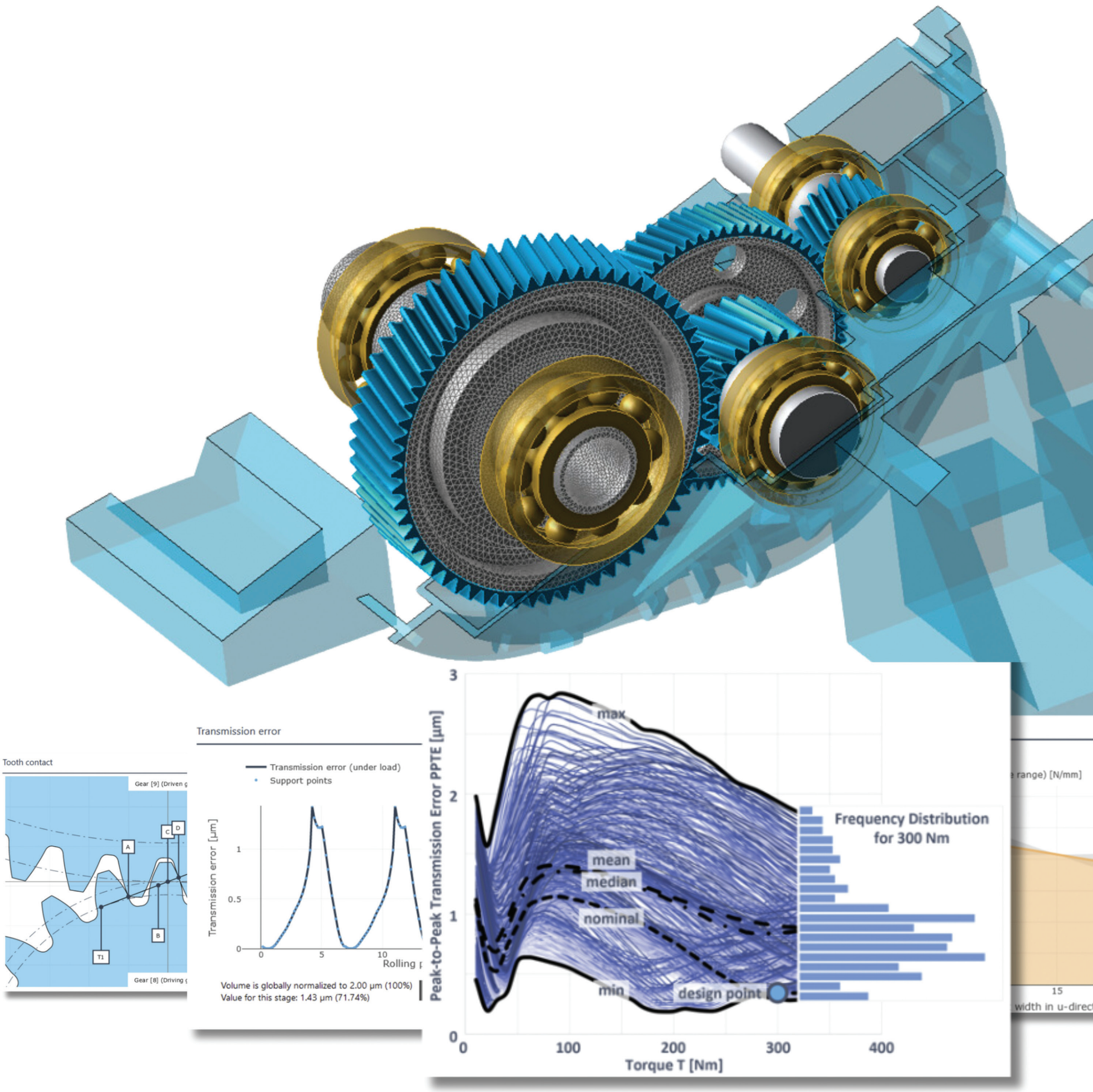
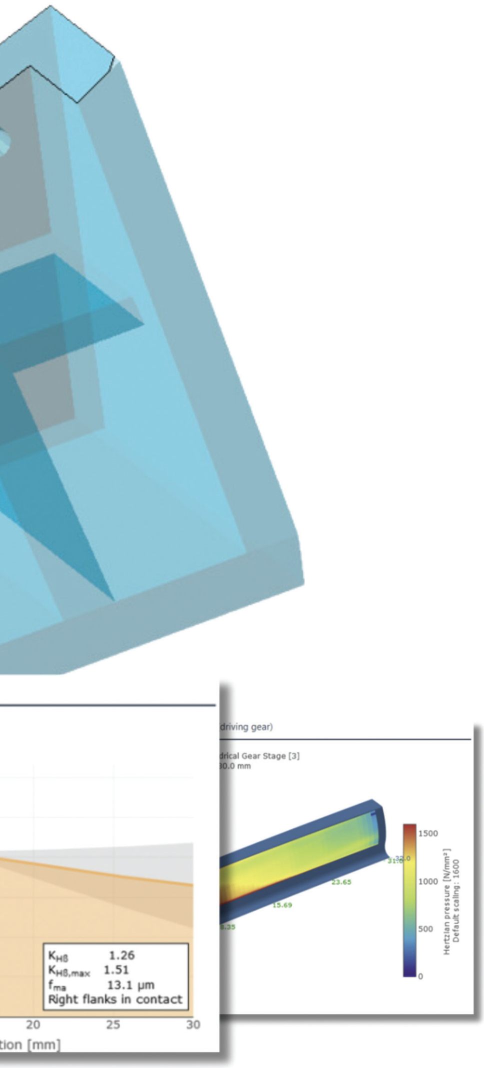

Tooth contact
Transmission error
Transmission error (under load)
Support points
Transmission error [µm]
Volume is globally normalized to 2.00 µm (100%)
Value for this stage: 1.43 µm (71.74%)
Peak-to-Peak Transmission Error PPTE [µm]
max
mean
median
nominal
min
design point
Frequency Distribution
for 300 Nm
Torque T [Nm]

NVH Optimization and Production Tolerances

Improving Performance and Sustainability in Gearbox Development



Resource efficiency and environmental protection are becoming increasingly important in modern transmission development processes, especially minimizing the CO2 footprint. These factors are critical for complying with regulatory limits and remaining competitive in a challenging market. Gearbox manufacturers are constantly increasing the power density of their transmissions to meet these requirements. This demands careful analysis and reduction of excess material reserves to optimize designs. The aim is to design gearboxes that meet customers' lifetime needs with quiet, vibration-free operation. These are the key characteristics of good NVH performance.

Development Process

Transmission development is an iterative process that often involves multiple design and test cycles to achieve the desired performance characteristics. Modern simulation methods play a key role, as they enable engineers to create virtual prototypes and predict the behavior of transmission systems under different operating conditions. This not only significantly shortens the development time, but also contributes to the cost efficiency of the development process. Proven tools like the FVA-Workbench [1] improve the design process with fast and reliable simulations.

Analysis & optimization

In transmission development, an understanding of the influences acting on the gearbox and the resulting loads is essential. Accurate knowledge of the load distribution [2] across the face width resulting from the tooth meshes and optimization of the microgeometry play a decisive role.

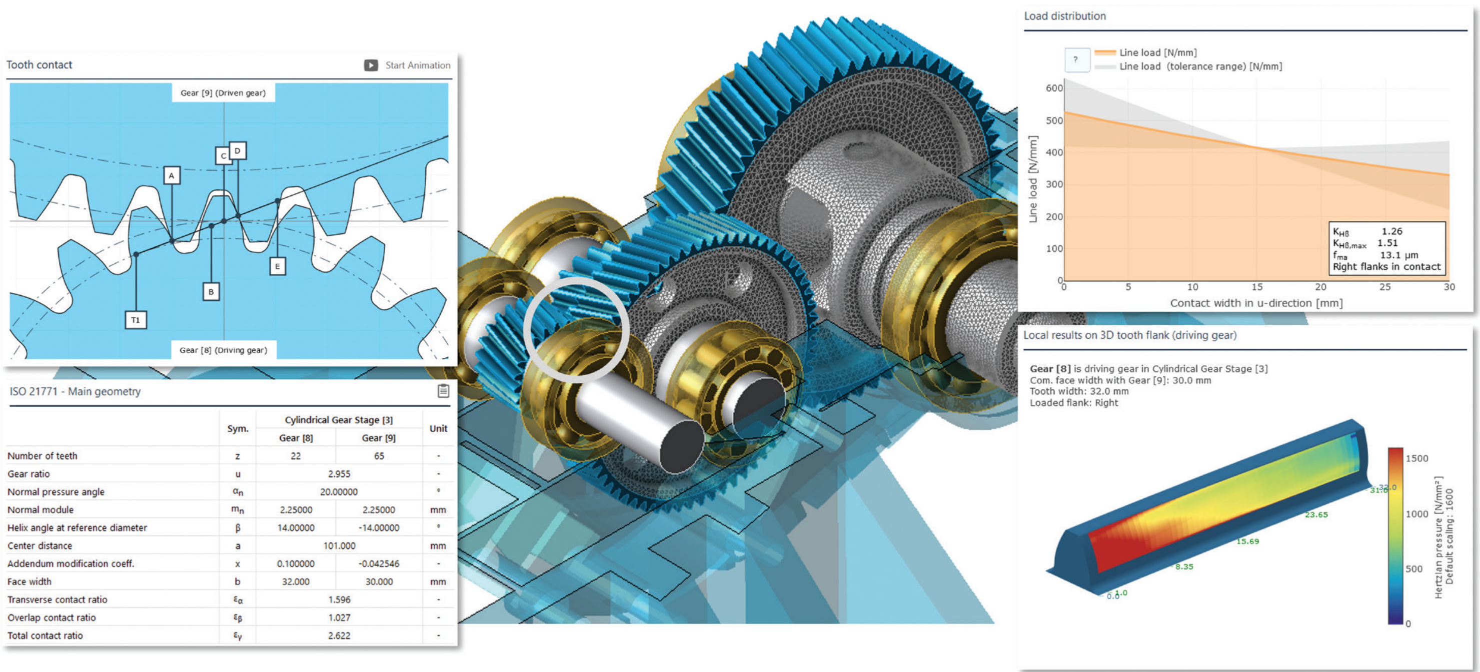
Load-related deformations and displacements in transmissions can lead to considerable misalignments in the gear meshes, and thus to uneven load distribution across the face width. Uneven load distribution across the flanks not only reduces the service life, but also worsens the noise excitation [3]. To avoid this effect, gear modifications must be designed to compensate for deformations and to achieve flat and even pressure distribution without stress peaks. This results in lower stiffness fluctuations in the tooth mesh, thus reducing gear noise excitation in the form of transmission errors. This requires detailed consideration of all deformations in the gearbox.

As with other manufacturing parameters, gear modifications are subject to inconsistency. An ideal design for the nominal load and geometry may prove to be suboptimal due to tolerances in the finished component. Angular modifications in particular are subject to substantial variance. For this reason, good nominal geometry and robust design are both of critical importance. The following provides an example of how the robustness of the design can be evaluated.

Calculation example

The following example uses detailed gearbox system analysis to show how the FVA-Workbench can automatically generate an initial flank modification design and then vary the characteristics to consider the influence of production tolerances. This makes it possible to determine an optimal and robust design for the relevant application.

This example uses a model of a reducer gearbox from an electric vehicle (EV), see figure 1. In addition to detailed modeling of the cylindrical stages and the shaft-bearing system, the gearbox casing, wheel bodies, and differential cage were also modeled as FE components to precisely consider all stiffnesses and cross influences that affect the gear mesh and the load distribution across the face width. As the gearbox was tested on a test bench, the model also includes mounting brackets on the gearbox housing.



	Sym.	Cylindrical Gear Stage [3]		Unit
		Gear [8]	Gear [9]	
Number of teeth	z	22	65	-
Gear ratio	u	2.955		-
Normal pressure angle	α_n	20.00000		°
Normal module	m_n	2.25000	2.25000	mm
Helix angle at reference diameter	β	14.00000	-14.00000	°
Center distance	a	101.000		mm
Addendum modification coeff.	x	0.100000	-0.042546	-
Face width	b	32.000	30.000	mm
Transverse contact ratio	ε_α	1.596		-
Overlap contact ratio	ε_β	1.027		-
Total contact ratio	ε_γ	2.622		-

+ Figure 1: Two-stage reducer gearbox design without flank modifications

In the FVA-Workbench, scripts can be used to perform customized mass calculations. The easy-to-use scripting language makes it possible to automatically calculate extensive analyses. This can be used to define all parameters of a model, run calculations, and then export the results, for example to Excel.

If extensive calculation studies are frequently required in the development process, mass calculations can be run in parallel to reduce the calculation time. A server solution such as the FVA SimulationHub is well-suited for these tasks, as it makes it possible to run calculation tasks simultaneously on any number of instances on the server. With the SimulationHub, the time savings are linearly scalable, meaning that two instances cut the calculation time in half.

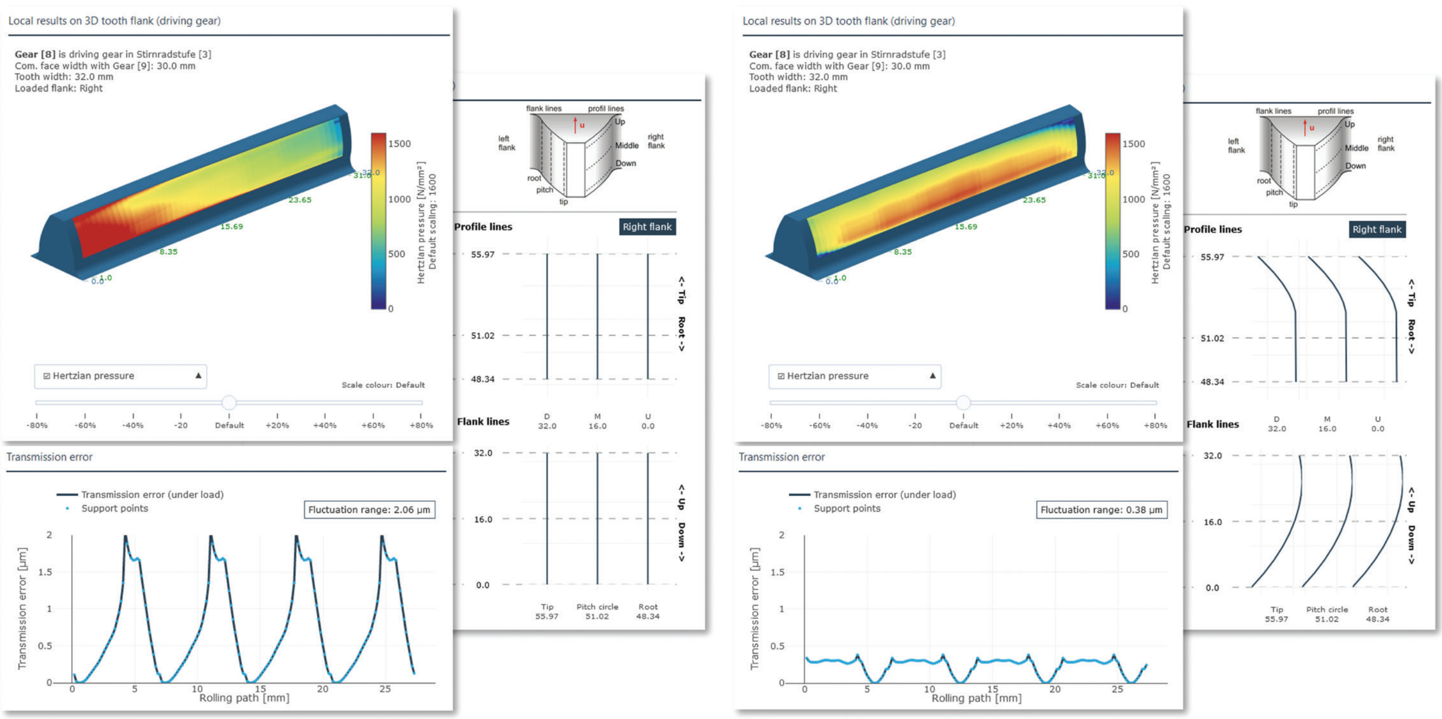
Automated design of basic flank modifications

A preconfigured script is used for an initial basic design of the flank modifications for all cylindrical gear stages in the gearbox in the FVA-Workbench. It initially calculates the gearbox without modifications and analyzes the contact and the load distribution across the face width. In a second step, it then calculates the recommended modifications, such as the tip relief according to Sigg [4] and a helix angle modification for a centered contact pattern. These are integrated into the model and then simulated, which makes it possible to directly compare the gear mesh and the gear excitation with and without modifications, as shown in figure 2.

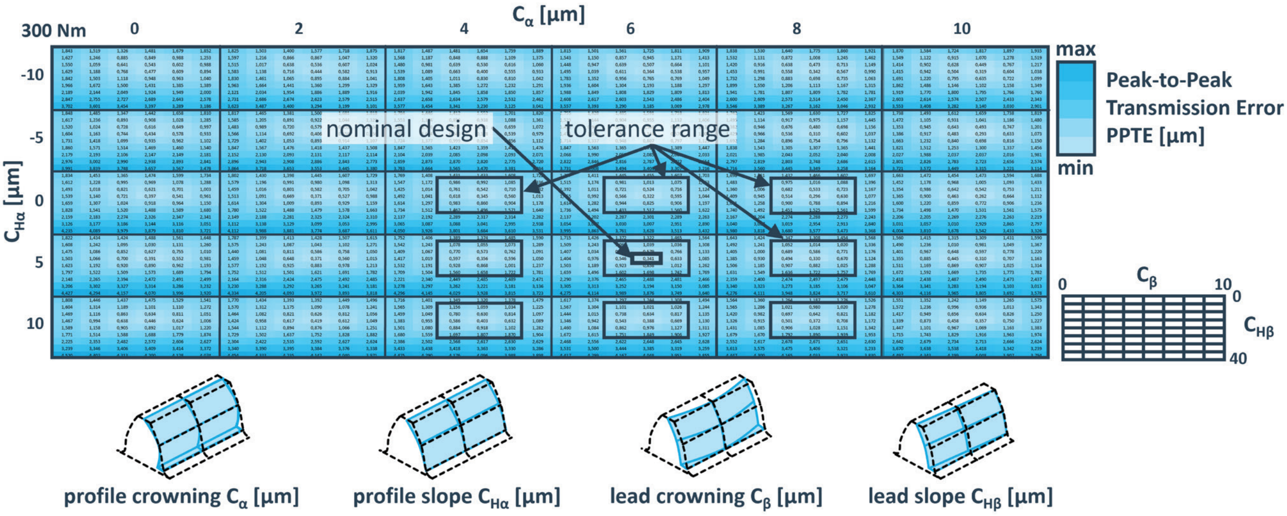
This automated preliminary design already results in a centered tooth contact with reduced stresses and no stress peaks at the contact edges, which leads to significantly lower fluctuations. As the different gear tooth stiffnesses influence the transmission deviation, it is not possible to directly compare the fluctuations of different gear designs and other gearboxes.
The fluctuation of the tooth loads and the resulting excitation level can also be calculated, which makes it possible to perform a qualitative and quantitative comparison of different cylindrical gear stages and gearboxes.

Parameter study on the influence of tolerances

In an additional study, the performance characteristics of the transmission error are determined for different torques T and variations of the four flank modifications: profile crowning, profile slope, lead crowning, and lead slope. This makes it possible to determine whether the nominal design of the flank modifications also produces consistently low gear mesh excitations over the production-related tolerance range, see figure 3.



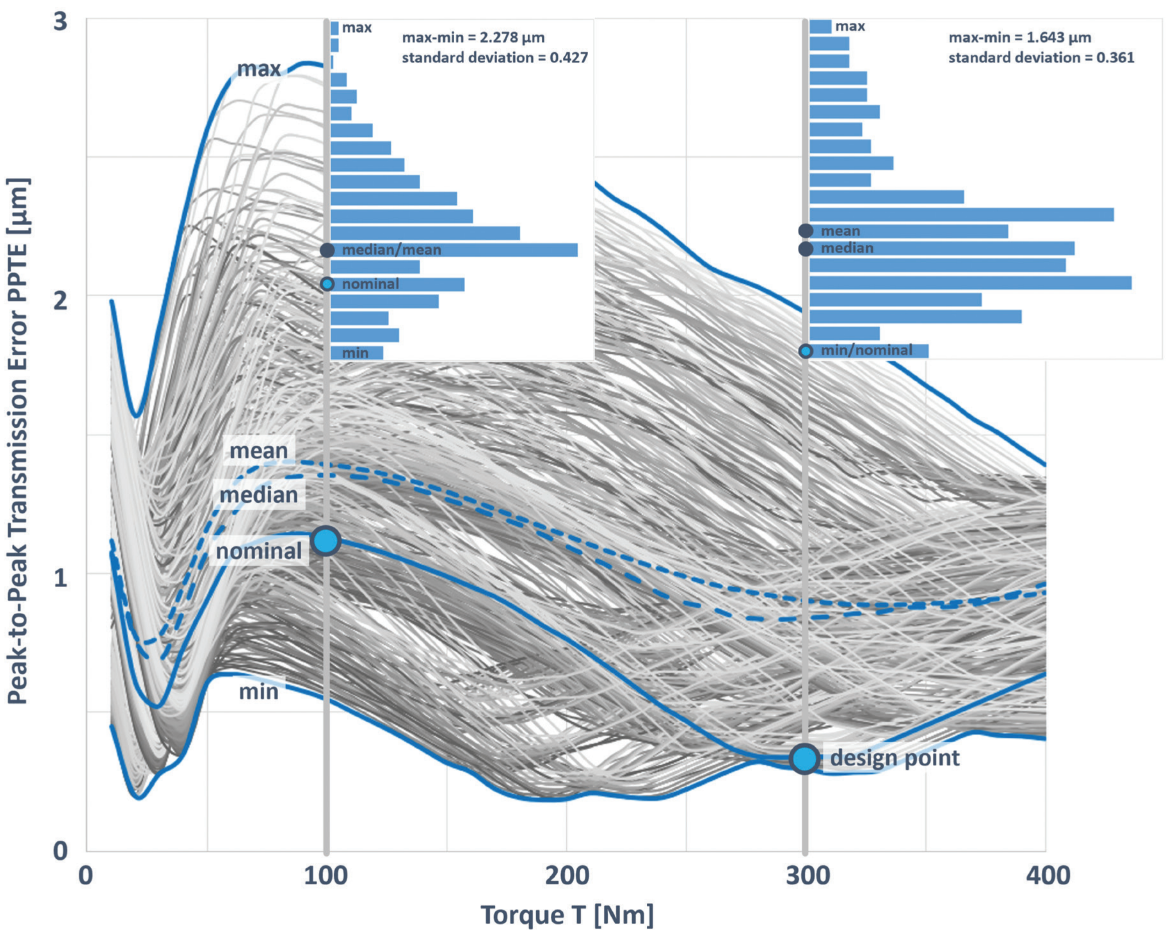
+ Figure 2: Results of the automated basic flank modification design on the contact pressure distribution of the gear mesh and the transmission error, both without (left) and with (right) modifications.



+ Figure 3: Transmission error at 300 Nm torque for four varied flank modification design parameters

The minimum and maximum transmission error are determined from the tolerance range results and the standard deviation is calculated as a measure for the robustness of the design.

The example in figure 4 shows that the design of the nominal flank modification leads to very little transmission error at 300 Nm torque. However, when the manufacturing tolerances are considered most of the results show significantly higher transmission deviation, even though the tolerances of the four input parameters are symmetrical to the nominal design. At 100 Nm torque the transmission error of the nominal design is significantly higher and much closer to the mean value for all results. These effects cannot be predicted without detailed analysis of the tolerance. Significantly higher safety factors must also be used in these cases, which makes the design larger, heavier, and more expensive.



+ Figure 4: Transmission deviation of all variations in the tolerance range over the torque, frequency distribution for 100 and 300 Nm

Conclusion

The FVA-Workbench can be used for simple, fast, and detailed calculation of complex transmission systems. All relevant details of the system in which the stiffness and behavior could potentially have an influence on the gear mesh are considered. The contact pattern can be optimized with targeted flank modifications, resulting in reduced stresses, longer service life, and low vibration –in other words, excellent NVH performance.

Flank modifications can nominally create an outstanding design under load. However, if the influence of manufacturing tolerances is not considered, there is a significant risk of producing inferior gearboxes. These may have to be reworked or rejected as scrap, which can lead to increased production costs, customer dissatisfaction, and reduced competitiveness.

With the FVA-Workbench the design process can largely be automated, allowing the user to focus on the important task of evaluating the results. This makes it possible to develop a robust gearbox in a short time and minimize the risk of problems during production. This not only saves time, but also lowers costs and material usage, thus lowering the CO_2 footprint of the gearbox.

About FVA GmbH

Founded in 2010, FVA GmbH actively collaborates with top-tier German research institutions and leading companies in the drive technology industry to facilitate the seamless integration of FVA's research findings into industrial practice. The culmination of this research is embodied in our proprietary calculation software, the FVA-Workbench. This software is designed for the comprehensive modeling and calculation of drive components and systems, with applications ranging across diverse industries including automotive, aerospace, marine propulsion, wind power, and industrial facilities. In addition to software, FVA GmbH offers services for companies looking to benefit from our knowledge. This includes creating customized gear models, performing intricate calculations, and specialized programming. With expertise in mechanical engineering and software development, FVA GmbH's experienced team collaborates closely with companies to provide expert support. FVA GmbH also boasts an extensive knowledge pool in the field of drive technology and a network that includes both research institutes and industrial enterprises. This depth of knowledge is integrated into industrial practice through FVA GmbH's diverse range of conferences and seminars. FVA GmbH has further expanded its focus with the establishment of its interop4X branch, specializing in providing solutions in the fields of industrial digitization and automation. With a specific emphasis on implementing interoperability and guiding transformation projects, this enables companies to achieve the full potential of their manufacturing processes.

For more information, please visit: www.fva-service.de.

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