DIGITAL INDUSTRIES SOFTWARE

Advancing bevel gear contact dynamic simulation

Enhanced mechanical 3D simulation of bevel gear performance and vibrations via finite element-based gear contact models

Executive summary

As the need for accurate gear models that integrate into a system-level design process for mechanical transmissions grows, a simulation technology gap for bevel gears becomes clear. Although spur and helical gear simulation methods accurately predict lightweight gears within flexible multibody simulations, numerically predicting bevel gear contact dynamics often faces challenges concerning contact detection and contact force calculation.

Thanks to research and development (R&D) efforts, engineers can accurately analyze bevel gear design challenges concerning gear dynamics and system-level noise, vibration and harshness (NVH) problems using Simcenter™ 3D Motion software and its new bevel gear contact formulation.

Simcenter is part of the Siemens Xcelerator business platform of software, hardware and services.

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Introduction

Bevel gears are a type of gear that is crucial for transferring power between intersecting rotating shafts and can mount at a 90-degree angle to each other, although other angular configurations are possible. We can categorize bevel gears into various groups based on tooth shape, with spiral bevel gears having the most complex tooth shape, manufacturing process and contact characteristics. Additionally, we can use them in a variety of sectors, including aerospace, automotive and general industries.

As engines become quieter or are replaced by electric motors and transmissions become lighter, transmission engineers need to define novel designs that increase power density, mechanical efficiency and durability while maintaining or enhancing NVH targets.[1] As a result, computer simulations are essential to accurately predict and optimize the component's behavior (for example, for gears or bearings) and the system's performance throughout all stages of a transmission's development cycle.

However, there is a gap in simulation technology for bevel gears when compared to cylindrical involute gearing. While modeling and simulation methods for spur and helical gears have evolved from analytical models[2, 3, 4] to component-based models for predicting lightweight gears via flexible multibody simulations,[5, 6, 7] the dynamic models for bevel gears depend on averaged tooth contact data that approximates the time-varying mesh stiffness over the mesh cycle.[8, 9, 10]

The complex geometry of bevel gear teeth and the resulting complexity of the contact phenomena can explain much of the simulation technology gap for bevel gears. Although the involute tooth profile is the standard for cylindrical gears, thanks to its beneficial contact properties, manufacturers typically create bevel gears using dedicated cutting processes, such as face-milling or face-hobbing.[11] Due to the 3D nature of the motion transfer, the contact occurs on a surface of action, for which an analytical solution is not generally available. Consequently, transmission manufacturers strongly rely on experimental testing and computerized tooth contact analysis (TCA) to design, analyze and optimize spiral bevel gear pairs. Figure 1 visualizes the concepts of plane of action for cylindrical gears and surface of action for bevel and hypoid gears.

Computerized TCA provides answers about the gear pair's key performance characteristics without needing expensive prototyping and testing.[12] Bevel gear performance indicators are usually linked to transmission error (TE) quality, the contact area under load and their sensitivity with respect to gear pair alignment errors, such as installment errors or system deflection. Unloaded TCA (UTCA) focuses mainly on determining the geometrical mismatch (referred to as ease-off topography) between two mating tooth profiles. Alternatively, loaded TCA (LTCA) predicts the loaded contact performance. Specialized computer-aided engineering (CAE) software for designing and analyzing bevel gear pairs typically includes both TCA types[13] and is usually complemented by finite element analysis (FEA) to determine tooth bending and contact stresses over the gear mesh cycle.[14, 15]

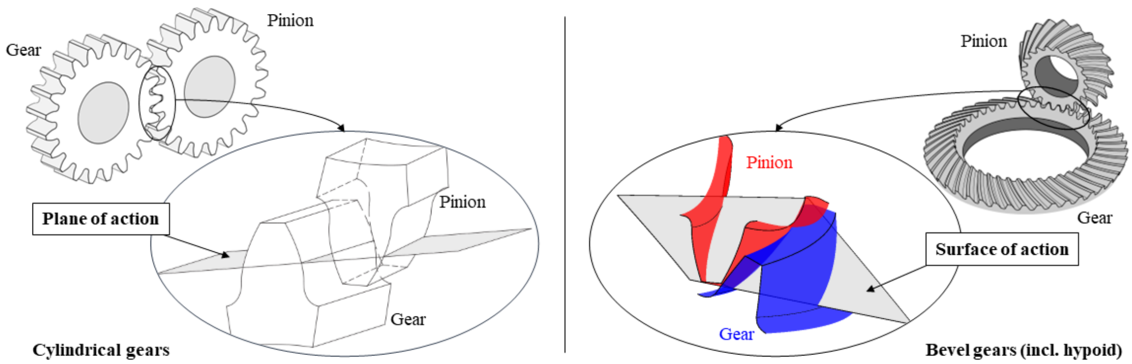

Figure 1. Illusrating plane of action concepts for cylindrical gears and the surface of action for bevel gears.

Solving bevel gear simulation challenges

An excellent solution for simulating bevel gear contact dynamics that meets industry user expectations not only accurately captures the gear pair's behavior but also predicts how the gear pair's behavior changes when installed in a transmission due to interactions with other components. Therefore, the proposed solution needs, first, to be numerically efficient, since the gear contact problem will be solved thousands of times during the dynamic simulation of the transmission. Second, it needs to accurately capture the correct component- and system-level behavior. Accuracy and efficiency are necessary for contact detection and contact force calculation phases, which are the two principal strategies in a numerical model that solve the dynamic gear contact problem.

Numerical methods to analyze bevel gear dynamics within a system-level environment face challenges related to capturing 3D, nonlinear tooth meshing characteristics in an accurate and computationally efficient way.[17] As mentioned, bevel gear design strongly relies on LTCA, which FEA complements. The finite element method (FEM) is a versatile technique that enables an accurate description of a complex component's structural deformation. However, when used in contact applications, it usually requires a large number of elements to correctly capture the deformation close to the contact zone. This results in large models that require a lot of computational resources and time to solve, limiting their use in dynamic time-domain simulations.

This white paper presents a solution that advances bevel gear simulation and analysis in all the above aspects. Firstly, a unique gear contact model, introduced by Vivet et al.[16, 17,] is extended to simulate spiral bevel gears dynamics within flexible multibody system dynamics simulation environment of Simcenter 3D Motion. Second, engineers can use a novel and highly accurate semi-analytical gear contact stiffness model, which models the gear contact deformation field using an FE-based global deformation field and the local contact deformation field using an analytical model. Combined, both novelties enable a precise prediction of the 3D load distribution and gear contact dynamics of spiral bevel gears, where the gear blank is of standard or lightweight design.

Simulating dynamic 3D bevel gear contact

The bevel gear contact element adopts a modular approach to combine fast 3D contact detection with accurate contact force computation, which requires computing data in a preprocessing phase.[18] For this, we developed dedicated procedures for kinematic analysis and automated FE-based stiffness computation. This is shown in figure 2. Due to the geometrical complexity of industrial bevel gears, the designed simulation strategy does not rely on internal procedures that could only provide an approximate bevel gear tooth flank geometry. Instead, we designed the dedicated procedures to analyze bevel gear sets in the multibody simulation environment, starting from typical bevel gear design data files.

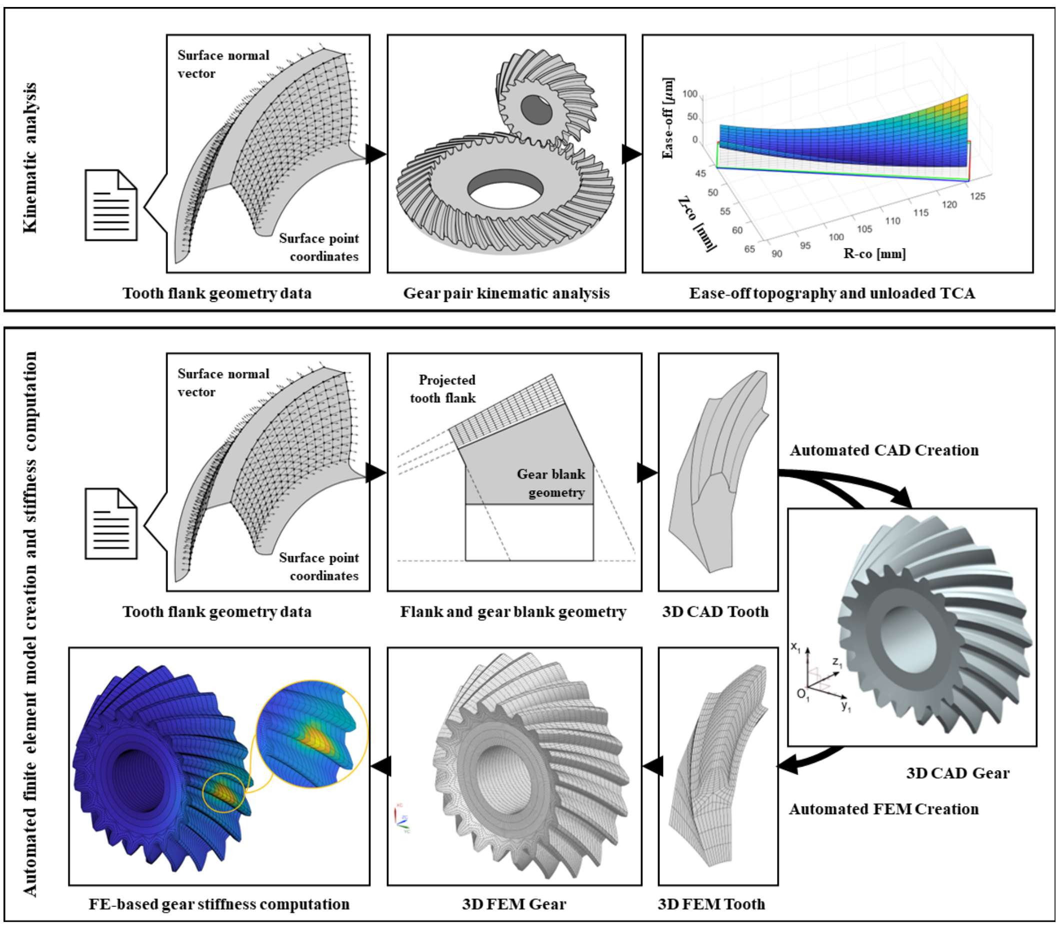

Figure 2. Process overview for bevel gear geometry modeling, FE model creation and stiffness computation.

Detecting efficient bevel gear contact

The developed gear contact element uses efficient bevel gear contact detection instead of general contact detection strategies, which treat contact surfaces as arbitrary and result in unoptimized contact searches. The approach exploits the kinematics of the near-conjugated tooth surfaces to efficiently determine the contact points. This is achieved by relying on the precomputed surfaces of roll angles for both contact flanks of the gear pair.[16, 17] The surfaces of roll angles allow the determination of contact locations on the surface of action, which is a generalization of the concept of line of action in cylindrical gears for fast contact detection. The contact locations are used to search for penetration δ between tooth flank segments of the pinion and gear elements, which can be done using equation 1.

$$\delta_{lk}^{(j)} = \left(\boldsymbol{r}_{lk}^{(1,j)} - \boldsymbol{r}_{lk}^{(2,j)}\right) \cdot \boldsymbol{n}_{lk}^{(j)}$$

Equation 1

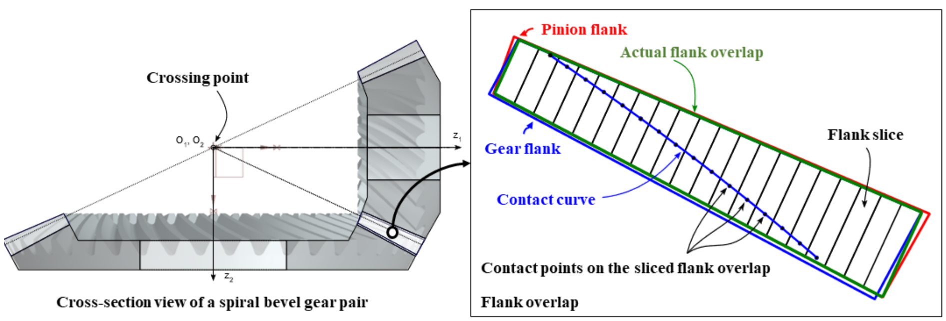

Figure 3. Illustration of the physical flank overlap calculation and the flank slicing technique.

Figure 3 below shows a visualization of the flank slicing approach, which is used to evaluate the flank penetration $\delta_{lk}^{(j)}$ for each slice segment k, each flank j and each tooth pair l, based on the coordinate vector r of the contact locations and the contact normal vector n. This process is performed for all teeth possibly in contact and for both tooth flanks at each time step of the dynamic simulation, enabling the analysis of tooth wedging, backlash, gear rattle and gear whine. The penetration vector for all tooth slices in contact is defined as δ.

Calculating accurate gear contact force

The bevel gear contact element includes three types of gear contact forces: a stiffness gear contact force, a viscous damping gear contact force and a Coulomb-based friction force. In this white paper, the stiffness gear contact force takes center stage, presenting the newly developed hybrid FE-analytical gear contact stiffness model and verifying it in the later sections. Additionally, it refers to the part of the contact force that directly depends on the penetration between the contacting gear flanks.

To compute the stiffness gear contact forces, the gear contact model translates the detected penetrations at every contact location into contact loads, assuming that the actual tooth flank deformation, due to the contact load, matches the measured penetration of the rigid tooth flanks. Figure 4 visualizes this concept together with the resulting contact stiffness force distribution.

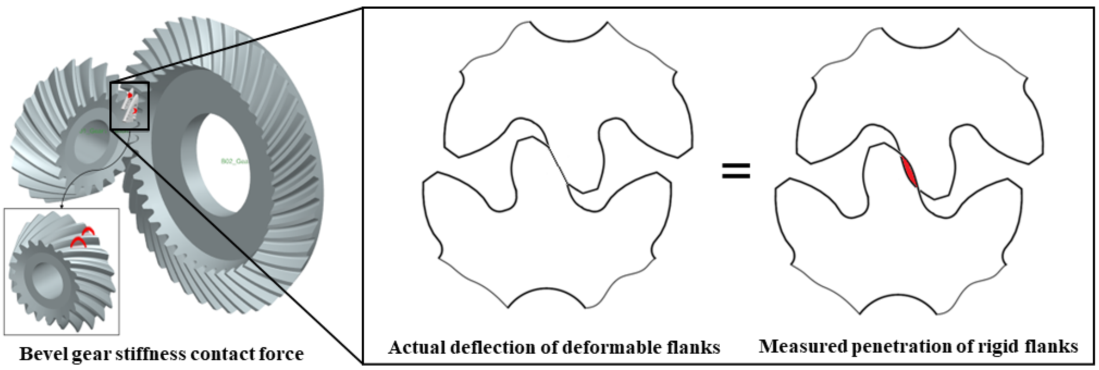

Figure 4. Penetration assumption when computing contact forces in the gear contact stiffness force.

Bevel gear FEM semi-analytical contact stiffness model

The hybrid FE-analytical approach models gear contact stiffness by approximating the bevel gear pair's contact deformation as a combination of global and local components.[19, 20, 21] This allows for a faster and more accurate solution time by using a complementary approach that mitigates some of the drawbacks of individual methods.

Modeling the deformation field

Developing numerical-analytical hybrid solutions requires finding an appropriate distance outside the contact zone where the numerical model's deformation field matches that of the analytical model. For bevel gears, the proposed approach separates the deformation field into a global component modeled with FEM and a local component using Hertzian contact theory's analytical expression. The global and local components are summed to approximate the total contact deformation field.

$$\boldsymbol{u}_{contact} = \boldsymbol{u}_{global}^{\mathrm{FE}} + \boldsymbol{u}_{local}^{\mathrm{AN}}$$

Equation 2

Figure 5 visualizes this methodology with the necessary boundary conditions. The global deformation due to the contact load is found using a coarse FE model in two steps. The total and partial FE deformation fields are summed to define the global FE deformation field. Figure 6 shows the correct global deformation field due to a unit nodal load.

$$\boldsymbol{u}^{\mathrm{FE}}_{global} = \boldsymbol{u}^{\mathrm{FE}}_{total} + \boldsymbol{u}^{FE}_{partial}$$

Equation 3

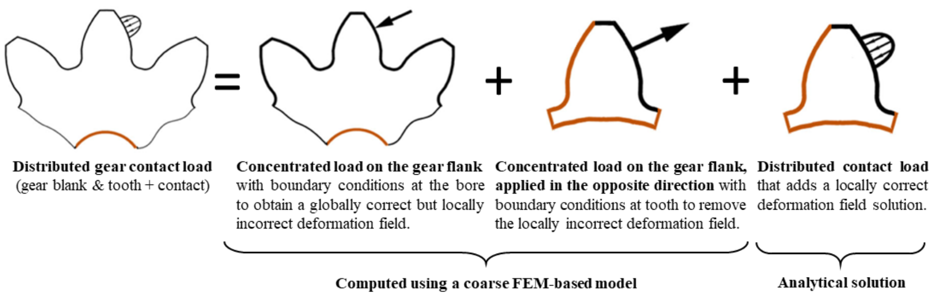

Figure 5. The adopted methodology to model the contact stiffness and deformation for bevel gears inspired by Cappellini et al.[6]

After removing the locally incorrect deformation field due to the concentrated load, the analytical expression then accurately constructs the complete gear contact deformation field using equations 2 and 4."

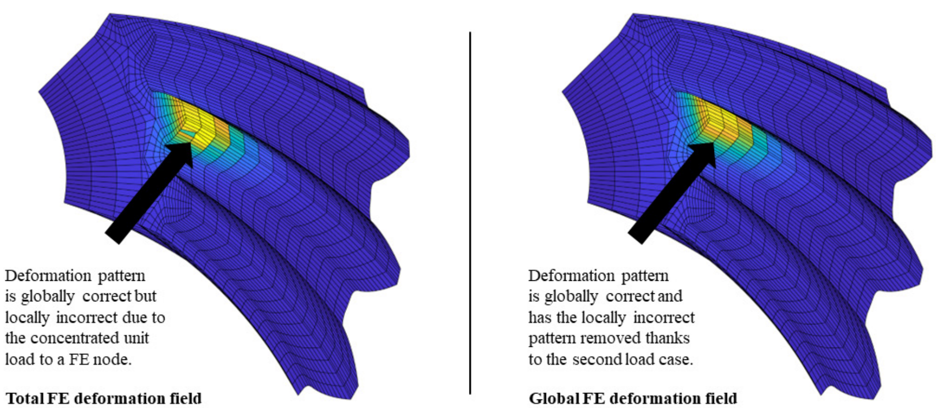

Figure 6. Comparison of the total FE deformation field and the global FE deformation field due to a nodal load.

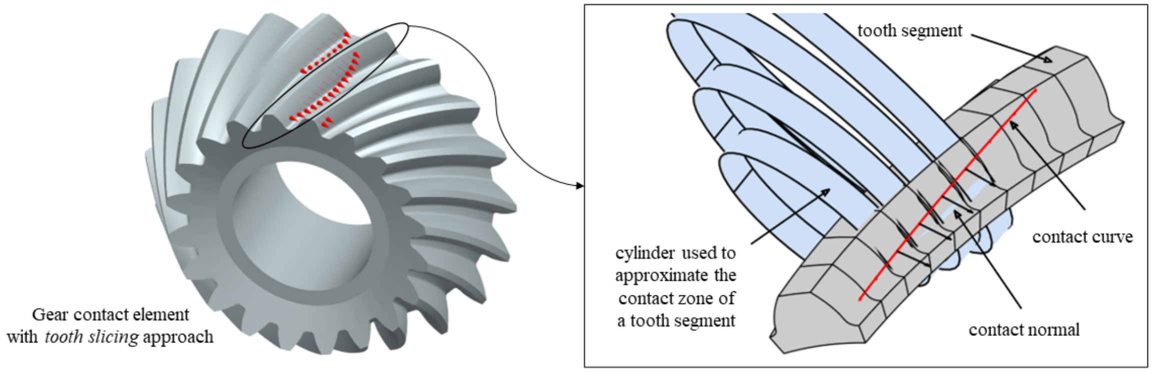

Figure 7. Adopting a Hertzian line contact to describe the local contact deformation of the tooth slices.[18]

In a general case of mismatched gear tooth flanks, the instantaneous contact between them can be described as a point contact under no-load conditions. However, as figure 7 shows, this point contact spreads the under load into a line contact that runs over part of the tooth flank. When using a flank slicing technique, as is the case for the bevel gear contact element and illustrated in figures 3 and 7, a Hertzian line contact that is oriented along the contact can effectively approximate the local contact distribution. The nonlinear contact deformation $\boldsymbol{u}_{local}^{\mathrm{AN}}$, which captures the deformation of the pinion and gear flank slices near the contact zone, is well-described by Weber and Banaschek's closed-loop formula.[22]

To efficiently implement on a computer, engineers can apply model order reduction (MOR) techniques,[23] which approximate the global deformation field $\boldsymbol{u}_{global}^{\mathrm{FE}}$ as a linear superposition of precomputed static deformation shapes and project the governing structural equations to a significantly smaller set of unknowns for each gear element of the bevel gear pair. During dynamic simulation, the spiral bevel gear contact element uses the reduced order model (ROM) of each gear to assemble the gear pair's global compliance matrix, $C = C^{(1)} + C^{(2)}$ where $C^{(i)}$ is the global compliance matrix of each gear i. Applying equation 2 to the contact points, the gear tooth flank deformation vector $\boldsymbol{d}(\boldsymbol{F}_n)$ is defined as equation 4.

$$\boldsymbol{d}(\boldsymbol{F}_n) = \mathbf{C}\,\boldsymbol{F}_n + \boldsymbol{U}(\boldsymbol{F}_n)$$

Equation 4

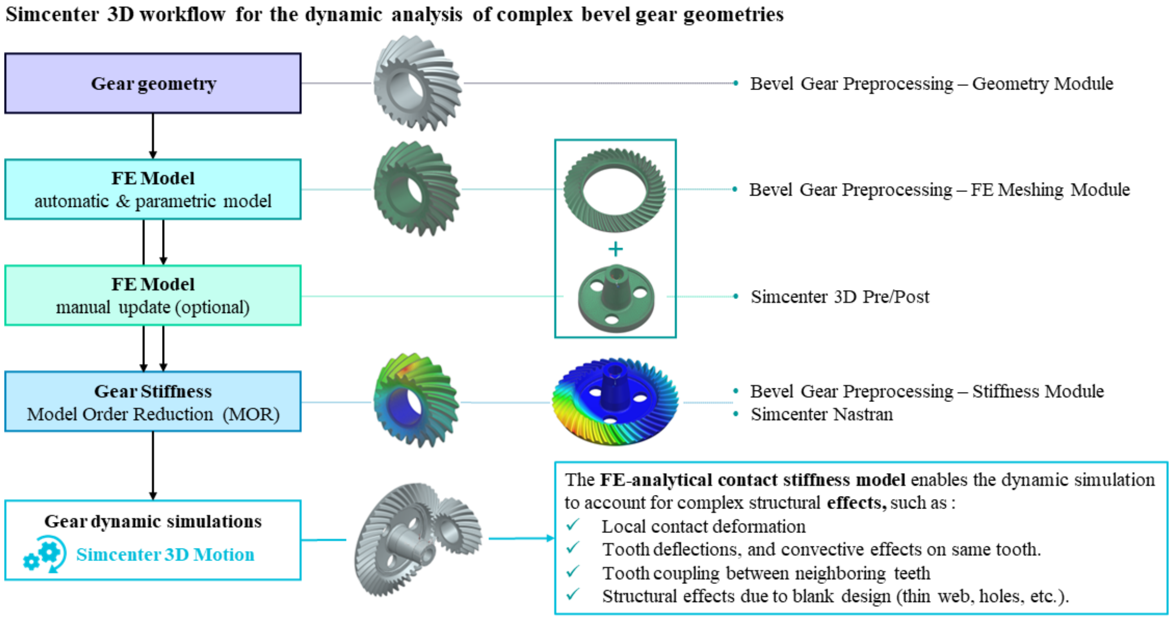

Figure 8. Leveraging the Simcenter 3D workflow for the dynamic analysis of complex bevel gear geometries.

In equation 4, $\mathbf{C}\,\boldsymbol{F_n}$ is the linear global deformation component, and $\boldsymbol{U}(\boldsymbol{F_n})$ is the nonlinear local contact deformation component due to contact loads $\boldsymbol{F_n}$, which are applied to the contact points on the bevel gear teeth. Engineers can then obtain the contact loads $\boldsymbol{F_n}$ by solving equation 4 under the assumption that $\boldsymbol{d}(\boldsymbol{F_n}) \approx \delta$.

By combining the FE-based method that accurately describes complex structural problems with analytical solutions that accurately and efficiently describe local contact deformation, the semi-analytical bevel gear contact stiffness model captures the following effects:

- Deflecting the tooth slice when applying a force to the slice (including local contact deflection)
- Coupling effects with neighboring slices when applying a force to a given slice on the same tooth
- Coupling effects with neighboring teeth when applying a force at a given tooth
- Structural effects due to the gear blank design (for example, thin web, holes, etc.)

Create FE models and calculate gear stiffness

The process to determine the FE-based global deformation shapes occurs in a preprocessing step for the dynamic gear contact simulations. Using the Simcenter 3D Motion Bevel Gear Preprocessor, engineers can automate the bevel gear geometry creation process as well as the parametric FE model generation and gear stiffness computation. Figure 2 shows a workflow that starts with macrogeometry parameters and the gear tooth flank surfaces, enabling engineers to create and analyze complex gear designs (for example, lightweight designs) via the workflow shown in figure 8.

Validating the methodology

The unique capabilities of the hybrid FE-analytical bevel gear contact stiffness model are validated against nonlinear finite element analysis (NLFEA) contact simulations, which are a higher level of modeling fidelity but also have a much larger computational cost and memory requirements.[24] Both latter aspects also limit the use of NLFEA to the analysis of dynamic contact problems, whereas it will be shown that the proposed methodology can be a faster, yet highly accurate, solution that enables the use within system-level transmission analysis.

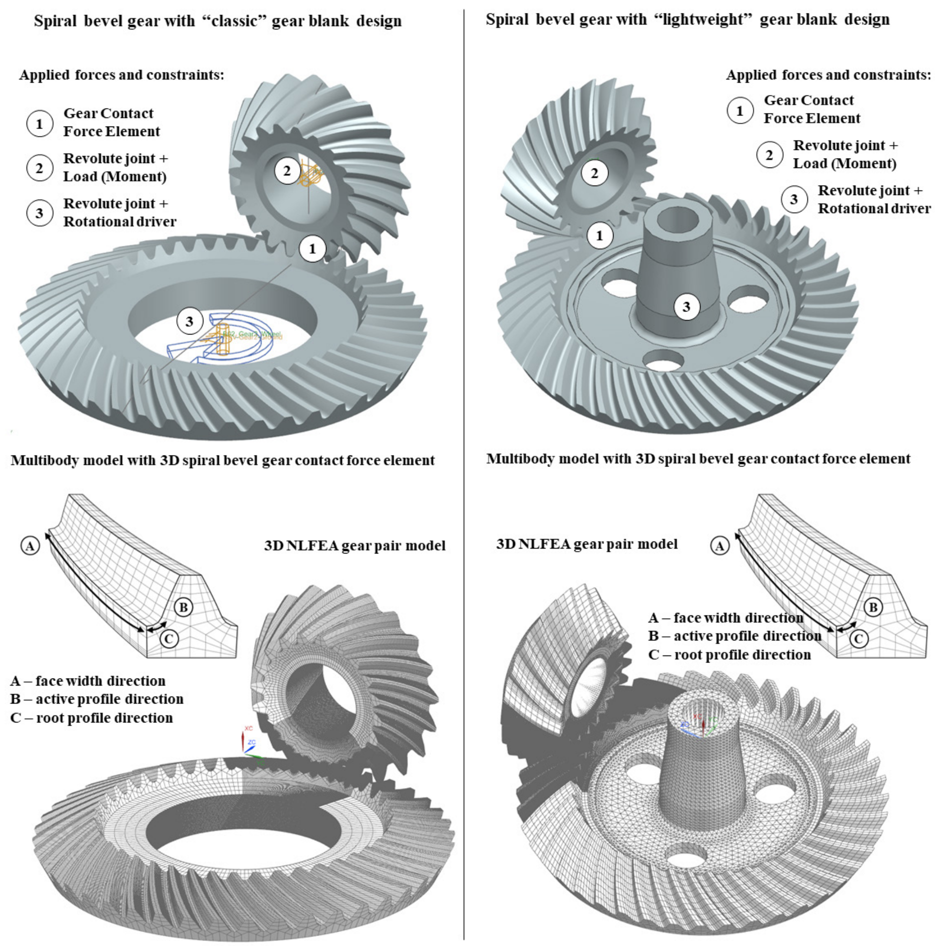

Figure 9. Overview of the multibody spiral bevel gear pair models, and the corresponding FE models for NLFEA-LTCA. The latter serves as a reference for the FE-analytical bevel gear contact stiffness mode's static validation.[24]

Analyzing the spiral bevel gear pair

To validate the model, we can analyze the spiral bevel gear pairs with data taken from the literature.[15] Figure 9 shows the two analyzed variants, one with a standard blank design and one with a lightweight blank design. Table 1 summarizes the gear blank geometry parameters, whereas table 2 summarizes the number of elements used to model the bevel gear stiffness in the FE-analytical model (multibody gear contact) and the high-fidelity validation model (NLFEA-LTCA).

Validating the multibody bevel gear contact element with the FE-analytical gear contact stiffness model focuses on the static behavior since the reference NLFEA-LTCA calculations must be performed statically. Therefore, engineers can apply the quasi-static loading conditions during the dynamic simulation of the multibody gear pair model by imposing a gear wheel rotation of 10 revolutions per minute (rpm) and applying the moment load to the pinion.

Table 1. Gear blank geometry data and material.

Gear blank data	Units	Pinion	Gear
Number of teeth	[-]	20	43
Hand of spiral	[-]	RH	LH
Mean spiral angle	[deg.]	32.000	32.000
Mean normal module	[mm]	4.325	4.325
Mean cone distance	[mm]	120.940	120.940
Face width	[mm]	41.000	41.000
Pitch cone angle	[deg.]	24.944	65.056
Root cone angle	[deg.]	23.167	61.817
Face cone angle	[deg.]	28.183	66.833
Material		Steel	Steel

Table 2. Overview of the number of elements used to model the contacting spiral bevel gear tooth stiffness in the FE-analytical stiffness model (multi-body gear contact) and the high-fidelity validation model (NLFEA-LTCA).

Number of elements	MB gear contact		NLFEA-LTCA	
per (fine) tooth flank	Pinion	Gear	Pinion	Gear
Elements along active flank direction	12	12	35	35
Elements along active face width direction	20	20	75	75

Transmission error results

Transmission error variation is often identified as the main source of gearbox noise and vibration issues. Hence, gear design aims to minimize the peak-to-peak (PtP) TE value for a certain load range. Therefore, the PtP TE value is selected as one of the key quality metrics for the validation study.[24]

Figures 10 and 11 present the TE curves for spiral bevel gear pairs with standard and lightweight blanks. Since there is no circumferential variation of the gear stiffness for the gear wheel with a standard blank, we only need to simulate two mesh cycles, whereas we simulate five mesh cycles for the gear pair with a lightweight blank to capture the circumferential stiffness variation due to the hole's presence. Tables 3 and 4 provide an evaluation of the mean TE and PtP TE values for both models. We then compare the results of the Simcenter 3D Motion FE-analytical bevel gear contact model (multibody-gear contact force element (GCFE)) to the results we computed by using the NLFEA-LTCA as a reference.

The PtP TE value and the shape of its signal enables the evaluation of how well the methodology captures the gear mesh stiffness and its fluctuation due to multiple gear tooth pairs rotating in or out of contact. We find an excellent correlation between the shape of the PtP TE signal and the PtP TE values when comparing the results of the Simcenter 3D Motion gear contact element with the FE-analytical bevel gear contact stiffness model to those of the reference NLFEA-based LTCA calculations for the standard and lightweight gear designs.

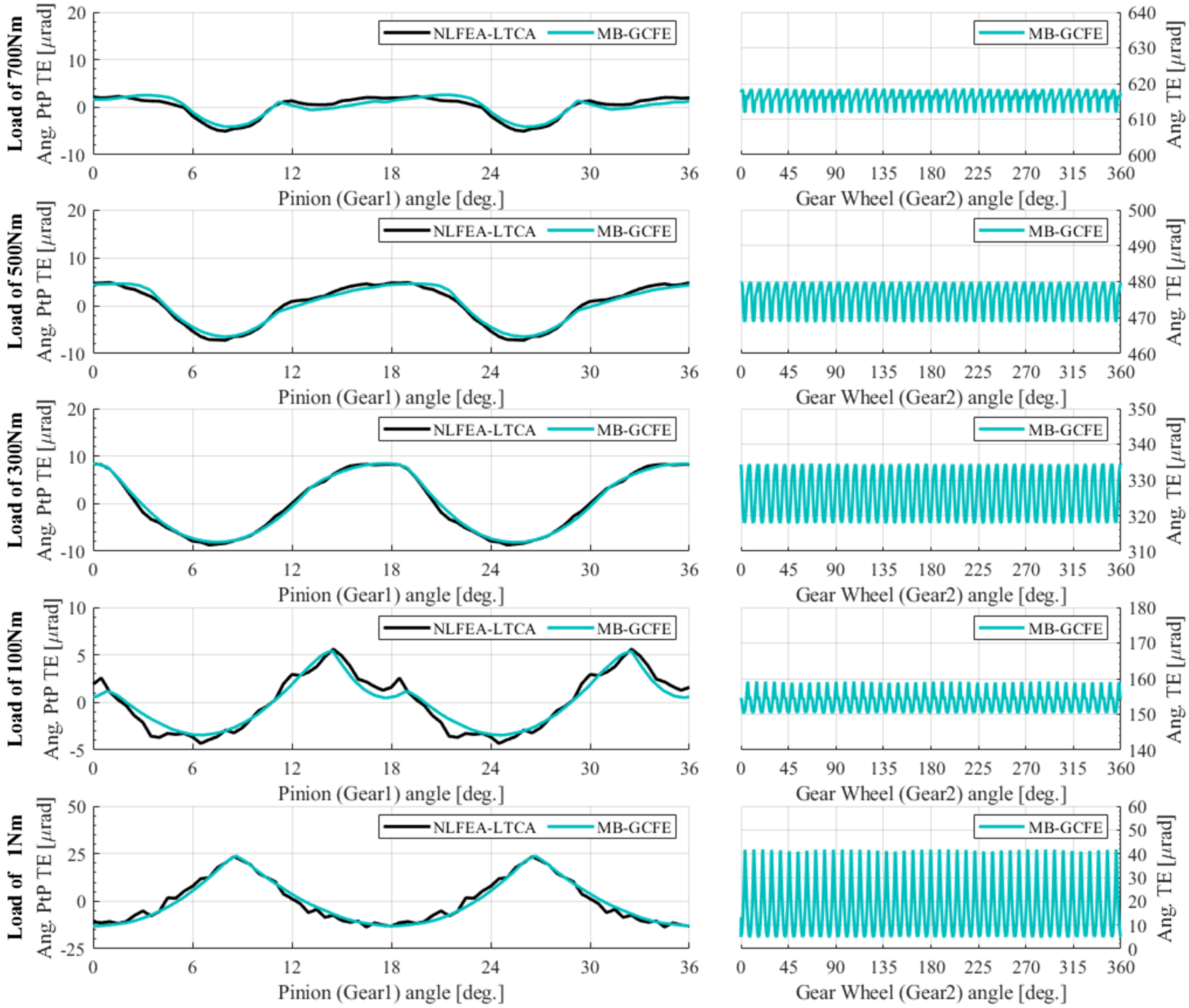

Figure 10. Comparison of the peak-to-peak transmission error (PtP TE) for the left tooth flanks of the spiral bevel gear pair with "standard" gear blank design. The TE curves are computed for various loads using Simcenter 3D Motion's bevel gear contact element (MB-GCFE) and the NLFEA-based LTCA reference approach.[24]

Table 3. PtP TE for the spiral bevel gear pair with a standard blank design, using the Simcenter 3D Motion bevel gear contact with FE-analytical gear contact model (multibody) and the NLFEA-LTCA (NLFEA) to compute.[24]

Transmission Error		Mean value [μrad]			Peak-to-Peak (PtP) [μrad]		
		Multibody	NLFEA	Difference	Multibody	NLFEA	Difference
Standard Blank	1 Nm	17.8	15.9	12.1%	37.0	37.0	0.0%
	100 Nm	153.8	157.7	2.5%	8.9	9.9	10.0%
	300 Nm	325.9	333.0	2.1%	16.6	17.1	3.1%
	500 Nm	475.3	484.1	1.8%	11.1	12.0	8.1%
	700 Nm	615.9	626.0	1.6%	6.7	7.3	8.0%

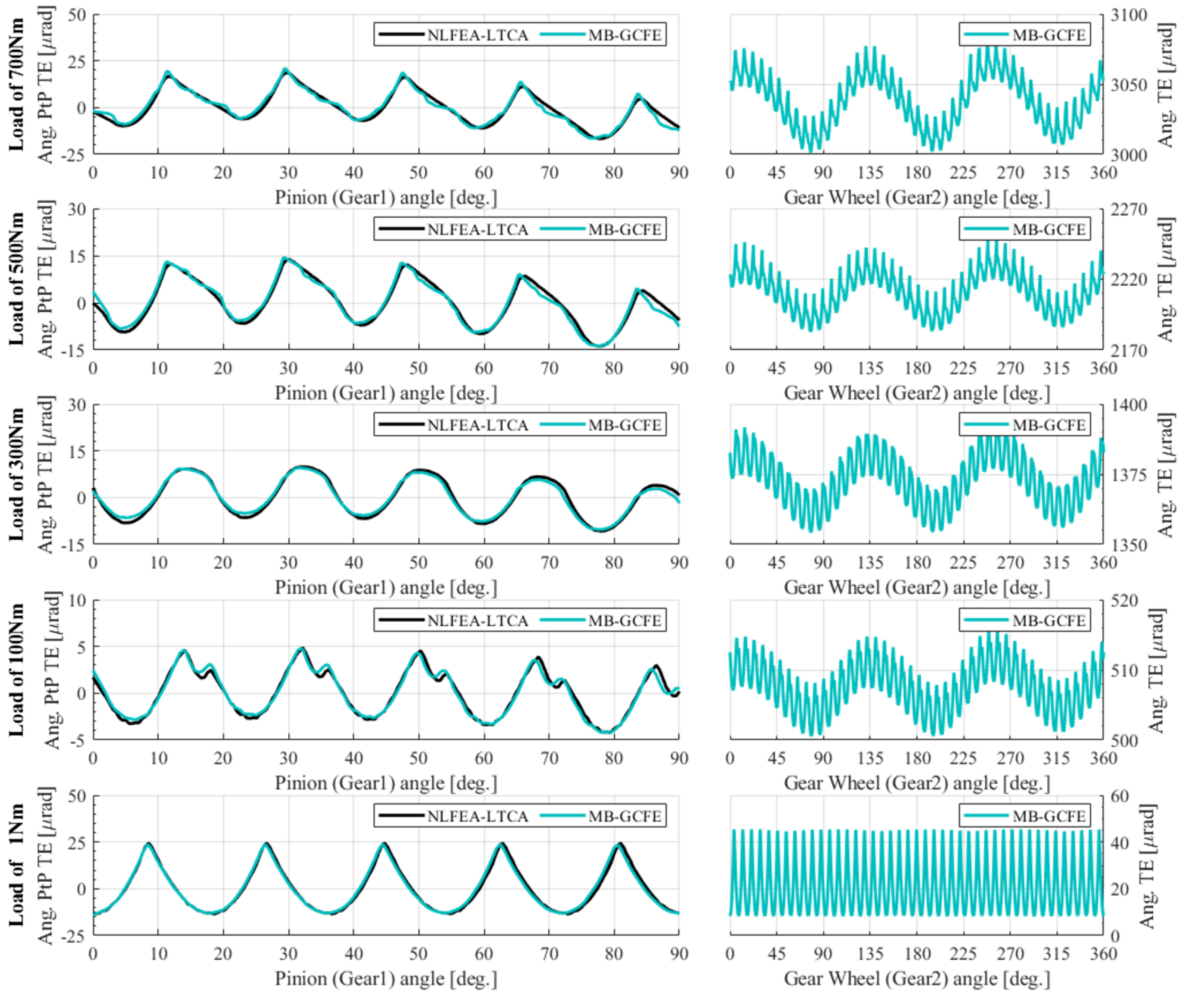

Figure 11. Comparison of the TE for the spiral bevel gear pair with a lightweight blank design when the left tooth flanks of the spiral bevel gear pair are in contact. Using the Simcenter 3D Motion bevel gear contact element (MB-GCFE) and the NLFEA-LTCA reference approach to compute the TE curves for various loads. The TE versus the gear wheel rotation angle clearly shows a modulation of order 3 due to the three holes' presence.[24]

Table 4. PtP TE for the spiral bevel gear pair with a lightweight blank design, using the Simcenter 3D Motion bevel gear contact with FE-analytical gear contact model (multibody) and the NLFEA-based LTCA (NLFEA) to compute.[24]

Transmission Error		Mean value [μrad]			Peak-to-Peak (PtP) [μrad]		
		Multibody	NLFEA	Difference	Multibody	NLFEA	Difference
Lightweight Blank	1 Nm	21.3	20.4	4.7%	37.0	37.9	0.1%
	100 Nm	509.9	513.3	0.6%	8.9	9.0	0.8%
	300 Nm	1,379.9	1,392.2	0.9%	19.8	20.5	3.6%
	500 Nm	2,222.5	2,242.5	0.9%	28.5	27.5	3.3%
	700 Nm	3,054.4	3,081.8	0.9%	37.7	35.3	6.7%

Table 5 compares the computation times of various models and methodologies for moderate and high loading conditions. When using Simcenter 3D Motion, the gear dynamics during multiple gear mesh cycles are predicted via time integration of the gear pair's equations of motion. In this study, a maximum integration step of 0.001 second (s) is used to accurately capture the nonlinear behavior due to the various tooth impacts under quasi-static conditions. The latter results in a much larger number of time steps when compared to the NLFEA-LTCA reference simulations, which predict the bevel gear pair contact via a series of static computations at various snapshot configurations throughout the mesh cycle. In this study, a snapshot was taken at each 0.5-degree pinion rotation.

Using the Simcenter 3D Motion gear contact element with FE-analytical bevel gear contact stiffness formulation is multiple orders faster (minutes versus days) than the NLFEA-based contact simulations, while achieving a similar accuracy level for the standard and lightweight gear pair design. This is possible due to efficient contact detection algorithms and advanced MOR techniques that embed the FE-based gear stiffness data within the bevel gear contact element.[24] The gear contact element can predict bevel gear dynamics and be applied in runup simulations of bevel geared drivetrain models, which is difficult to do with NLFEA-based LTCA.

Table 5. Overview computation time (CPU time) for the Simcenter 3D Motion (multibody dynamics simulation) bevel gear contact element with the FE-analytical stiffness contact model and the reference NLFEA-LTCA (statics) calculations for the standard and lightweight bevel gear pair model variants at two pinion load levels (300 Nm and 700 Nm).[24]

	Multibody (dynamics)	Mesh cycles	# Time steps	Max. int step	CPU (total)	CPU (step)
300 Nm (pinion load)	Standard Blank	2	300	1E-3 s	~ 4.0 min	~ 0.8 s
	Lightweight Blank	5	1,453	1E-3 s	~13.5 min	~ 0.6 s
	NLFEA-LTCA (statics)	**Mesh cycles**	**# Steps**	**Ang. step**	**CPU (total)**	**CPU (step)**
	Standard Blank	2	73	0.5 deg	~ 0.9 days	~ 1,100 s
	Lightweight Blank	5	181	0.5 deg	~ 2.1 days	~ 1,020 s
700 Nm (pinion load)	**Multibody (dynamics)**	**Mesh cycles**	**# Time steps**	**Max. int step**	**CPU (total)**	**CPU (step)**
	Standard Blank	2	300	1E-3 s	~ 4.5 min	~ 0.9 s
	Lightweight Blank	5	1,473	1E-3 s	~14.0 min	~ 0.6 s
	NLFEA-LTCA (statics)	**Mesh cycles**	**# Steps**	**Ang. step**	**CPU (total)**	**CPU (step)**
	Standard Blank	2	73	0.5 deg	~ 1.0 days	~ 1,150 s
	Lightweight Blank	5	181	0.5 deg	~ 2.2 days	~ 1,075 s

Contact pattern results

Figure 12 shows a contact pattern comparison for the highest load case (700 Newton meters (Nm)). Engineers can analyze this case since it causes the largest tooth deflection and the highest number of teeth to contact, making it a good case to assess load sharing accuracy. The figure shows the envelope of contact forces (red) and gear teeth in contact (blue) throughout the mesh cycle, which is visualized on the 3D spiral bevel pinion tooth flanks (left). The contact pattern is extracted from the mesh cycle by projecting all contact points onto a common projection plane (right). We can find a good quantitative correlation between the Simcenter 3D Motion bevel gear contact element (FE-analytical) and the reference NLFEA-based LTCA calculations.[24]

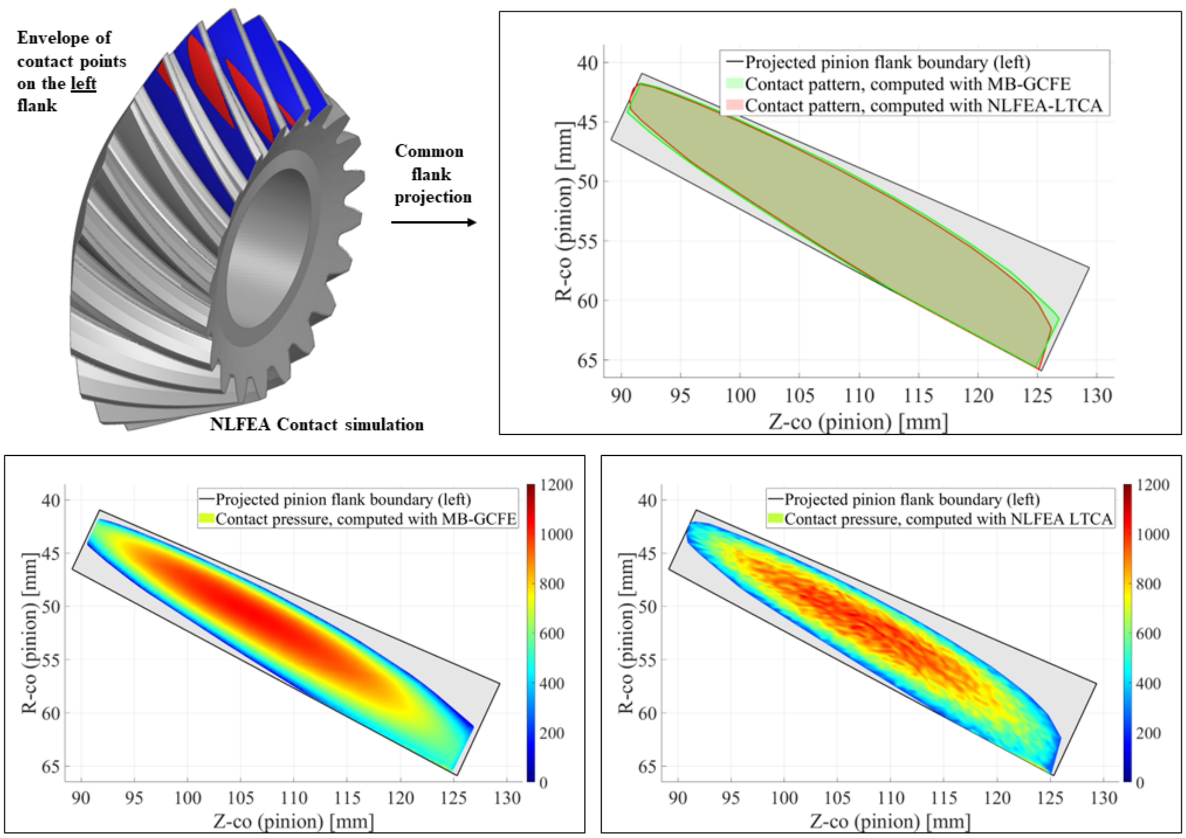

Figure 12. Contact pattern for a load of 700 Nm when the left tooth flanks of the spiral bevel gear pair are in contact.[24]

Use case examples

The bevel gear contact element with FE-analytical gear contact stiffness formulation in Simcenter 3D Motion has been used in two use cases to demonstrate its applicability in bevel gear dynamics analysis. The first example compares the differences between a bevel gear pair's static and dynamic TE under a given load. The second example focuses on the dynamic response of a flexible bevel gearbox during a runup simulation.

Static transmission error versus dynamic transmission error

In current bevel gear design and analysis, it is often assumed that the static transmission error (STE) is a good enough approximation for the dynamic transmission error (DTE). To evaluate this assumption, a validated spiral bevel gear contact force element is used in the multibody simulation environment to predict the bevel gear pair's TE under both quasi-static and dynamic operating conditions.

Two runup simulation variants are defined using the lightweight spiral bevel gear pair variant. In the quasistatic simulation, the pinion accelerates from 0 to 10 rpm. Whereas in the dynamic simulation, the pinion accelerates from 0 to 1,000 rpm. Both simulations are synchronized in the angle domain to evaluate the TE signals. Figure 13 presents the DTE signal together with the quasi-STE signal in the angle domain for the first revolution of the pinion element. When comparing these signals, a transient response is clearly revealed in the DTE signal at the end of the acceleration to the target angular velocity (around 30 degrees). The difference in PtP values between the DTE and quasi-STE signals due to the operating conditions (10 versus 1,000 rpm) is significant. Table 6 provides the computation time for the dynamic runup simulation (1 to 1,000 rpm).

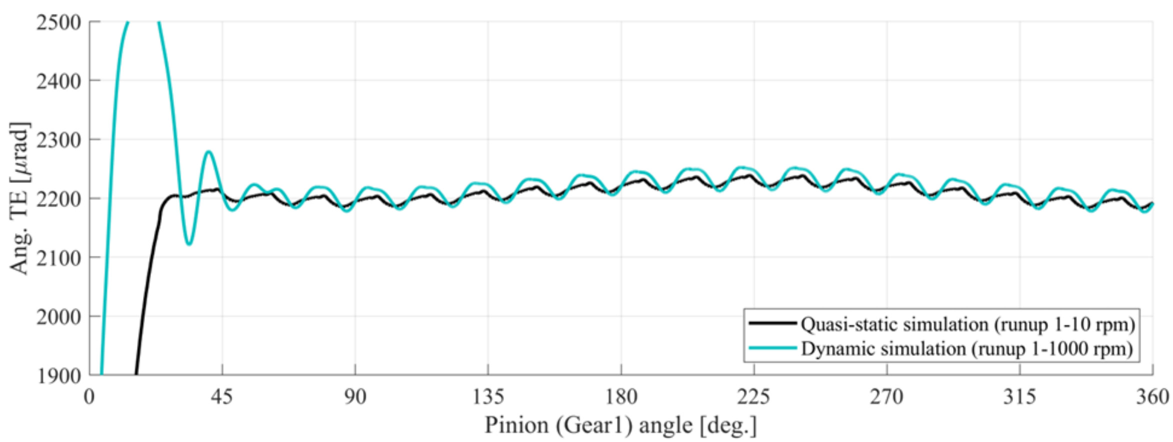

Figure 13. Comparison of quasi-STE (10 rpm) and DTE (1,000 rpm) for the spiral bevel gear pair of a lightweight design.

Table 6. Overview of computation time (CPU time) for the Simcenter 3D Motion (multibody dynamics simulation) bevel gear contact element with FE-analytical stiffness contact model for both runup simulations (1 to 10 rpm and 1 to 1,000 rpm).

System level (runup)	Analyzed load case of 300Nm (pinion load)					
Multibody (dynamics)	RPM range	Sim. time	# Time steps	Max int. step	CPU (total)	CPU (step)
Lightweight Blank	1 to 1,000 rpm	0.15s	15,258	1E-5 s	~ 1.5 h	~ 0.4 s

Simulating system-level bevel gear transmission dynamics

This use case example focuses on the system-level simulation of spiral bevel gear dynamics using Simcenter 3D Motion. Figure 14 shows an example of using a flexible multibody gearbox model with a FE-analytical bevel gear contact model to evaluate the gearbox dynamics during a runup simulation.

Figures 15 and 16 show the time domain computed bearing forces are transformed to the frequency domain to create the spectrograms, which enable engineers to evaluate system resonances and relevant orders. The gear meshing orders are harmonics of order 20 (since the pinion has 20 teeth).

Comparing the spectrogram of the lightweight gear pair variant to that of the standard gear pair, additional orders, which turn out to be harmonics of order 1.4, become visible. These harmonics arise due to the presence of three holes in the gear wheel's lightweight blank design. Hence, when they are expressed against the gear wheel's rotation, they become harmonics of order 3. The circumferential variation of the gear wheel's (meshing) stiffness also causes side bands around the gear meshing frequencies. These side bands can alter the noise spectrum of the gearbox, as shown in "Mastering bevel gears simulation towards quiet transmissions."[25, 26]

Such complex effects can only be modeled, analyzed and quantified with an accurate solution like the presented FE-analytical bevel gear contact method.

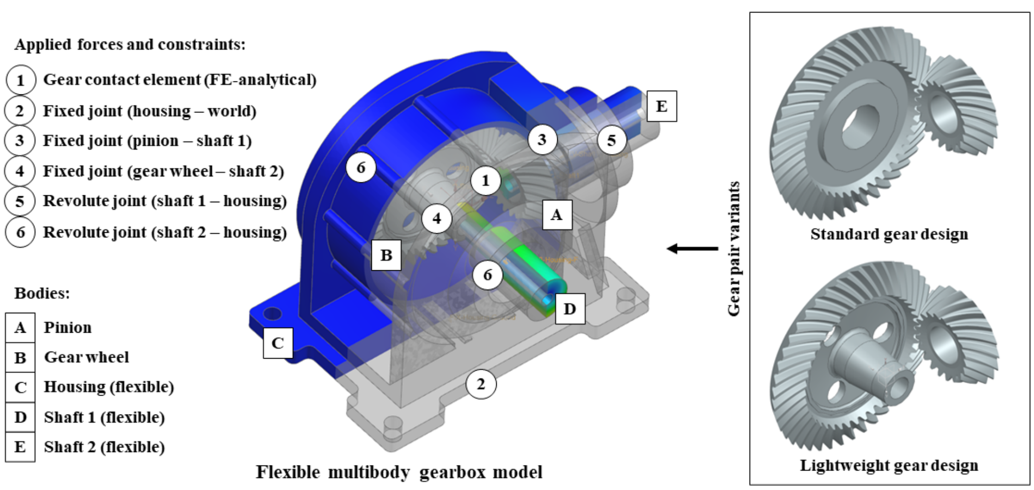

Figure 14. Overview of the flexible multibody gearbox model with spiral bevel gear pair used in use case two.

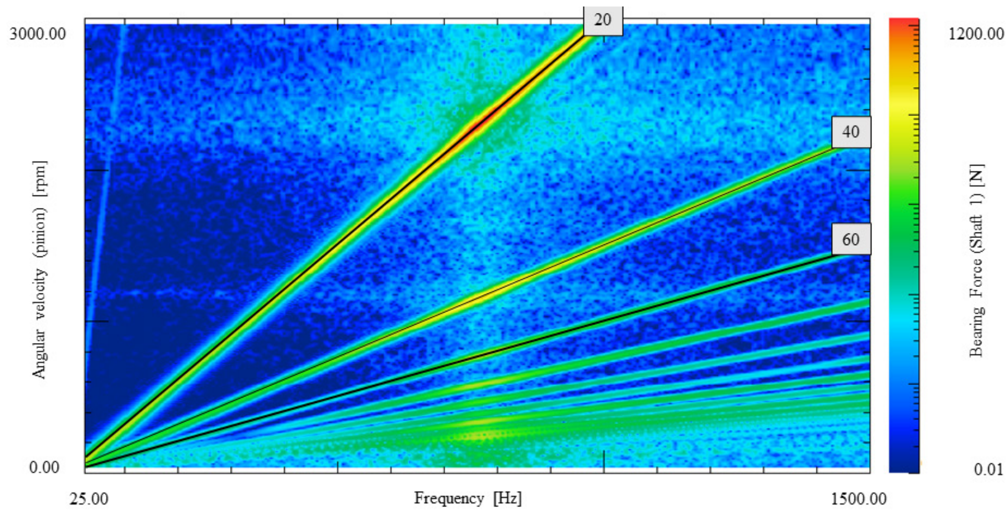

Figure 15. The time domain-computed bearing forces in the frequency domain (spectrogram) to identify the system resonances and relevant orders for the standard gear pair.

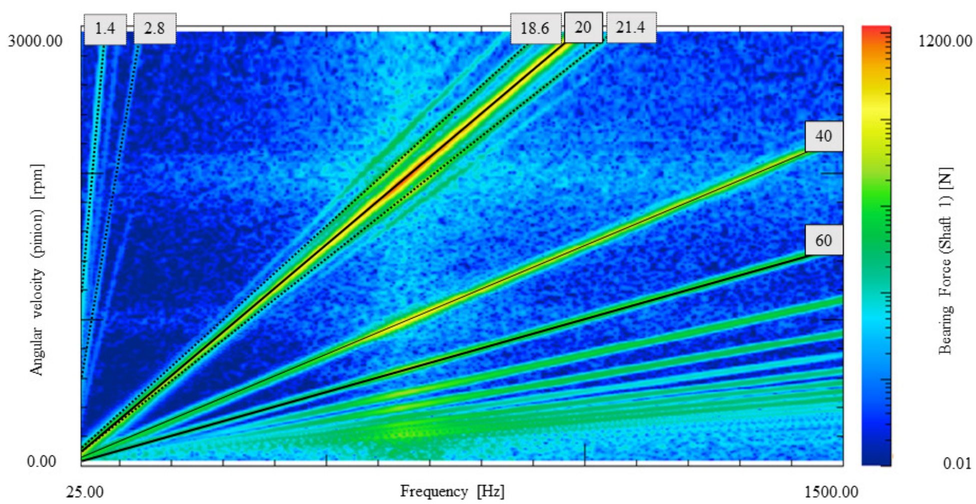

Figure 16. The time domain-computed bearing forces in the frequency domain (spectrogram) to identify the system resonances and relevant orders for the lightweight gear pair.

Simcenter 3D solutions and workflows

The various software codes that are used throughout this work are briefly listed here. The Simcenter 3D Transmission Builder[27] Bevel Gear Preprocessor is used to compute the bevel gear kinematics and the bevel gear global stiffness. The latter is derived based on the FE model's stiffness matrix, using Simcenter Nastran software for computation.[28] Additionally, the gear contact simulations are computed using the Simcenter 3D Motion multibody solver.[29] With Simcenter Nastran (Advanced Nonlinear), engineers can create the reference results for the validation of the presented FE-analytical bevel gear contact stiffness model.[29] The bevel gear dynamic results can further drive simulations using Simcenter 3D Acoustics[30] or optimization with HEEDS™ software,[31] which is also part of the Siemens Xcelerator business platform.

Conclusion

This white paper presents a new solution for simulating bevel gear dynamics that enables manufacturers to optimize the noise and vibration performance of their products. Figure 16 summarizes the solution. The white paper introduces a novel bevel gear contact force element that uses a FE-analytical gear contact stiffness model to predict the 3D gear contact force distribution accurately and efficiently. This methodology is validated against detailed NLFEA-based contact simulations, showing a highly accurate correlation with reference calculations. The presented methodology is further demonstrated in two use cases, highlighting the difference between static and dynamic transmission errors and analyzing the differences in dynamic system responses. These new capabilities of Simcenter 3D will be available in June 2024, allowing manufacturers to predict bevel gear noise and vibration behavior in the design phase, which is crucial to achieving quiet transmissions.

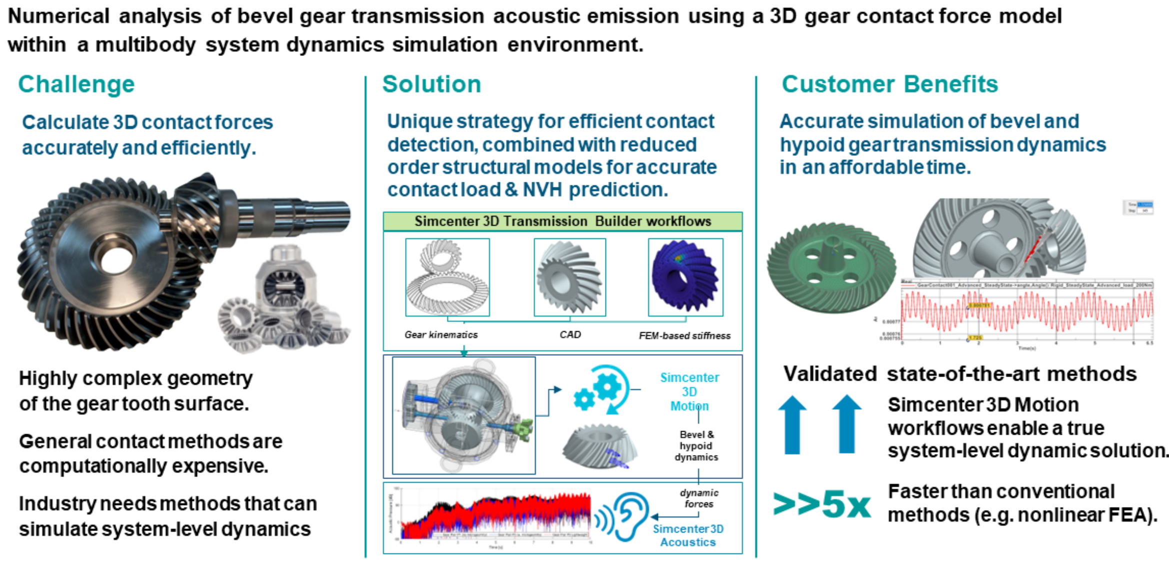

Figure 17. Summary of challenges, solutions and customer benefits that this white paper addresses.

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