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Improving wind turbine gearbox simulation

ZF Wind Power explores Simcenter 3D Motion transmission builder to enhance drivetrain design

Executive summary

Wind energy production and power output from wind turbines are rapidly increasing. Drivetrains are a critical subsystem for guaranteeing optimal performance for the expected lifetime of these machines. Transmission engineers need to be able to predict the system level to ensure 20 to 25 years of service. More accurate and faster virtual prototyping tools are needed to accomplish this task. This white paper introduces the latest evolution of Siemens Digital Industries Software's drivetrain simulation portfolio. Its capabilities and the significant advances it brings to the field of numerical simulation are shown in the context of a collaboration between Siemens and ZF Wind Power, in which a wind turbine drivetrain system has been simulated using this newly developed method.

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Introduction

In recent years, wind energy production has seen rapid growth, with policymakers and wind turbine manufacturers pushing for an increase in efficiency and energy production capabilities. Given that, for most wind turbines, drivetrains are a critical subsystem in terms of reliability, virtual prototyping and accurate system-level numerical simulation of transmissions, which are of paramount importance in the design process of wind turbines. Gears and bearings, which are fundamental elements of transmission, must be accurately modeled to obtain reliable results. The Simcenter™ 3D Motion Drivetrain software transmission builder capability and other drivetrain simulation solutions offer designers a user-friendly environment to quickly and easily build models from scratch and set up simulations. The state-of-the-art numerical models allow you to obtain accurate results for a great variety of applications.

This white paper introduces the latest addition to the Siemens drivetrain simulation portfolio, a new gear contact element that allows the user to capture multiple key phenomena, including a correct representation of dynamically evolving flexibility effects. Its capabilities are demonstrated in the context of a collaboration between Siemens and ZF Wind Power, a world leader in the field of wind turbine design and manufacturing. Within the context of this activity, Siemens showcased the potential of Simcenter 3D Motion transmission builder and Simcenter 3D Motion solver capabilities by simulating the behavior of a complex ZF wind turbine drivetrain system. The results show the level of accuracy is similar to what can be obtained from a typical, expensive and complex-to-setup nonlinear finite element (FE) simulation solution, while the Simcenter 3D Motion solution achieves this in a fraction of the time. Figure 1 shows the user workflow.

Several levels of modeling fidelity that show the new simulation methods, which were developed by the multibody research team at Siemens Digital Industries Software, lead the way to new possibilities in the field of transmission simulation.

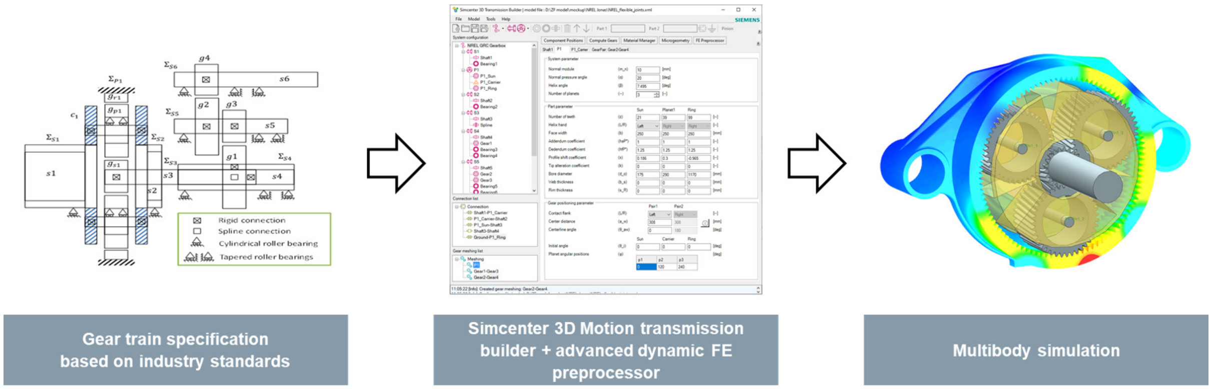


Figure 1. Using gear design specifications, engineers can employ the Simcenter 3D Motion transmission builder to quickly define the transmission layout and generate the multibody simulation model. The advanced dynamic FE preprocessor solution allows the user to obtain even more accurate results in a computationally efficient manner.

Background: wind energy and gearbox simulation

Driven by heightened environmental concerns and the need to address climate-change-related challenges, the global community is striving to evolve to a more carbon-neutral economy, which so far has boosted the development of wind energy production capabilities over the last decade to a cumulative capacity of 651 gigawatts (GW) in 2019.[1] Economies of scale push wind turbine manufacturers to maximize the amount of power produced, resulting in an increase in the size of modern-day wind turbines.[2] Most of these currently use a configuration that includes a drivetrain composed of a multiple stage gearbox.

A larger-sized wind turbine implies higher loads that act on the critical drivetrain components, such as gears, shafts and bearings. The drivetrain components are subjected to a combination of dynamic loads that arise from aerodynamic effects, inertial loads, generator torque loads or other transient loads that are introduced by control system actions such as blade pitching, yawing, starting up and emergency braking.[3]

Designing reliable transmission has therefore become a critical aspect of wind turbine performance during its expected lifetime. Conflicting design constraints must typically be satisfied by finding a tradeoff between the required component strength, support for rotor loads and the desire for a lightweight design to minimize the overall structural loads on the system. Virtual prototyping tools are crucial for successfully completing such tasks since they allow you to quickly and efficiently validate different design ideas by using numerical simulation and analysis.

Gearbox simulation presents significant design engineering challenges. One is to accurately capture the nonlinear dynamic behavior of critical drivetrain components in a computationally efficient manner. System-level-based simulation tools, such as flexible multibody simulation packages, are typically the preferred approach since only system-based design and analysis will allow the user to obtain sufficiently accurate predictions about nonlinear dynamics, noise and vibration performance and durability in a feasible timeframe. To obtain an accurate system-level description, component-level models are required to correctly represent the behavior of the overall system. Finally, another important challenge in the field of system-level drivetrain simulation is the time-consuming process of building up a full transmission model, which has been until recently an error-prone and complex manual process.

The solutions that are presented in this white paper allow design engineers to efficiently set up transmission models and use state-of-the-art numerical tools to accurately model all the drivetrain elements in a computationally efficient manner.

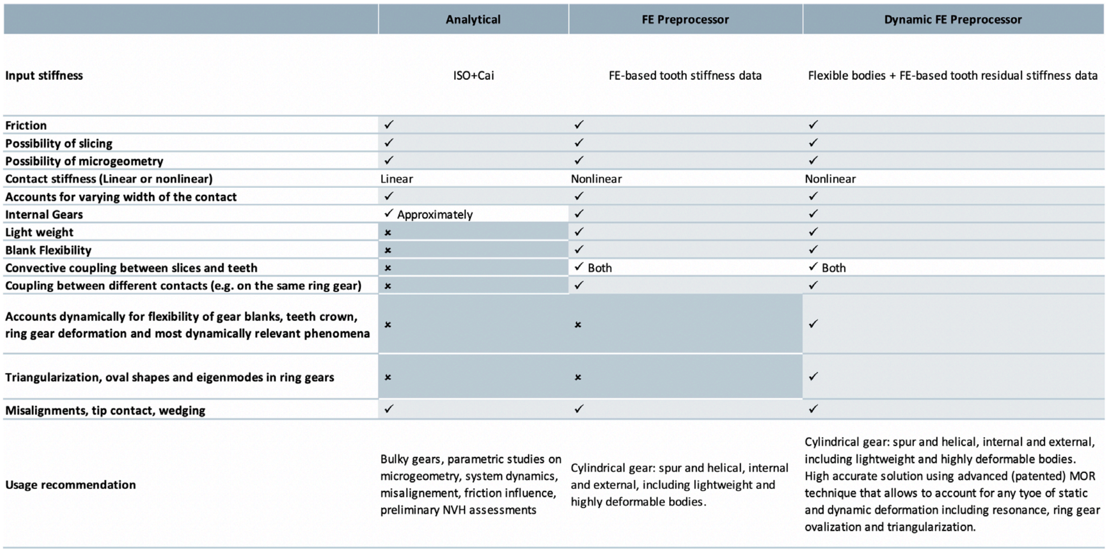
Siemens portfolio solutions for transmission simulation

Simcenter 3D, which is part of Xcelerator™ portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software, offers drivetrain engineers an excellent simulation environment to tackle transmission simulation and analysis.

The Simcenter 3D Motion Drivetrain product module includes a specific capability dedicated to streamlining the transmission simulation process. This capability is called transmission builder, and it provides an easy-to-use interface to build complex transmission systems.[4] Transmission builder dramatically decreases the model creation time, while simultaneously streamlining the definition of boundary conditions, joints, constraints, etc., and the setup of the gear contact elements, which are fundamental for simulating the drivetrain system. The Simcenter 3D Motion gear contact force element aims to improve the speed, accuracy and usability of gear-meshing analysis by using a modular approach.

The gear contact element's main tasks are to detect the contact between the gear teeth, compute the corresponding tooth deflections and translate these deflections into accurate contact loads. The resulting gear contact forces are considered by the multibody solver to calculate the system-level loads. This state-of-the art solution builds on ideas described in solid theoretical studies[5,6,7,8,9] and combines analytical solutions and automatic FE-based preprocessing in a hybrid approach that provides an optimal tradeoff between accuracy and computational efficiency. The methodology is available for any cylindrical involute gear type – spur and helical, external and internal – and is particularly powerful for analyzing the dynamics for gears with a complex, lightweight or highly deformable gear blank design.

The latest evolution of the gear contact element adds the advanced dynamic FE preprocessor (AD-FE) solution,[10,11] which further expands the capabilities for gearbox simulation: This new methodology[12] accounts for complex phenomena that are generally not captured by other multibody formulations. An extensive but not exhaustive list of captured effects includes dynamic gear body deformation, ovalization, triangular and quadrangular deformation of ring gears due to planet interactions and deformation coupling between multiple gear contact. All of this makes the advanced dynamic FE preprocessor method



	Analytical	**FE Preprocessor**	**Dynamic FE Preprocessor**
Input stiffness	ISO+Cai	FE-based tooth stiffness data	Flexible bodies + FE-based tooth residual stiffness data
Friction	✓	✓	✓
Possibility of slicing	✓	✓	✓
Possibility of microgeometry	✓	✓	✓
Contact stiffness (Linear or nonlinear)	Linear	Nonlinear	Nonlinear
Accounts for varying width of the contact	✓	✓	✓
Internal Gears	✓ Approximately	✓	✓
Light weight	×	✓	✓
Blank Flexibility	×	✓	✓
Convective coupling between slices and teeth	×	✓ Both	✓ Both
Coupling between different contacts (e.g. on the same ring gear)	×	✓	✓
Accounts dynamically for flexibility of gear blanks, teeth crown, ring gear deformation and most dynamically relevant phenomena	×	×	✓
Triangularization, oval shapes and eigenmodes in ring gears	×	×	✓
Misalignments, tip contact, wedging	✓	✓	✓
Usage recommendation	Bulky gears, parametric studies on microgeometry, system dynamics, misalignement, friction influence, preliminary NVH assessments	Cylindrical gear: spur and helical, internal and external, including lightweight and highly deformable bodies.	Cylindrical gear: spur and helical, internal and external, including lightweight and highly deformable bodies. High accurate solution using advanced (patented) MOR technique that allows to account for any tyoe of static and dynamic deformation including resonance, ring gear ovalization and triangularization.

Table 1. Overview of gear contact solution methods implemented in Simcenter 3D Motion. In the context of this white paper, only the FE preprocessor and dynamic FE preprocessor results are shown.

the most accurate yet computationally friendly solution, when a highly accurate description of the load transfer path is required throughout the gearbox.

Table 1 highlights the main differences between, and characteristics of the gear contact elements supported by Simcenter 3D Motion transmission builder. For the purposes of this white paper, given the complexity of the use case at hand only the advanced FE preprocessor and dynamic FE preprocessor are discussed.

The gear element is complemented by the analytical bearing element, which is the Siemens go-to solution for accurate bearing simulation. Similar to the gear contact element, this physics-based force element accurately computes the bearing reaction forces at system level, allowing for a seamless integration in the Simcenter 3D Motion simulation environment.[13,14]

Modeling and simulation of a wind turbine gearbox

To demonstrate the new advanced dynamic FE preprocessor-based gear contact element capabilities and verify our best practices regarding drivetrain simulation, the Siemens Digital Industries Software Research and Technology Development (RTD) team in Leuven, Belgium joined efforts with ZF Wind Power for the drivetrain simulation project. Within the scope of this activity, a ZF wind turbine planetary gearbox has been modeled and analyzed with various levels of accuracy to study and assess the importance of fidelity on the simulated stage transmission error and contact patterns. Results have been compared by ZF Wind Power against their know-how and inhouse best practices and proved to be precise when compared to physical measurements.

Due to confidentiality, only a mockup representation of the gearbox is shown in figure 2 (which was done by using the similar topology of the NREL gearbox).[15] The system contains a helical planetary gearbox, where three planet gears are in mesh with a floating sun gear and a ring gear. This latter component is connected via bolts to an external housing, which is modeled as connected to the ground. The planet gears are mounted on the carrier by means of tapered roller bearings.

To model the drivetrain system, the following motion drivetrain simulation solutions were used:

- Simcenter 3D Motion transmission builder, which facilitates a quick and easy creation and analysis of multibody drivetrain models with different levels of desired modeling fidelity
- The advanced FE preprocessor-based gear contact elements of Simcenter 3D Motion are used to model the planet gears since this solution provides an optimal tradeoff between accuracy and computational efficiency and is excellent for modeling bulky external gears
- The advanced dynamic FE preprocessor-based gear contact element of Simcenter 3D Motion is used to model the floating sun gear and the ring gear. The flexibility of these bodies plays a key role in the overall dynamic behavior of the system. The advanced dynamic FE preprocessor is a unique solution with terrific accuracy at reasonable computational speed. It accurately considers the effects of complex dynamic phenomena, for example, ring gear deformation, while remaining extremely accurate at tooth contact level. The combination of global dynamic effects and accurate local tooth-level deformation and contact mechanics make this an excellent solution in terms of speed and accuracy
- The Simcenter 3D Motion analytical bearing contact element is used to correctly model the reaction loads of tapered roller bearings, which are placed between the planet gears and the carrier pins

In the context of this work, three specific models with different levels of fidelity are considered:

- Model 1 focuses on correctly capturing the gearbox kinematics, while making use of the advanced FE preprocessor-based gear contact elements to describe the contact forces. However, the component dynamic flexibility (for example, using flexible bodies in the multibody simulation) is not yet considered. The tapered roller bearings are represented using revolute joints
- Model 2 increases the fidelity by including the flexibility of the carrier. Additionally, the dynamic flexibility of the sun gear is also included to study the effect of this component's increased fidelity on the gearbox's behavior. The remaining planet-ring gear mesh contacts are described using the advanced FE preprocessor solution. The behavior of the tapered roller bearings is also still modeled with revolute joints
- Model 3 represents the highest level of fidelity, which is considered within the context of this work. In addition to the carrier, the external housing is modeled as flexible. The gear contacts for the planet-ring meshing are modeled using the combination of an advanced FE preprocessor and advanced dynamic FE preprocessor solution for the planet-gear and ring-gear components respectively. Coulomb friction is also added to all planet-sun and planet-ring gear contacts. Finally, the tapered roller bearings are represented via analytical bearing elements

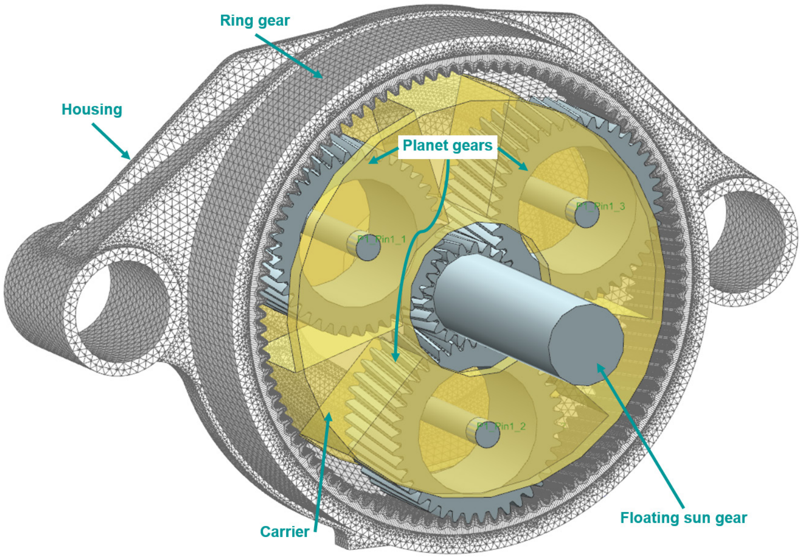


Figure 2. Transmission example – planetary stage gearbox with external housing.

Table 2 shows an overview of the three models in increasing order of fidelity.

Model number	Body flexibility		Planets connection to carrier (tapered roller bearings)		Gear contact elements			Gear contact friction
	Carrier	Housing	Revolute joints	Analytical bearing	Sun	Planet	Ring	
1			✓		A-FE	A-FE	A-FE	No
2	✓		✓		AD-FE	A-FE	A-FE	No
3	✓	✓		✓	AD-FE	A-FE	AD-FE	Yes

Table 2. Overview of the three developed models. The advanced FE preprocessor solution is initially used to represent all gears. As the model complexity increases, the advanced dynamic FE preprocessor solution is then adopted to model the sun and the ring gear.

Results

The objective of the activity is to assess the effect that model complexity has on the evaluation of transmission error and contact patterns for measurement data. Two performance indicators are considered:

- Stage transmission error (stage TE): Given two gears meshing, TE is the difference between the effective position of the driven gear and the one that it would instead have if the meshing was kinematically perfect. This concept can be extended to the entire planetary gearbox to define a stage TE, using the output rotation of the planetary stage to calculate a global TE for the drivetrain. Stage TE has been computed and analyzed in the order domain for each of the three developed models for different load cases and compared with in-house experimental results from ZF Wind Power
- Contact patterns: Contact patterns are surfaces obtained by superimposing all the contact lines over the duration of a meshing cycle. They represent where the contact zones are situated on the tooth flank of each individual meshing. With reference to the tooth profile, a well-designed contact pattern should be symmetric and centered under nominal load. For each meshing of each developed model, a contact pattern has been computed

Figures 3 and 4 show error curves for each simulation model compared to in-house experimental results from ZF Wind Power on first and second order components for 10 different load cases. The curves for each plot are normalized according to the highest error value given the confidentiality of the experimental results and should be used for a comparative analysis. In terms of absolute errors – not reported here – ZF Wind Power has been pleased with the accuracy. It is possible to notice a general reduction of the error over the entire load spectrum as the model fidelity increases. The addition of the advanced dynamic FE preprocessor gear contact element on model 2 clearly improves the accuracy and overall validity of the model under diverse loading conditions. This highlights the need for such an accurate methodology to model complex components such as floating-sun gears.

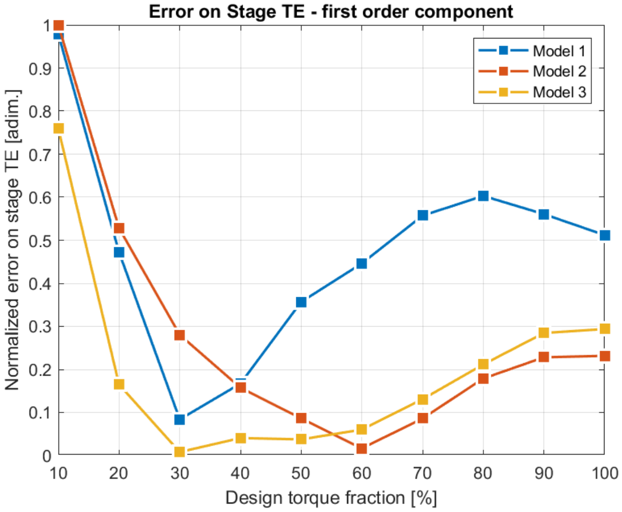


Figure 3: The normalized error in stage TE for the first-order component.

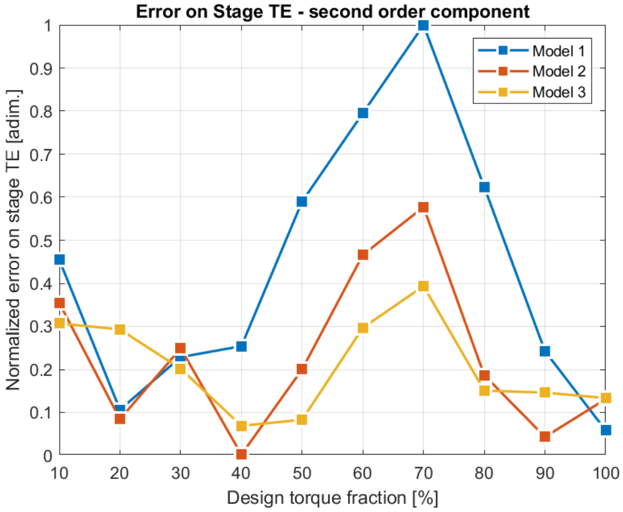


Figure 4. The normalized error in stage TE for the second-order component.

Table 3 shows the evolution of the contact pattern for each meshing for the three models. It's possible to observe how by increasing the model complexity and fidelity, the patterns tend towards a smooth symmetry around the tooth profile center. This effect is caused by the floating sun and ring gear coupled interaction and is well captured by the advanced dynamic FE preprocessor method used in models 2 and 3. In particular, the contact pattern for the planet-ring meshing for model 3 is clearly symmetric and centered, which indicates that using an advanced dynamic FE preprocessor is fundamental for obtaining an accurate solution. Only by considering the complex gear deformations to which the ring-gear body is subjected is it possible to obtain an accurate contact pattern.

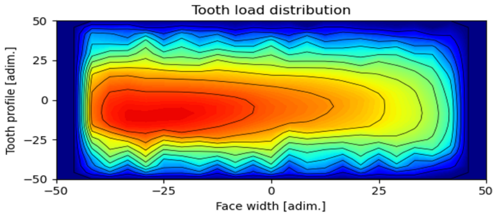
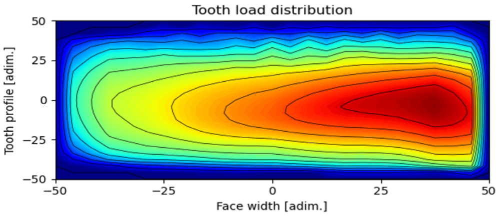
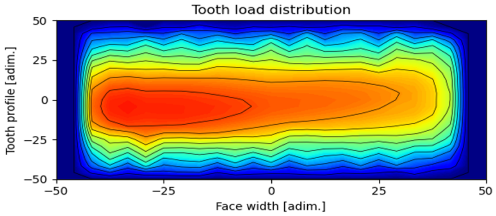
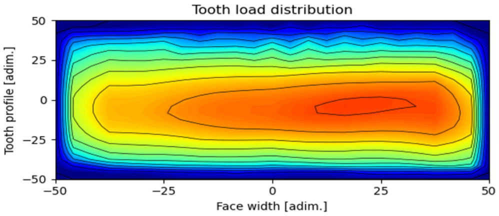
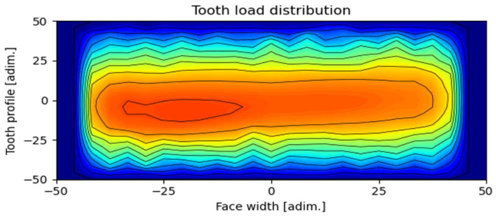
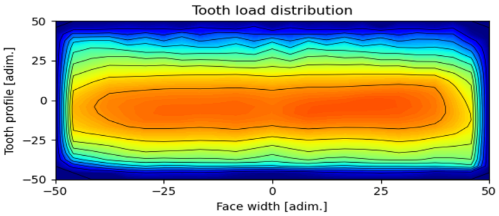
Model description	Contact pattern for the sun – planet meshing	Contact pattern for the planet – ring meshing
Model 1 • FE preprocessor for all gear contacts • Revolute joints for tapered roller bearings • Rigid carrier		
Model 2 • FE preprocessor for planet gears • FE Preprocessor for ring gear • Dynamic FE Preprocessor for sun gear • Revolute joints for tapered roller bearings • Flexible carrier		
Model 3 contains: • FE Preprocessor for planet gears • Dynamic FE Preprocessor for sun gear • Dynamic FE Preprocessor for ring gear • Friction coefficient for gear contacts • Analytical bearing for tapered roller bearings • Flexible carrier • Flexible housing		

Table 3. The contact patterns for the respective sun-planet and planet-ring meshing and for each of the three described models.

Conclusion

This white paper has presented the new advanced dynamic FE preprocessor, the latest addition to the Simcenter 3D Motion Drivetrain product module. The method is a significant improvement over the existing solutions, especially when simulating new and complex drivetrains, which are characterized by highly deformable bodies and complex gear dynamics. The accuracy and effectiveness of this modeling approach has been shown in the context of a collaboration between Siemens and ZF Wind Power, in which the effect of model complexity on transmission error and contact patterns has been investigated. Thanks to the usage of the dynamic FE preprocessor, Siemens was able to present accurate simulation results and exceed customer’s expectations.

The Simcenter 3D Motion RTD team continues to work on novel simulation solutions. Cutting-edge bevel and hypoid gears, new bearing types, spline connections and lubrication are among the main research topics that are being tackled by the team to further address the range of complexity found in industrial applications.

Acknowledgements

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Siemens Digital Industries Software

Headquarters
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 972 987 3000

Americas
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 314 264 8499

Europe
Stephenson House
Sir William Siemens Square
Frimley, Camberley
Surrey, GU16 8QD
+44 (0) 1276 413200

Asia-Pacific
Unit 901-902, 9/F
Tower B, Manulife Financial Centre
223-231 Wai Yip Street, Kwun Tong
Kowloon, Hong Kong
+852 2230 3333

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