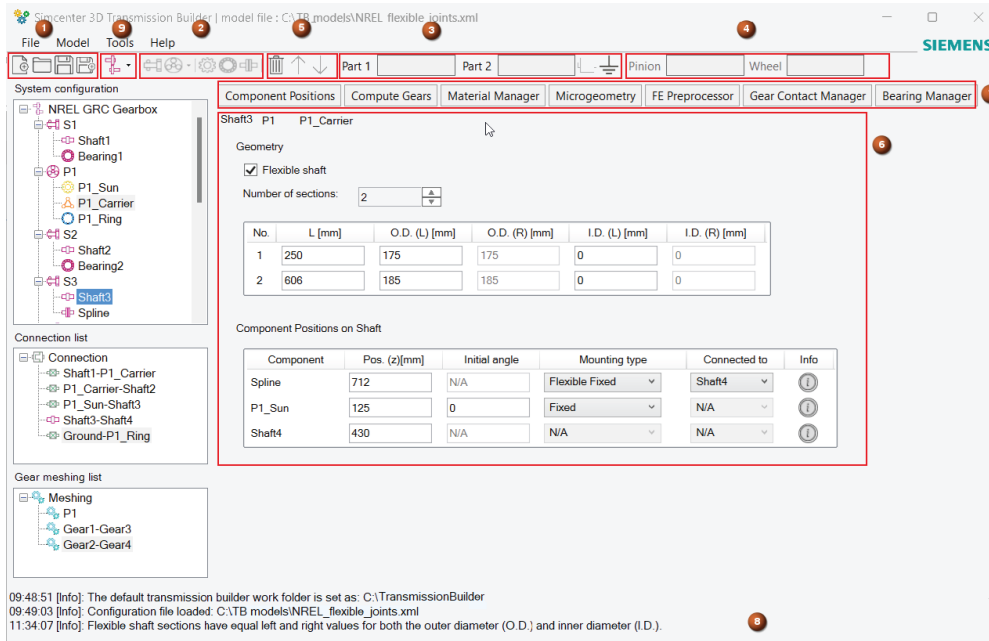


Figure 2. The main window layout of Transmission Builder.

The main window layout of Transmission Builder is shown in figure 2. One can distinguish the following elements:

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 meshing 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, gear contact and bearings.

8. Log window: Display user’s action performed and warning/error messages.

9. Link to Simcenter 3D Motion: Create/update the model in Simcenter 3D Motion.

The Transmission Builder closely follows the workflow of the user so he/she can make 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, planetary gear and compound planetary gear systems. Thereafter, a gear geometry calculation compliant with the International Organization for Standardization (ISO) 21771 standard is performed, generating the gear geometry from the transmission design parameters according to the standard.⁴ The Transmission Builder then is used to create the 3D geometry models in Simcenter 3D Motion. Next, the gear microgeometry is created with a single click (see figure 3): profile and flank line modification or their combinations, as well as file creation for the gear contact model input. The

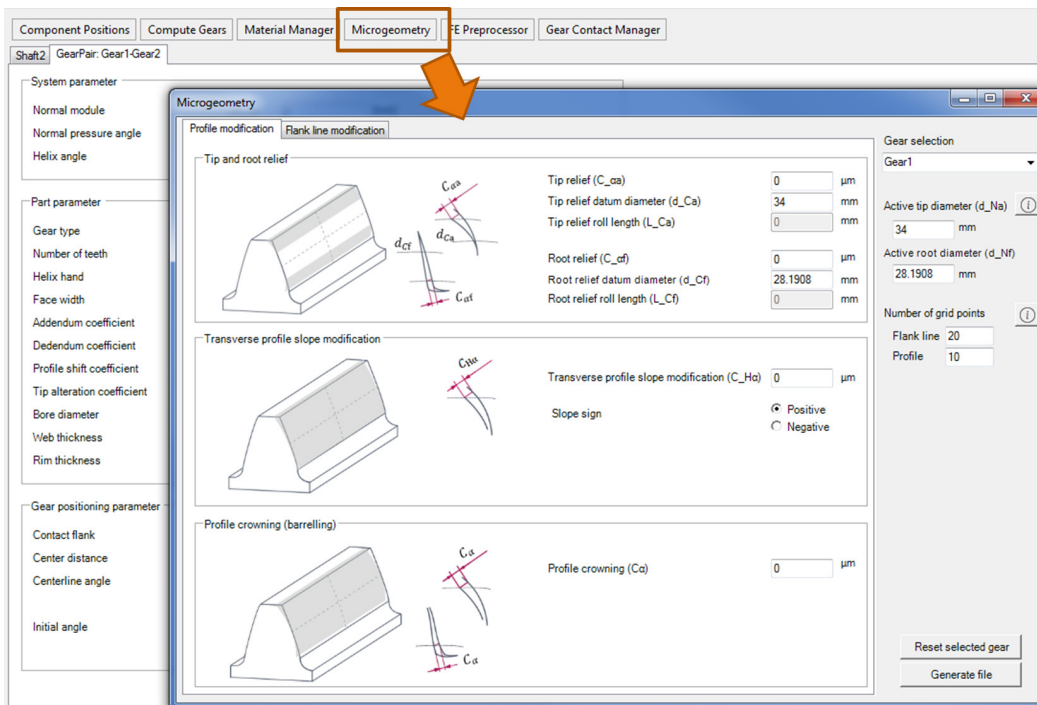


Figure 3. Microgeometry creation in a simple click.

Transmission Builder can then be used to create the initial conditions: component initial angles, automatic gear phasing, joints (bearings and coupling), constraints, etc. The gear contact manager enables interfacing with the gear contact model to set the required level of fidelity and to assign the correct microgeometry modifications. Finally, the bearing manager allows the user to set the required level of fidelity for the bearing analysis so the user is ready to solve the transmission system.

3 Solving the transmission system

The main tasks performed by the gear contact element consist of detecting the contacts, computing the required deflections and translating deflections into loads. Gear contact forces are accurately considered by the multibody solver to calculate the system-level loads, and hence the durability and NVH behavior. Figure 4 shows the most important geometrical effects that are dynamically captured by the new gear contact element.



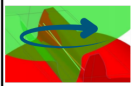
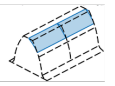
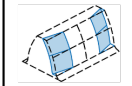
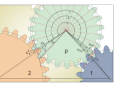
						
What?	In-plane and off-plane relative translations	Axial relative translation	Angular misalignment	Profile modifications Profile errors	Flank line modifications / errors Full topological modifications	Mesh phasing
What is it relevant for?	Backlash as function of load Gear rattle Low frequency fluctuations due to eccentricity	Load distribution fluctuation transmission error fluctuation	System-level dynamics Gear Whine Modulation sideband	Contact pattern Optimization of transmission error under load	Contact pattern Optimization of transmission error under load	Amplitude modulation at planetary gear

Figure 4. The gear contact element enables all aspects of contact detection that are relevant to predict system-level transmission behavior: dynamics, noise, durability.

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

1. Standard (based on ISO standards with optional user input).
2. Analytical (ISO + CAI, empirical).
3. Advanced (FE preprocessor).

These methods have been implemented within the Simcenter 3D Motion solver, a general-purpose multibody software.

3.1 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 using ISO formulas.⁵ The gear-pair meshing stiffness computed in this way is a qualitative approximation of the true stiffness of the analyzed gear pair, but 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 relevant. No microgeometry modification or tip contact is allowed, since no tooth-per-tooth contact is defined, only the global behavior of the contact pair. Misalignment is included in an averaged sense. The stiffness is not load-dependent, so the nonlinear stiffening effects with increasing load are 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.

3.2 The analytical methods

This class of methods allows a significant step up as compared to the standard method. 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) is not relevant.

The accuracy of the contact detection is drastically increased when using this method. In particular, 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 several slices in which the instantaneous axial overlap is divided. The contact detection is performed efficiently for each slice in the gear contact pair, while considering 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 five and 20 usually proves sufficient for most applications without a dramatic effect on computational performance.

3.2.1 Analytical ISO-CAI

The stiffness function used combines the ISO tooth-pair stiffness with specific formulas designed to provide the bending stiffness for the tooth-pair of spur and helical gears.^{5,6,7} The stiffness curves provided by the formulas are linear with respect to load and do not include nonlinear stiffening effects.

3.2.2 Analytical empirical method

The analytical empirical method can be used as a higher fidelity alternative to the analytical ISO+CAI method, especially for helical gears where it considers more accurately the stiffness coupling between slices and the axial stiffness. On top of that it can also consider the effect of tooth coupling. It provides good accuracy that is on par with the advanced FE methods. It works with basic gear inputs without the need for any FE preprocessing or mesh creation.

The analytical empirical gear contact force relies on empirical formulas for evaluating tooth pair contact stiffness based on the work of Weber and Benachek, Sainsot et al, and Xie et al.^{8,9,10} It calculates the stiffness online based on the contact location and considers the coupling effect between the different contact points.

3.3 The advanced FE preprocessor method

With this novel method, the user can go a level further with respect to accuracy. If lightweight gears, ring-gear flexibility and gear bulk deformation are important (for example, causing side bands in the dynamic transmission error (DTE) due to holes in gear blanks), an even higher level of fidelity is required compared to the previous methods. 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 combining the ideas coming from solid theoretical studies and advanced numerical techniques originating from the model order reduction field.^{11,12, 13 14, 15, 16} The user can employ this advanced method in a straightforward way and let the algorithm work on the advanced numeric behind the scenes. The advanced FE preprocessor method exploits the power of the Simcenter Nastran FE software together with an FE preprocessing tool. This tool is linked with an easy-to-use interface and

enables you to create parametric FE meshes of spur and helical gears and the stiffness data that is needed for the computations in the multibody solver. The method is powerful thanks to the coupling of FE-based tooth stiffness data that accounts for gear-body deflection in a 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 the 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 trade-off between accuracy and computational performance.

4 Results

4.1 Advanced FE preprocessor method: microgeometry modification analysis

It is important to design a gearbox so the microgeometry modifications are optimized for the operational conditions of the system. With the Transmission Builder it is easy to create a model of a two-stage layshaft system, common for most passenger electric vehicles (EVs) today. The model includes a flexible housing and a contact-based nonlinear coupled rolling bearing model to represent the housing and bearing compliance respectively.¹⁴ A different set of microgeometries is applied to the left and right tooth flanks of both helical gear pairs. For microgeometry, slope and crowning in both the profile and flank line direction are created and applied to all gears. Typically, microgeometry

modifications are applied to achieve a minimum static transmission error (STE) at a desired nominal torque. Figure 6 shows the advanced FE preprocessor method and demonstrates that 10 slices can capture this effect clearly. The input or motor shaft is driven by a constant revolutions per minute (rpm) while a torque is applied to the output shaft. Several torques are evaluated and the STE is shown in figure 6. At low torque the typical shape dictated by the imposed microgeometry modification is captured; furthermore, the STE reaches a minimum at the rated torque of 100 newton-meter (N·m) while further increasing at higher torque with the typical quasi-sinusoidal shape often reported for helical gears.

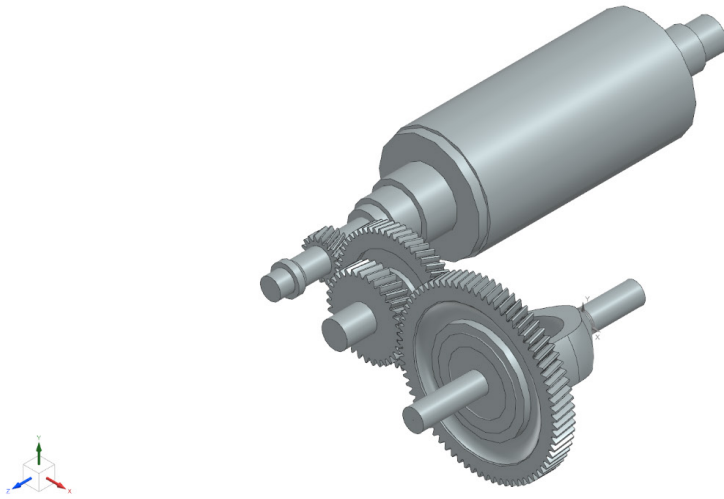


Figure 5. Two-stage layshaft system with helical gear pairs.

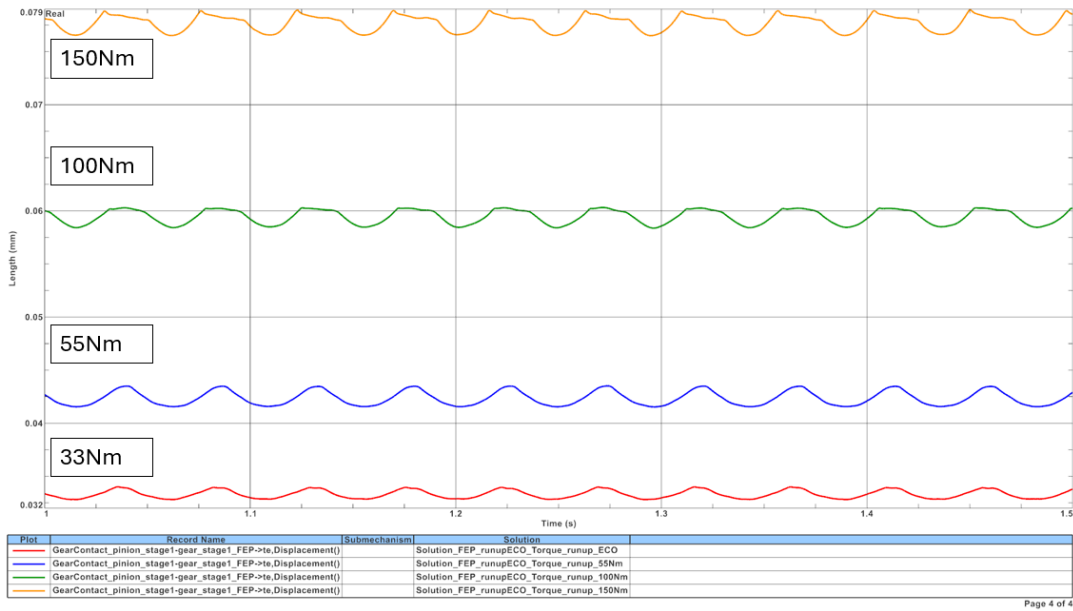


Figure 6: Quasi-static TE for increasing load.

Table 1 shows the peak-to-peak transmission error (TE) for the different gear contact stiffness methods for a resistance torque of 150N·m applied to the output shaft. The advanced methods consider the effect of the differential geometry on the gear contact stiffness. As a result, the overall gear contact stiffness is lower compared to the analytical methods. Because of this, the gear load distribution is more spread on the tooth flank, resulting in lower peak-to-peak TE values. Moreover, for the advanced FE preprocessor method considering the gear flexible body, the gear deformation will influence the contact detection. This is clearly illustrated in figure 7, where the effect of the loads on the gear deformation is shown. The effect of this out-of-plane bending of the gear on the load distribution on the tooth flank can also be seen on the contact pattern plots shown in figure 8. To summarize, the gear contact behavior is strongly coupled with the full transmission system level behavior.

Gear contact stiffness method	Peak-to-peak TE 150N·m (μm)
Analytical ISO-CAI	10.886
Analytical Empirical	8.952
Advanced FE Preprocessor	6.888
Advanced FE Preprocessor Flexible	5.951

Table 1: Peak-to-peak TE for 150N·m for different gear contact stiffness methods.

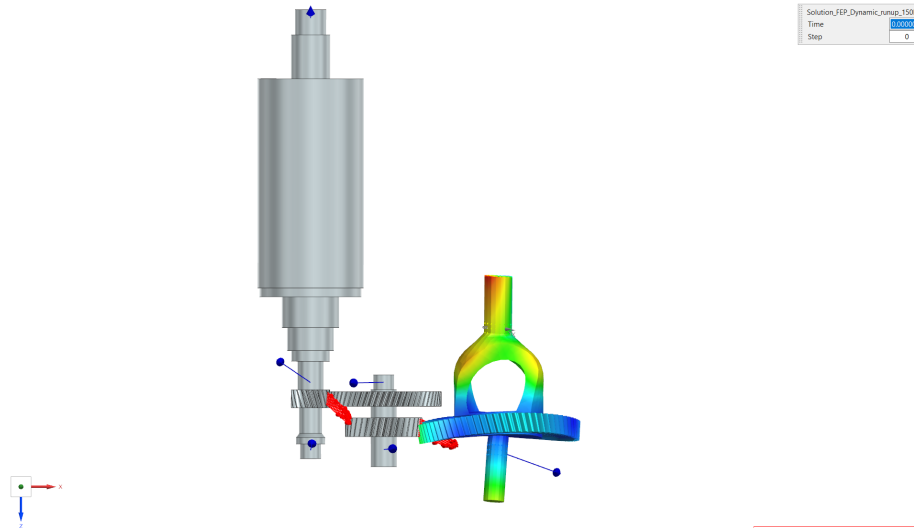


Figure 7: Gear and bearing forces resulting in deformation of the flexible gear differential.

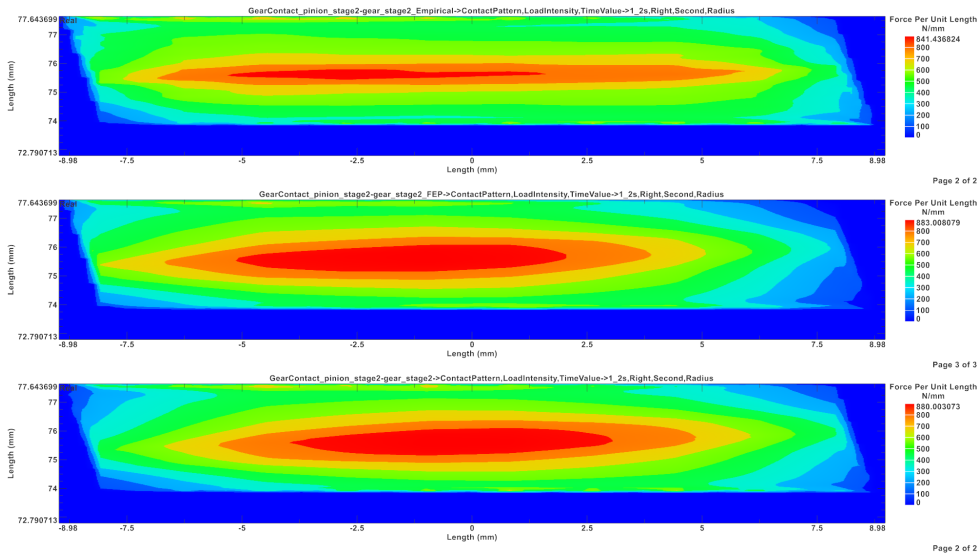


Figure 8. Load intensity contact pattern plots for the differential between gear contact stiffness methods.

4.2 Dynamic analysis of a two-stage layshaft gearbox

The advanced FE preprocessor method also enables gearbox design engineers to assess the frequency content of the system dynamics response to the excitation coming from the gears. The same model as in the previous section is simulated in Simcenter 3D Motion with a speed on the input shaft ramping up from zero to 6,000 rpm. Figure 9 shows the bearing force in the global X direction on one of the bearings connecting the input shaft to the housing. The graph shows some resonances due to the gearbox eigenmodes. When looking at this bearing force in the frequency domain (figure 10), you can clearly identify the gear meshing orders (10.25 and 18). Gear order 18 corresponds to the pinion gear on the input shaft, while gear order 10.25 corresponds to the gear wheel on the output shaft. The Campbell diagram allows engineers to not only identify the gear meshing orders, but also critical resonances that might lead to unwanted NVH performance issues. The bearing forces will excite the housing, resulting in housing surface vibrations and radiated noise.

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 11. With this process, the influence of a design change (for example, 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 to optimize a design and mitigate NVH phenomena like rattle and whine.

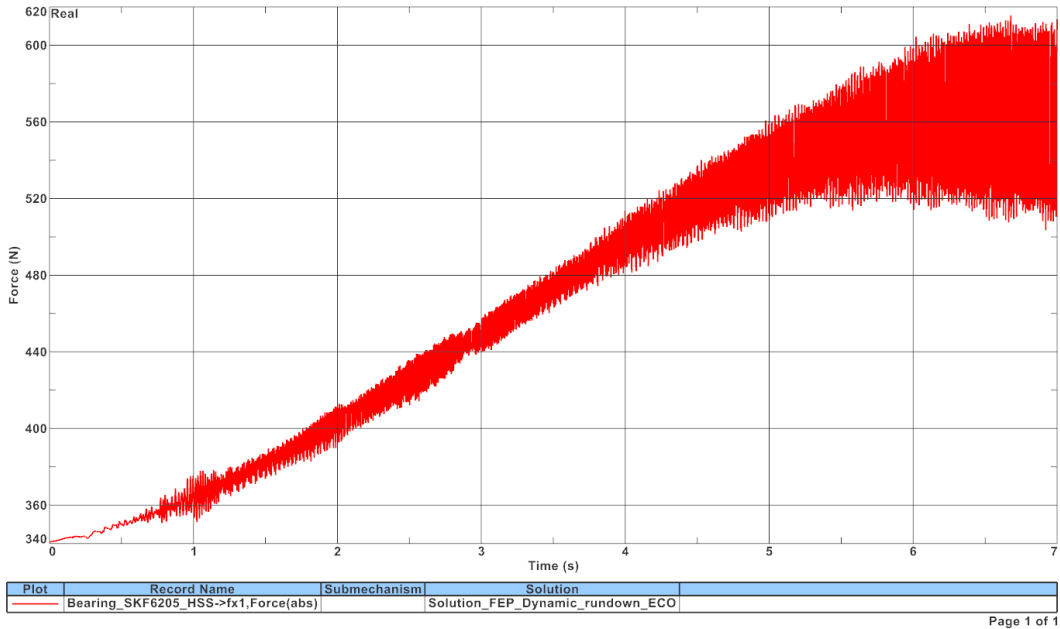


Figure 9. Bearing force in global X-direction on the input shaft.

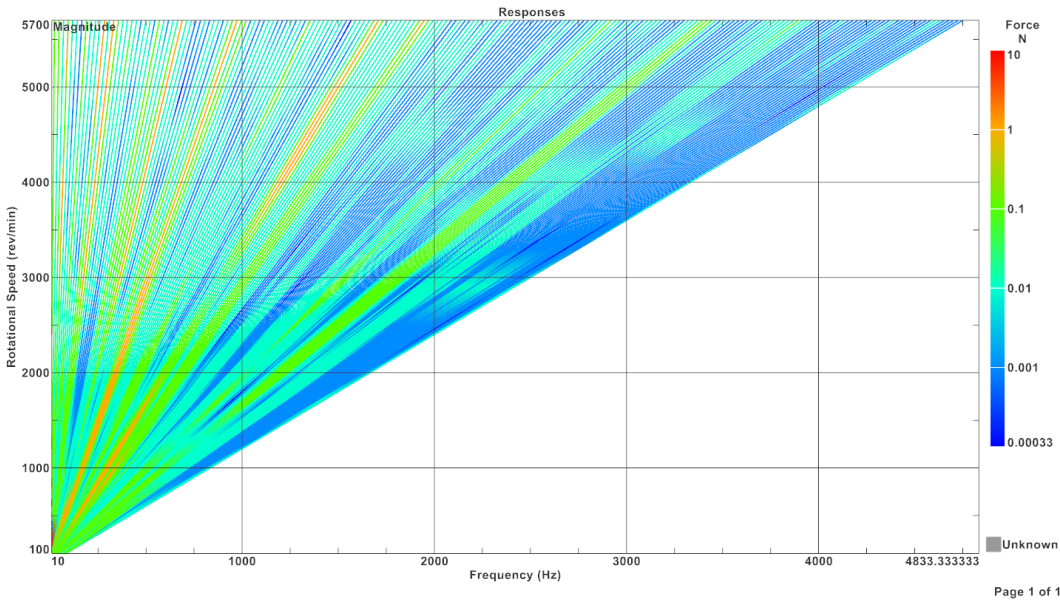


Figure 10. Campbell diagram of the bearing force in global X-direction on the input shaft.

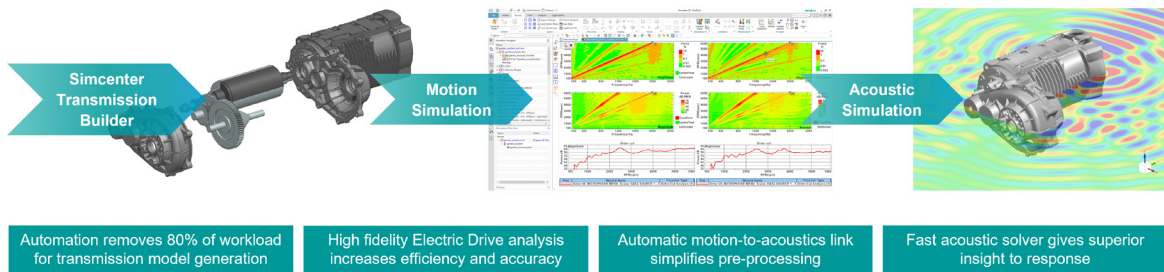


Figure 11. Typical workflow to assess acoustic radiation of a gearbox.

4.3 Motion advanced FE-preprocessor: flexibility, friction and experimental validation

The in-depth correlation of an individual tooth contact with test data shows that it might become crucial to consider the effects of flexibility and friction in the simulation-based design of gears. This can be done with the advanced FE preprocessor method, as shown in this third example. The advanced FE preprocessor method has been developed by Siemens RTD together with the KU Leuven and the University of Calabria. Figure 12 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,^{18, 19} which are 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 . Figure 12

shows that at low load the friction has little influence, and the transmission error takes up the typical parabolic shape dictated by the microgeometry. The simulated transmission error without friction shows the expected trend of modified gears: a clear reduction in the peak-to-peak value of the transmission error. On the contrary, both the experimental results and the advanced FE preprocessor method show an almost identical trend with an increase in the peak-to-peak value for the transmission error and some sharp peaks. This last effect is clearly caused by friction that presents a load reversal at the pitch point along the line of action where the sliding contact speed changes direction. This result shows how the advanced FE preprocessor method allows engineers to capture complex phenomena in a seamless fashion, including the nontrivial coupling between gear flexibility, friction effects and microgeometry modification.

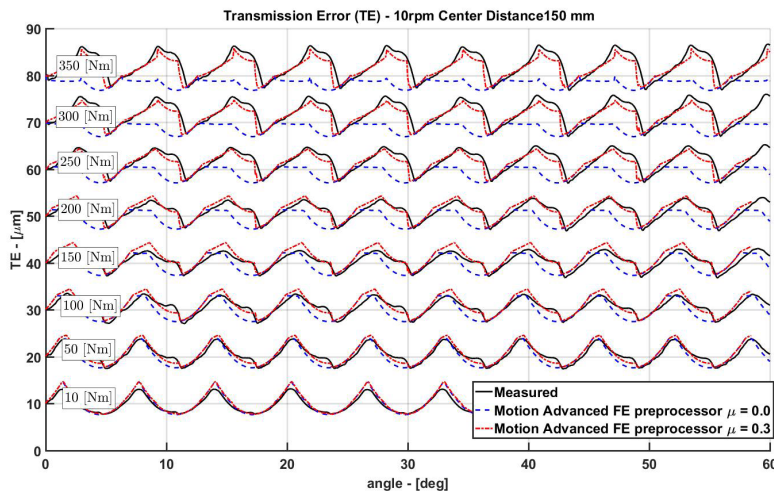


Figure 12. Experimental validation of transmission error against Simcenter 3D Motion – advanced FE preprocessor method – and the influence of microgeometry and friction with increasing load.

Conclusion

With the Simcenter 3D Motion Transmission Builder, the user can create models easily and thus increase productivity choosing from a comprehensive set of contact methods that are scalable in complexity to address a range of industrial applications. Several industrially relevant results have been presented and discussed. It has been shown the advanced FE preprocessor method has unprecedented features with respect to accuracy for output linked to NVH (gear whine, rattle) and durability analysis with good computational performance for the provided accuracy.

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