Psychoacoustic Optimization of Gear Noise - Chaotic Scattering of Micro Geometry and Pitch on Cylindrical Gears

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Introduction and Motivation

Increasing sensitization for the topic noise, reduced masking noises and increased customer demands lead to an increasing importance of transmission noise. Especially due to the tonal characteristic of gear whining, gear noises move quickly and negatively into the customer's focus (Ref. 1). One of the most important criteria in the qualitative evaluation of gear transmissions in automotive engineering is the noise behavior (Ref. 2). The control of vibrations and the optimization of noise behavior inside of the vehicle is therefore an important development aim of automobile and transmission manufacturers (Ref. 3). A large part of the vibrations and noises inside of the a vehicle are generated in the drive train. Especially in motor vehicles, the reduction of masking noise sources through downsizing as well as electrification and hybridization of the drive train increases the importance of a low-noise transmission (Ref. 4).

However, increasing the quality of the gears and decreasing the gear excitation does not prevent the gear noise from being perceived as annoying. For an improvement of the perceived noise quality, a reduction of the noise level alone is not always the best solution. The characteristics of the noise and thus the human perception are decisive (Ref. 5).

In the design of transmissions, the high demands on running and noise behavior are fulfilled by specific topography designs. A compromise must be found between low gear excitation, sufficient load carrying capacity and high efficiency. The selection of the target topography for an optimized operational behavior over a wide torque range is the challenge in gear design (Ref. 6). Up to now, the quasi-static transmission error of a gear set is used as an evaluation variable for the resulting noise behavior.

The dominant noise characteristic of gears is howling and whining at high frequencies. This is caused by rolling the gear pair under load. Figure 1 shows the source-path-receiver concept in the automotive technology, based on Carl (Ref. 5). The source-path-receiver concept systematically describes the origin and transfer of the gear whining up to the hearing-related evaluation of the noise. Here, the noise behavior of a transmission can be represented by the machine acoustic transfer chain consisting of noise excitation (source, tooth mesh), noise transfer (path, structure-borne noise) and noise radiation (receiver, airborne noise).

The starting point of the noise generation chain is the quasi-static gear excitation. The gear excitation is quantifiable as the transmission error (TE) of a gear set and leads in interaction with the operating point-dependent dynamics of the drive train to a dynamic load fluctuation in the gear mesh. The resulting vibrations in the tooth contact are transmitted as structure-borne noise to the shaft bearing system and subsequently to the housing surface. Depending on the structural dynamic

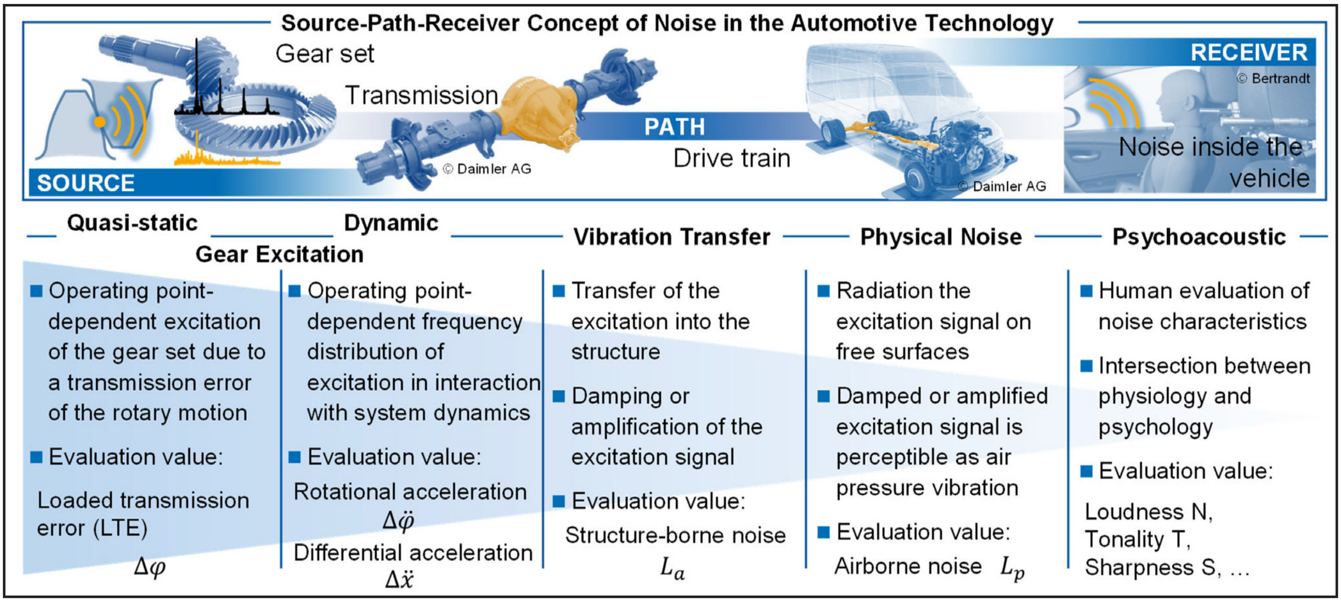

Figure 1 Source-path-receiver concept of noise in the automotive technology based on Carl (Ref. 5).

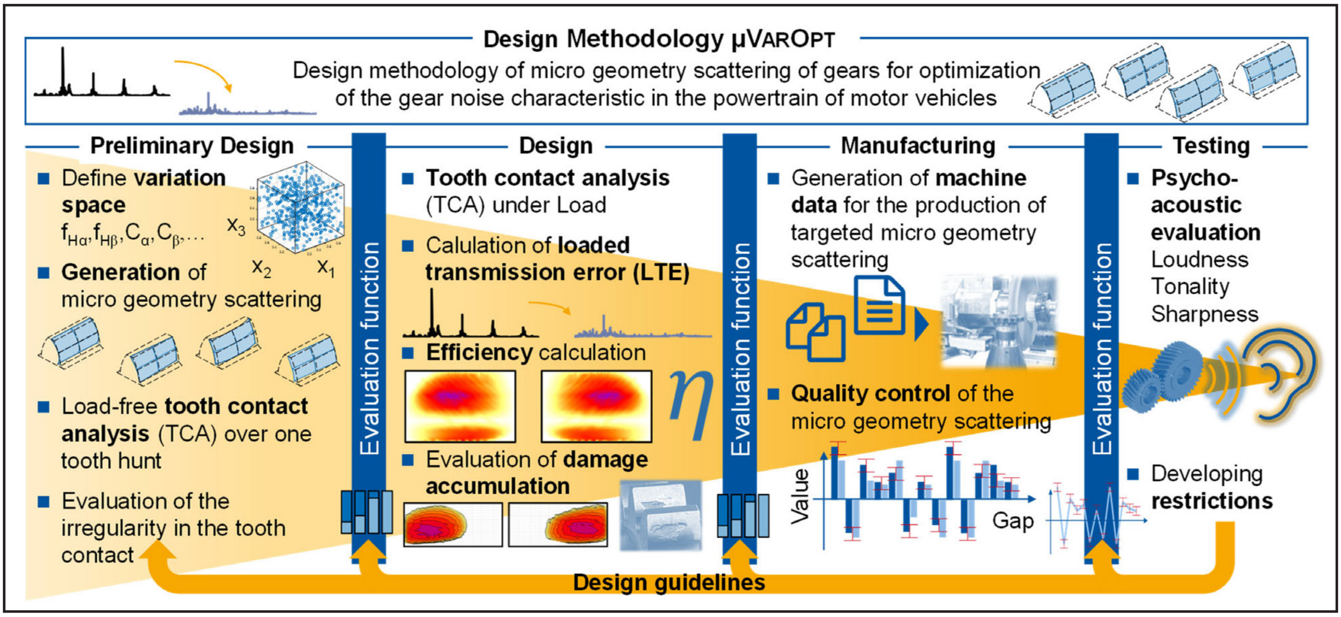

Figure 2 Design methodology µVarOpt.

properties of the transmission, the structure-borne noise is converted into airborne noise in the form of noise pressure fluctuations on the surfaces. Psychoacoustic evaluation methods are used to assess the effect of physical noise on the human hearing. The principle illustrates the connection between the gear excitation and the perception-specific noise characteristics of a transmission. (Ref. 5).

Objective and Approach

In the gear design process, increasingly extensive simulation options are being used to counter the rising requirements placed on modern gears. In addition to sufficient load capacity, good noise and running behavior with high power density is required for gear units. A target design for the application is generated on the basis of the framework conditions of the specifications.

With the minor disturbance of the meshing conditions by micro geometry scattering, the regularity of the transmission error signals in the time domain is disturbed and the background noise is increased. This is a new approach for the design of the target geometry of gears. This approach has already been used successfully for bevel gears (Refs. 7–9).

In this context, it could already be shown that a targeted micro geometry scattering on a beam style rear axle in a light commercial vehicle resulted in an improvement of the noise inside the vehicle (Refs. 9–10). The investigations described in the present paper were conducted as a part of a project sponsored by German Research Foundation (DFG) [Project Number BR 2905/82-1], which is carried out with the cooperation partners Daimler AG and Klingelnberg GmbH. The objective of the research project is the development of a method for the perception-oriented design of gears by the application of a targeted micro geometry scattering. The research hypothesis is that a specific design of a micro geometry scattering on gears leads to an improvement of the noise characteristics without loss of efficiency or load capacity.

The micro geometry scatters designed with the µVarOpt methodology were machined in a discontinuous profile grinding process. It was observed that the grinding of the micro geometry scatter results in a stochastic course of the pitch error. The research question in this report is the influence of a stochastic course of the pitch error compared to a micro geometry scattering on the excitation and noise behavior of cylindrical gears. For this purpose, the quasi-static excitation behavior of cylindrical gears with and without a stochastic course of the pitch error, as well as cylindrical gears with and without micro geometry scattering, is first investigated in the test field. Then, a simulation model is built to represent the quasi-static excitation behavior with stochastic course of the pitch error and the micro geometry. The simulation model is built using the FE-based tooth contact analysis ZaKo3D developed at Laboratory of Machine Tools and Production Engineering (WZL). The simulation results are validated using real transmission error measurements with the WZL cylindrical gear measuring cell.

The validated simulation model is used to analyze more in-depth investigations into the influence of a stochastic course of the pitch error on the quasi-static excitation behavior. In addition to the quasi-static behavior, the dynamic excitation behavior of the different gear set variants is also investigated. Here, the rotational acceleration close to the gear mesh is recorded and evaluated. In addition, noise behavior is analyzed by airborne noise measurements with psychoacoustic metrics (loudness and tonality).This is realized with a separate test rig setup for dynamic investigations.

Methodology µVarOpt for the Design of Micro Geometry Scattering on Gears

The design methodology µVarOpt for the determination of a targeted micro geometry scattering is about the limit setting of reliability at given high validity or in other words the design of a controlled chaos. The multistage perception-oriented design method µVarOpt of micro geometry scattering is shown in Figure 2. In the first step of the first design stage (preliminary design), gear sets with individual micro geometries are generated on the basis of a variation space. A basic design of macro

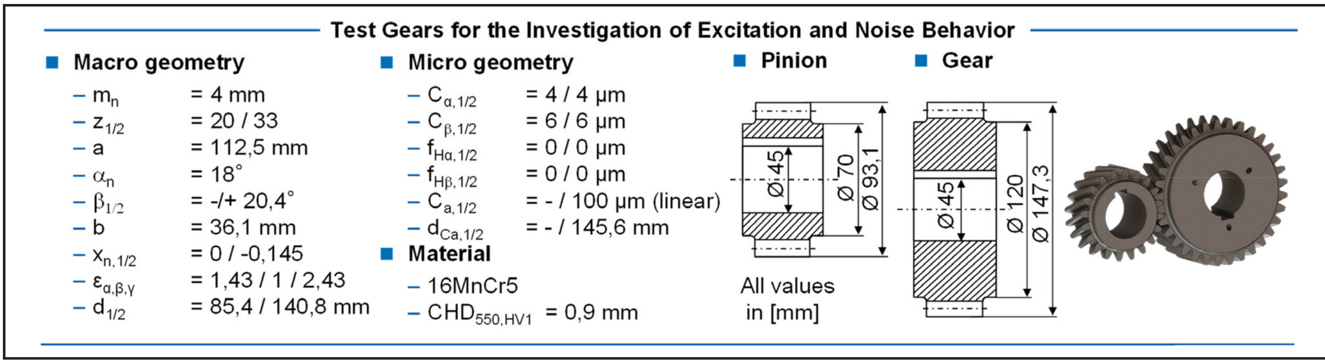

Figure 3 Test gears.

and micro geometry, which is to be varied, must be defined. In addition, it must be specified whether micro geometry scattering is to be generated at the pinion and/or mating gear, together with the respective number of individual micro geometries. Also, the type of distribution of the micro geometry scattering can be chosen between random and normally distributed. After the generation of a variant with micro geometry scattering, the FE-based tooth contact analysis ZaKo3D is automatically activated and the load-free transmission error over a tooth hunt is calculated. The evaluation of the simulation results is stored in a result matrix. At the end of the first stage of the variant calculation, all variants are evaluated with an evaluation function and the best variants in the load-free case are selected. The amplitudes of the first four gear mesh orders of the load-free transmission error are evaluated. In addition, the stochastic component in the transmission error course is evaluated by a modified autocorrelation function and is used to describe the irregularity of the tooth contacts (Ref. 7).

In the second stage, a tooth contact analysis under load is performed for the selected variants. The tooth contact analysis ZaKo3D is used to calculate the excitation behavior under load. In order to represent the signal-noisy effects of a micro geometry scattering under load, a tooth hunt is also simulated. In addition, the tooth contact analysis FE Stirnradkette Stirak can be controlled to calculate the efficiency, as well as the evaluation of damage accumulation due to irregular tooth meshing. At the end of the second stage, all variants calculated with a tooth contact analysis under load are graded with an evaluation function and the best gear set variant is determined.

In the third step, machine data for the grinding process is automatically generated to produce a targeted micro geometry scattering. After manufacturing, the quality control of the designed scattering of the micro geometry is carried out and evaluated.

In the fourth and final step, the manufactured gear sets are examined with regard to their operational behavior. The focus here is on the psychoacoustic evaluation of the noise behavior. With all the information obtained, restrictions can then be worked out and design guidelines can be made, for example, for the parameterization of the evaluation functions.

In the research work of Kasten et al., restrictions for the design of micro geometry scattering on ground bevel gears were developed. In addition, it could be shown that an optimization of the excitation behavior can already be achieved by applying a topography scattering with two to four different micro geometries, which are randomly distributed over all teeth of the component. The complexity of manufacturing and quality control of gears with mixed topographies (micro geometry scattering) is reduced by this insight. By comparing different types of scattering, the random application of micro geometry parameters and the random distribution of the different micro geometries from tooth to tooth were identified as the successful approach. The identification of the main influencing variables of the micro geometry parameters showed that the scattering of the angle modifications (profile and flank angle modifications) have a significant influence on the psychoacoustical optimized excitation behavior. By separately applying micro geometry scattering to the pinion and the gear, it could be demonstrated that the complete optimization potential of micro geometry scattering on gears can be achieved by generating mixed topographies on pinion and gear (Ref. 7)

Test Method

In this chapter, the test gears for the excitation and noise investigations are presented first. This is followed by a description of the two test rig setups for the quasi-static and dynamic investigation of the excitation behavior.

Test Gears

The test gears for the investigation of the excitation behavior is a helical gear set with normal modulus of $m_n = 4$ mm, a gear ratio of $z_{1/2} = 20/33$ and a helix angle $\beta_{1/2} = \pm 20.4°$ (Ref. 11). Both the macro geometry and micro geometry data are shown in Figure 3. The gears is made of 16MnCr5 steel alloy. The heat treatment selected is case hardening followed by cleaning blasting. With a center distance of $a = 112.5$ mm, the gear set can be applied to the test rigs described below.

Test Rig Setups

Test Rig Setup for the Investigation of the Quasi-static Excitation Behavior

For the investigation of the quasi-static excitation behavior of cylindrical gears, the WZL Cylindrical gear measuring cell was used for single flank test under operating conditions, see Figure 4 (left part). The measuring cell has an open design with oil injection. An oil cover serves as splash protection. Bearings are provided by bearing blocks at the input and output. The gears are supported by flanges. In order to provide misalignments caused by bending, an additional bearing is mounted on the shaft side facing away from the bearing block. The oil injection temperature is monitored and controlled to $T_{Oil} = 60°C$.

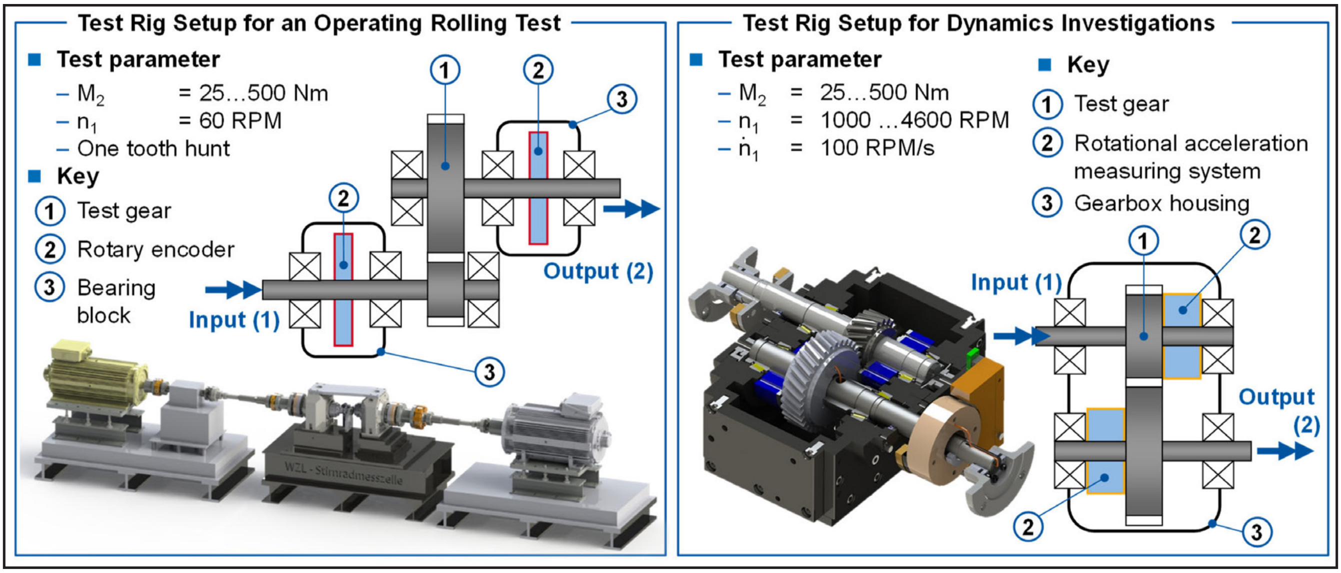

Figure 4 Test rig setups for quasi-static and dynamic investigation of excitation and noise behavior.

During the single flank test under operating conditions, at a low input speed of $n_1 = 60$ RPM and a maximum output torque of $M_2 = 500$ Nm, the transmission error of the gear set (Ref. 1) is detected by incremental rotary encoders (Ref. 2).

Test Rig Setup for the Investigation of the Dynamic Excitation Behavior and the Noise Behavior

The test rig setup for the dynamics investigations is carried out on the WZL's universal transmission test rig, which consists of an electric input machine and two electric output machines. The motors and the test object are each located on separate clamping fields, which are supported by air springs. This decoupling of the individual clamping fields from the building avoids excitations of the test object which are not generated by the drive train itself. An acoustic measuring chamber, which encloses the clamping field of the test object, allows the measurement of the airborne noise without the influence of external noise sources, such as the noise sources of the pump for the circulating oil lubrication and the noise of the electrical machines. For the investigation of the dynamic excitation behavior and the noise behavior, the WZL dynamic measuring cell (single-stage cylindrical gear set) developed by Carl was used (Ref. 5). The basic design of the measuring cell as well as the measuring technique used are shown in Figure 4 on the right side. The WZL dynamic measuring cell enables the investigation of the differential acceleration by means of rotational acceleration measuring systems (Ref. 2), which are mounted close to the gearing for a metrological recording of the dynamic gear excitation. By means of the speed ramp-ups at constant torque, the dynamic behavior of the different gear set variants was investigated. To ensure reproducibility, the gearbox temperature $T_{Gearbox}$ and the oil injection temperature T_{Oil} were measured. The oil injection temperature was $T_{Oil} = 60°C$.

Influence of Chaotic Scattering of the Pitch and Micro Geometry on the Quasi-static Excitation Behavior

In this chapter, the influence of a chaotic scattering of the micro geometry and the pitch on the quasi-static excitation behavior of cylindrical gears is investigated. For this purpose, the manufactured gear set variants are first characterized with respect to micro geometry and single pitch deviation. Then, an FE-based simulation model for reproducing the effects of micro geometry scattering and a stochastic pitch error course is validated with experimental results. The validated simulation model is used to build a deeper understanding of the influence of a chaotic scattering of the micro geometry and the pitch on the quasistatic excitation behavior.

Table 1 Overview of the gear set variants

Feature		Pinion / Gear	Pinion / Gear	Pinion / Gear	Pinion / Gear
Pitch	f_{pmax} [µm] (IT)	2.7 (IT3) / 1.0 (IT1)	3.3 (IT3) / 2.1 (IT2)	7.7 (IT6) / 3.1 (IT3)	10.3 (IT7) / 2.3 (IT2)
	F_p [µm] (IT)	11.8 (IT4) / 4.1 (IT1)	16.0 (IT5) / 13.1 (IT4)	17.6 (IT5) / 12.0 (IT4)	18.4 (IT5) / 10.8 (IT3)
	Course	Sinusoidal	Stochastic	Stochastic	Stochastic
Micro geometry	$f_{H\beta max}$ [µm] (IT)	–3.6 (IT4) / 2.8 (IT3)	–3.4 (IT4) / 3.7 (IT4)	5.3 (IT5) / 4.9 (IT4)	–12.5 (IT7) / –2.5 (IT3)
	$f_{H\alpha max}$ [µm] (IT)	4.4 (IT4) / –2.9 (IT3)	4.2 (IT4) / –2.1 (IT3)	–2.9 (IT4) / –2.6 (IT3)	–4.7 (IT5) / 6.5 (IT5)
	Course	Sinusoidal	Sinusoidal	Sinusoidal	Stochastic

Overview of the Variants

A total of four gear set variants were manufactured to investigate the influence of chaotic scattering of the micro geometry and pitch on the excitation behavior. The maximum deviation with respect to micro geometry and pitch as well as the characteristics of the course are shown in Table 1. Only the right tooth flanks of the gearing are considered, since these flank sides are strained in the transmission.

A gear set variant with no targeted micro geometry scattering serves as reference REF. The course of the values of the profile line angle deviation $f_{H\alpha}$

and the flank line angle deviation $f_{H\beta}$ are sinusoidal. Likewise, the pitch error course is also sinusoidal. The µVarOpt variant was designed with a focus on optimizing the noise characteristics for the design torque $M_2 = 400$ Nm. The µVarOpt design methodology was used to design a targeted micro geometry scattering within the IT7 quality limit according to DIN ISO 1328-1 for the profile line angle deviation $f_{H\alpha}$ and the flank line angle deviation $f_{H\beta}$ (Ref.12). Likewise, the profile crowning C_α was scattered by a maximum of ±4 µm and the width crowning C_β by ±6 µm. The grinding of the µVarOpt variant also leads to an irregular course of the pitch due to manufacturing and design reasons in addition to the scattering of the micro geometry. The irregularity in the course of the individual pitch deviations f_p results from the wear of the grinding wheel, dressing errors, errors when re-centering the grinding wheel, the quasi-stochastic sequence of the gap selection and the different profile and flank angle modifications of the design. In addition, two gearset variants were manufactured with a stochastic pitch error course. In the fp_Random variant, the wear of the grinding wheel and a quasi-stochastic choice of the order in grinding the gaps were used to achieve a stochastic course of the single pitch error f_p. The objective of the fp_µVarOpt variant was to achieve as similar a course and characteristic of the single pitch deviations f_p as possible as with the µVarOpt variant. For this purpose, the same grinding program was used for profile grinding of the fp_µVarOpt variant as for the µVarOpt variant, with the adjustment that the targeted scatter of the micro geometry was set to zero.

Characterization of the Micro Geometry and Pitch

The profile and flank lines of all tooth gaps as well as the individual pitch deviations f_p are measured for each gear set variant on a precision measuring center P16 from Klingelnberg. Figure 5 shows the measured tooth flank deviations of the pinion for each gear set variant. As a reference, the limits of tolerance class IT5 according to DIN ISO 1328-1 are drawn in (Ref. 12).

The systematic and sinusoidal scattering of the micro geometry in the form of a small wobble and eccentricity can be seen for the REF, fp_Random and fp_µVarOpt variants. The micro geometry of the µVarOpt variant shows the intended chaotic course. The single pitch deviations f_p of the variants µVarOpt and fp_µVarOpt are comparable in their course and characteristics, so that with these two gear set variants the influence of a chaotic pitch error can be investigated with and without micro geometry scattering. The maximum single pitch deviation of µVarOpt is $f_{pmax} = 10.33$ µm (IT7) and for the variant fp_µVarOpt $f_{pmax} = 7.7$ µm (IT6). The REF variant shows a sinusoidal course of the pitch error, with the maximum single pitch deviation at $f_{pmax} = 2.7$ µm (IT3). The course is caused by the wear of the grinding wheel. The pitch error of the fp_Random variant is in the same order of magnitude $f_{pmax} = 3.3$ µm (IT3). However, since the teeth in the fp_Random variant were ground in a random sequence, the course of the pitch has a stochastic component and is not purely periodic. Analogous to the manufacturing deviations with regard to the micro geometry and pitch on the pinion, qualitatively similar deviations can be observed on the gear.

Validation of the Simulation Model

The quasi-static excitation behavior of the gear set variants already presented was investigated in the following. For this purpose, the loaded transmission error (LTE) (ptp: peak-to-peak) of the gear set variants is investigated on the test rig with the WZL cylindrical gear measuring cell and, in addition, a simulation model is set up to represent the LTE with a scattering of the micro geometries and the pitch in cylindrical gears.

Figure 6 shows the experimental results for the loaded transmission error (LTE) of the gear set variants on the left side. Shown are in each case the course of the first and second gear mesh order 1.fz & 2.fz of the LTE over the load with respect to $M_2 = 500$ Nm. The LTE is measured at a constant drive speed of $n_1 = 60$ RPM. For this purpose, a tooth hunt is performed and each gear set variant is measured three times. The test results in

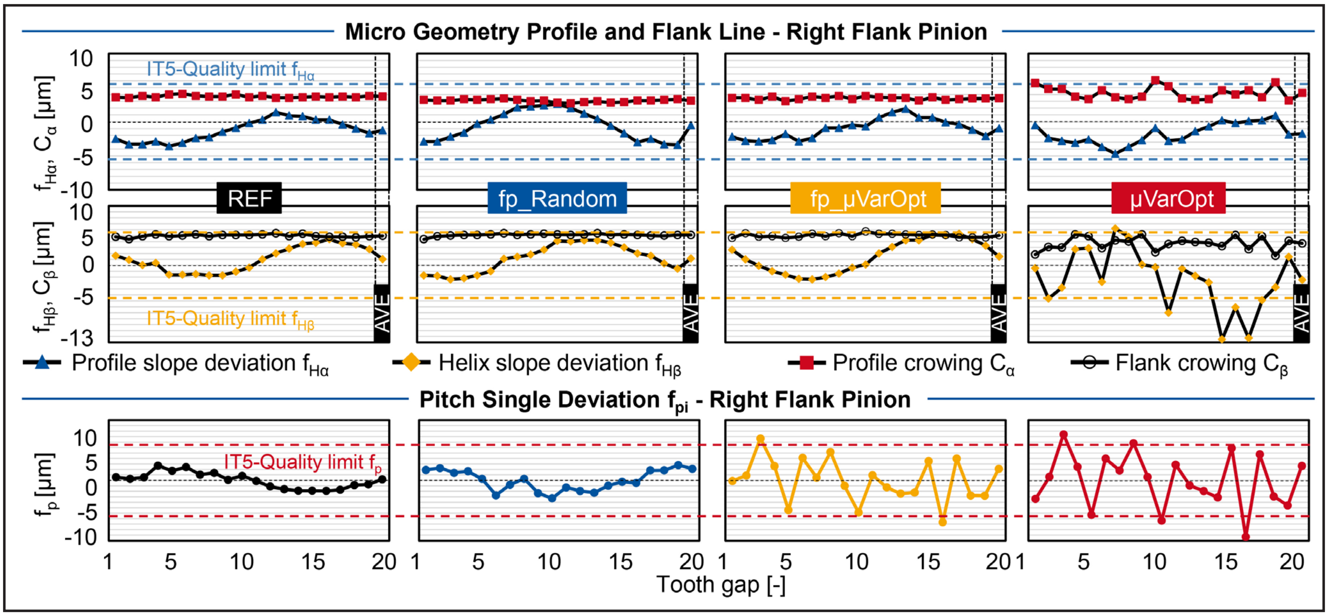

Figure 5 Course of deviations pitch and micro geometry on the pinion for all gaps.

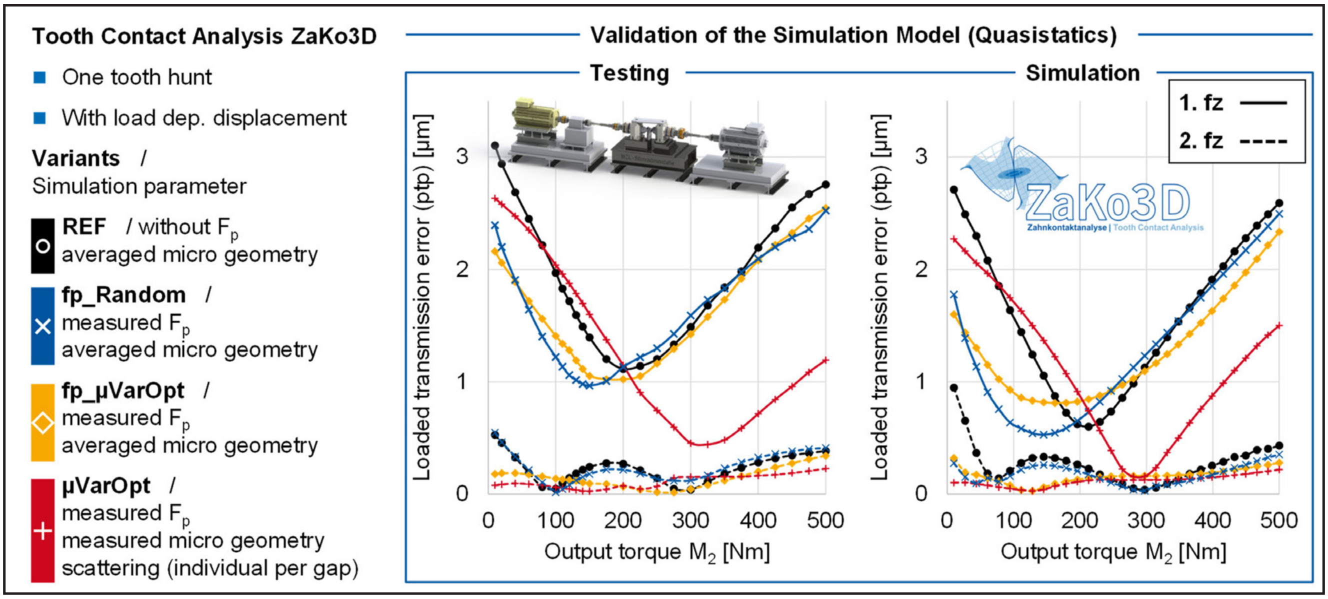

Figure 6 Validation of the simulation model for modeling the quasi-static excitation behavior.

Figure 6 show the mean value from the three measurements.

The gear set variant REF with a low wobble and a sinusoidal pitch error curve shows a high excitation of the first gear mesh order 1.fz of $\Delta\varphi_{LTE,1.fz} = 3.1\,\mu m$ in the LTE at a low torque of $M_2 = 10\,Nm$. With increasing torque, the amplitude of the first gear mesh order 1.fz of the LTE decreases to a minimum of $\Delta\varphi_{LTE,1.fz} = 1.1\,\mu m$ at $M_2 = 200\,Nm$. A further increase of the torque leads to an increase of the amplitude of the first gear mesh order 1.fz up to $\Delta\varphi_{LTE,1.fz} = 2.7\,\mu m$ at $M_2 = 500\,Nm$.

All other gear set variants with chaotic deviations over the circumference of pinion and gear basically show a similar course as REF. A high excitation of the amplitude of the first gear mesh order 1.fz over a prominent minimum of the excitation up to again increasing amplitudes.

However, the amplitudes as well as the prominent minimum are differently distinct. Thus, the variant fp_Random shows a low amplitude of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ in the torque range $M_2 = 10–200\,Nm$. In addition, the prominent minimum is shifted to a low torque of $M_2 = 150\,Nm$. From a torque of at $M_2 = 200\,Nm$, REF thus also fp_Random show similar amplitudes. For the second gear mesh order 2.fz of the LTE $\Delta\varphi_{LTE,2.fz}$, the two variants REF and fp_Random are comparable in their excitation. It can be observed that a comparatively low stochastic pitch error course of the variant fp_Random shows advantages of a lower excitation especially in the load range up to the minimum of the amplitude of the first gear mesh order 1.fz.

Compared to the variant fp_µVarOpt with a more pronounced stochastic course of the single pitch deviation f_p, this stronger irregularity in the pitch error also leads to a reduction of the amplitude of the LTE of the second gear mesh order $\Delta\varphi_{LTE,2.fz}$. Moreover, the prominent minimum is characterized over a wider torque range of $M_2 = 150–225\,Nm$. At higher torques from $M_2 = 225\,Nm$, the variant fp_µVarOpt shows slightly lower amplitudes of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$. The increase of the stochasticity in its expression and amplitude in the course of the single pitch deviation f_p is combined with a further decrease of the amplitude of the first two gear mesh orders of the LTE. If the fourth gear set variant µVarOpt, with a very comparable stochastic course of the single pitch deviations f_p as fp_µVarOpt and an additional targeted micro geometry scattering within IT7, is included in the comparison, differences of the two stochastic deviations become clear. In the µVarOpt variant, the excitation minimum is shifted to $M_2 = 300–325\,Nm$. This shift can be attributed to the scatter of the twist S_α and the scatter of the profile crowning C_α. The superposition of a chaotic scattering of the micro geometry and the pitch error leads to significantly lower amplitudes of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ for torques from $M_2 = 225\,Nm$. The amplitude of the second gear mesh order 2.fz of the LTE $\Delta\varphi_{LTE,2.fz}$ continues to be lower than with the REF variant over a wide torque range.

For the simulation of the quasi-static excitation behavior with chaotic scattering of micro geometry and pitch, a model was built in the FE-based tooth contact analysis ZaKo3D. For this purpose, the macro geometries of pinion and gear were tool-based generated using the geometry generation *GearGen*. To calculate the LTE of the REF variant, the measured and averaged micro geometry after manufacturing was taken into account. The course of the pitch error was not considered in the model for REF. For the two variants with stochastic course of the single pitch deviation f_p fp_Random and fp_µVarOpt, the pitch error was considered in the model in the form of the measured sum pitch error F_p. The measured and averaged micro geometry was specified as for the REF variant. For the µVarOpt variant, the individual and measured micro geometry from tooth to tooth was also specified in the model in addition to the measured sum pitch error F_p. In addition, a load-induced displacement of the gear set was assumed. The characteristic of a change in the center distance a as well as the inclination and skew under load was determined with the help of the measured course of the amplitude of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ of REF. One pitch per torque was calculated for the REF variant, and one tooth hunt of 660 pitches per torque is necessary to calculate the effects of stochastic deviations over the circumference of the pinion and gear on the excitation behavior.

The results of the simulated quasi-static excitation behavior of the four variants are shown in the right part of Figure 6. The simulation model can rebuilt the characteristic features of the four gear set variants already described very validly in terms of quantity and quality under the assumption of the selected load-induced displacement. The increasing complexity of the gear geometry can be countered with an increased individual consideration of micro geometry and pitch. Basically, the amplitudes of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ are slightly lower in the simulation model compared to the experimental results. The differences between the individual variants can be modelled realistically by the simulation model. The tooth contact analysis is thus well suited for further simulative investigations as well as the design of targeted micro geometry scattering.

Influence of a Chaotic Pitch Error Course

The validated simulation model will be used in the following to build up a deeper understanding of the influence of a chaotic pitch error course on the quasi-static excitation behavior. After presenting the experimental results, the question is raised at which amplitude or IT quality class of the pitch error an optimum for improving the noise characteristics exists. For this purpose, ten variants each were generated within an IT quality class of IT1–IT8 with a stochastic pitch error. Care was taken to ensure that both the individual pitch deviations f_p and the resulting summed pitch deviation F_p were within the respective IT quality class. The REF (IT0) variant is used as a reference for which no pitch error was specified in the simulation model.

During the simulation, one tooth hunt with 660 pitches was performed and the output torque of $M_2 = 10–500$ Nm was examined. No load-related displacement was specified. The results of the simulation study on the influence of different IT quality classes of a stochastic pitch error on the LTE are shown in Figure 7. In each of the four diagrams, the curves of the averaged LTE ($M_2 = 10–500$ Nm) from the first to the fourth gear mesh order 1.fz–4.fz are shown. In addition, the scatter bands of the averaged excitation are shown with the course of the maximum and minimum amplitudes. It can be seen that in the considered torque range a stochastic scattering of the pitch in the quality class IT6 causes the strongest decrease of the amplitude of the first gear mesh order 1.fz of the averaged LTE $\Delta\varphi_{LTE,1.fz}$. The amplitude of the first gear mesh order 1.fz can be reduced by 20.2% on average. For the amplitude of the second gear mesh order 2.fz, a minimum can be detected at the maximum deviation within the IT7 class. The amplitudes of the third and fourth gear mesh order 3.fz–4.fz decrease continuously with the increased stochasticity of the pitch. Likewise, it can be observed that with an increase in the stochasticity of the pitch from IT6, the amplitude of the first gear mesh order 1.fz increases again and can even exceed the excitations without pitch error at IT8. In addition, the risk of premature teeth meshing increases with increasing pitch error. IT7 and IT8 are to be judged as critical. Therefore, for the considered torque range $M_2 = 10–500$ Nm, an optimum of stochasticity can be found in the pitch error curve at IT6. This corresponds to the pitch error curve of the variant fp_µVarOpt investigated in the test field.

Superposition of Chaotic Scattering of Micro Geometry and Pitch

Following, the influence of a micro geometry scattering with a layered pitch error is investigated. Four gear set variants were generated for this purpose. The REF variant has no scattering of the micro geometry and the pitch. For the variant fp_µVar, a stochastic pitch error curve within the IT5 limit for the single pitch deviation f_p and the sum pitch deviation F_p was applied in the simulation model. The micro geometry corresponds constantly to the REF variant for all teeth. For the variant MGS_µVar, a stochastic scattering of the profile line angle deviations $f_{H\alpha}$ and the flank line angle deviation $f_{H\beta}$ within the IT5 limit was specified as micro geometry scattering (MGS). No pitch error was considered for the variant MGS_µVar. The variant fp_MGS_µVar has the identical scatter of the pitch as fp_µVar and the identical dispersion of the micro geometry as MGS_µVar. The stochastic deviations for the variants fp_µVar, MGS_µVar and fp_MGS_µVar

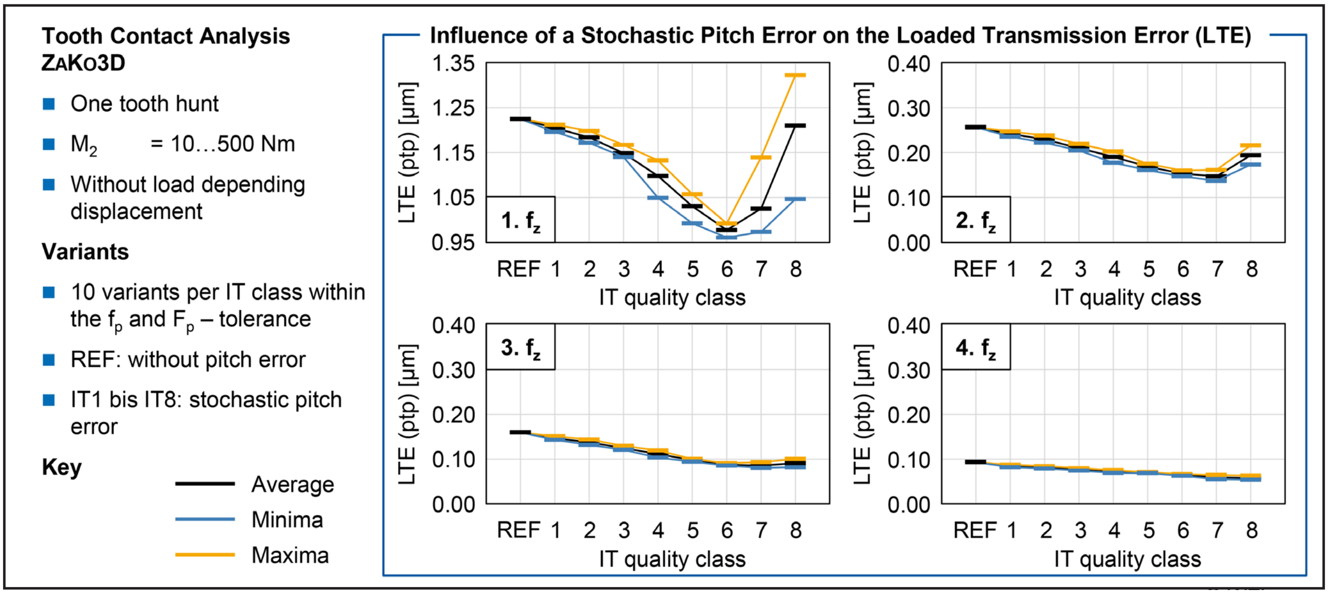

Figure 7 influence of a stochastic pitch error curve on the loaded transmission error (LTE).

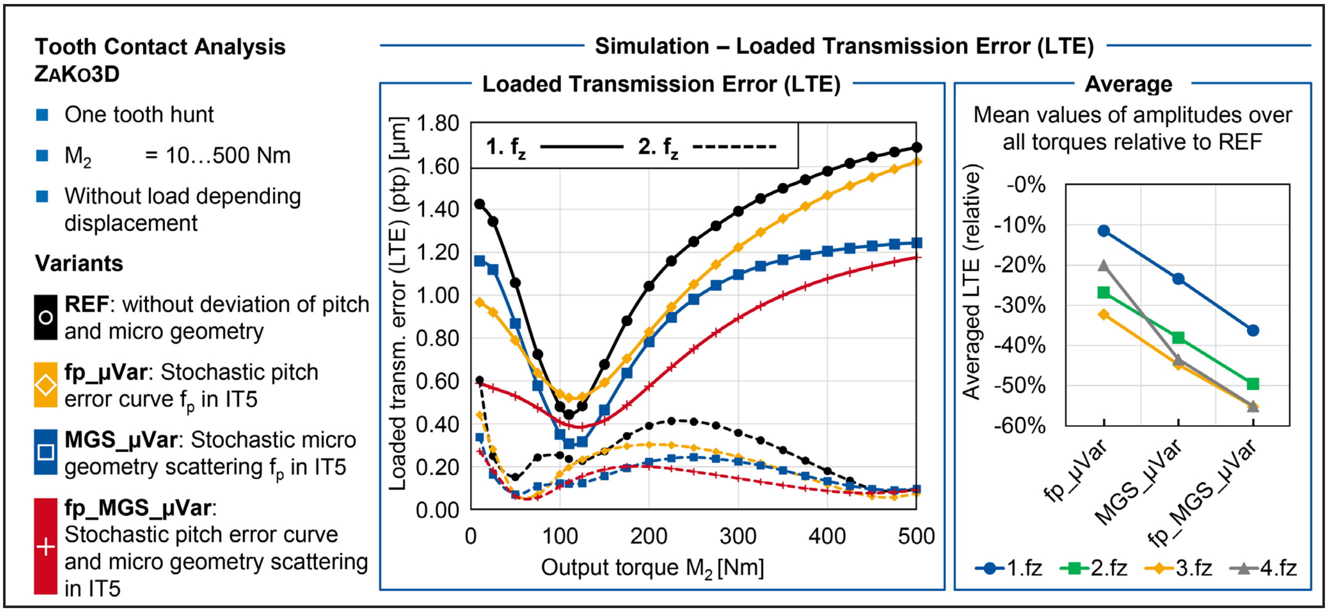

Figure 8 Superposition of the influences of a stochastic pitch error curve and a micro geometry scattering on the loaded transmission error.

were generated on the pinion as well as on the gear.

In the simulation of the loaded transmission error (LTE), one tooth hunt was calculated for the variants with stochastic deviations over the circumference. For the reference variant, only one pitch was calculated. No load-induced displacements were assumed.

Figure 8 shows the amplitude curves of the first two gear mesh orders 1.fz and 2.fz of the LTE over the validated load range up to $M_2 = 500$ Nm. It can be seen that the effects of amplitude reduction for the first gear mesh order 1.fz is larger for a stochastic pitch error up to the torque of $M_2 = 60$ Nm compared to a stochastic micro geometry scattering. The stochastic micro geometry scattering in the form of the variant MGS_µVar shows a larger decrease of the first gear mesh order 1.fz at higher torques from $M_2 > 60$ Nm. The superposition of stochastic pitch error course and stochastic micro geometry scattering (fp_MGS_µVar) shows the best results for the reduction of the first and second gear mesh order 1.fz–2.fz.

The effects on the higher harmonics up to the fourth gear mesh order are shown in the right part of Fig. 8 when calculating the mean values of the amplitudes over all torques relative to the results of REF. It can be seen well that both the first and the higher harmonics up to the fourth gear mesh order can be reduced more and more as the proportion of stochastic deviations increases over the circumference. Thereby, a stochastic pitch error course has a smaller influence on the reduction of the amplitudes of the first four gear mesh orders 1.fz–4.fz compared to the stochastic micro geometry scattering. The averaged relative comparison to the REF variant also shows that a superposition of stochastic scattering of the micro geometry and the pitch has the greatest effect on the reduction of the excitation amplitudes of the gear mesh orders. In contrast to the results from the test rig or the validated simulation results, the variant MGS_µVar as well as fp_MGS_µVar do not show any shift of the prominent excitation minimum of the first gear mesh order 1.fz. In the variants, only the profile line angle deviations $f_{H\alpha}$ and the flank line angle deviations $f_{H\beta}$ were scattered, so that a reduction of the amplitudes of the first gear mesh orders 1.fz of the LTE is possible in a very large torque range. If one does without an additional scattering of the crowning and the twist, no shift of the excitation minimum is to be expected.

Investigation of the Dynamic Excitation Behavior

In this chapter, the dynamic excitation behavior of the gear set variants is investigated experimentally. For this purpose, the WZL dynamics measurement cell was set up and operated on the WZL universal transmission test rig.

To investigate the dynamic excitation behavior, the signals of the differential acceleration were evaluated. Figure 9 shows the measurement results of the differential acceleration for the first four gear mesh orders 1.fz–4.fz above the output torque M_2. The gear set variants examined at 12 measuring points in a range of $M_2 = 20–470$ Nm. For each measuring point, the signals were measured over a speed ramp-up of $n_1 = 1000–4600$ RPM and then the arithmetic mean (single number value) was calculated. The ordinate of the diagrams is scaled in dB.

The course of the reference REF for the first gear mesh order 1.fz starts at its maximum value, then falls to a prominent minimum at $M_2 = 150$ Nm and then rises again with increasing torque. The curve matches the simulated and tested curves from quasi-statics in Figure 6. Only the prominent minimum is at $M_2 = 200$ Nm in the quasi-static curves. This is caused by the different displacement behavior under load of the measuring cells used. The measurement results of fp_Random follow the course of REF, but due to the stochastic pitch error course in the marginal areas of the investigated torque range, slight advantages arise with respect to the excitation of the first gear mesh order 1.fz. The µVarOpt variant shows, similarly to quasi-statics, a more significant shift of the minimum $M_2 = 250$ Nm. The results show stronger excitation in the torque range $M_2 = 80–180$ Nm. For lower torques $M_2 = 10–80$ Nm or higher torques $M_2 = 180–500$ Nm, there is less excitation. At the higher harmonics, the reference REF always has the highest excitation in the examined load range up to $M_2 = 470$ Nm.

The frequency spectra for the measuring point with

$M_2 = 400$ Nm are shown in Figure 10. The frequency spectra are scaled in dB, the drive speed n_1 is plotted on the abscissa and the frequency on the ordinate. The gear mesh orders can be identified as rising straight lines in the spectrum. It can be clearly seen that in the comparison of the gear sets from left to right (increase in the degree of chaotic scattering of the micro geometry and pitch), the level of the gear mesh orders decreases and more orders are excited in between.

In the case of the REF variant, the individual amplitudes of the gear mesh orders in the frequency spectrum can be clearly seen in Figure 10, as well as the sidebands caused by the sinusoidal deviations of the gear geometry.

The variant fp_Random also clearly shows the amplitudes of the gear mesh orders in the frequency spectrum. The sidebands occur in a narrower band. Due to the slight stochastic course of the pitch error f_p, the excitation of the first gear mesh order is lowered by 8.3% at a torque of $M_2 = 400$ Nm (see order spectrum in the lower part of Fig. 10). A greater effect is seen in the reduction of the higher harmonic gear mesh orders, where the amplitudes could be reduced by 45.9% and more. The stronger chaotic scattering of the pitch error fp with variant fp_µVarOpt intensified the observed effects. Thus, the amplitude of the first gear mesh order was reduced by 33.1% and the higher harmonics by 64% and more. The best excitation behavior results shows the µVarOpt variant, only the first gear mesh order becomes prominent and the amplitude could be reduced by 59.4% compared to REF. The higher harmonics are lost in the background noise, since the amplitudes of the higher harmonics are lowered by 81.8% and more.

Investigation of the Noise Behavior

Analogous to the investigation of the dynamic excitation behavior, the noise behavior was measured in the form of airborne noise from the drive train and evaluated as a frequency and order spectrum. A ½” free-field microphone was set up at a distance of 1 m from the measuring cell. The test rig is located in a Q2 certified acoustic measurement room according to DIN EN ISO 3744 (Ref. 13). By using an acoustic measuring room, noises

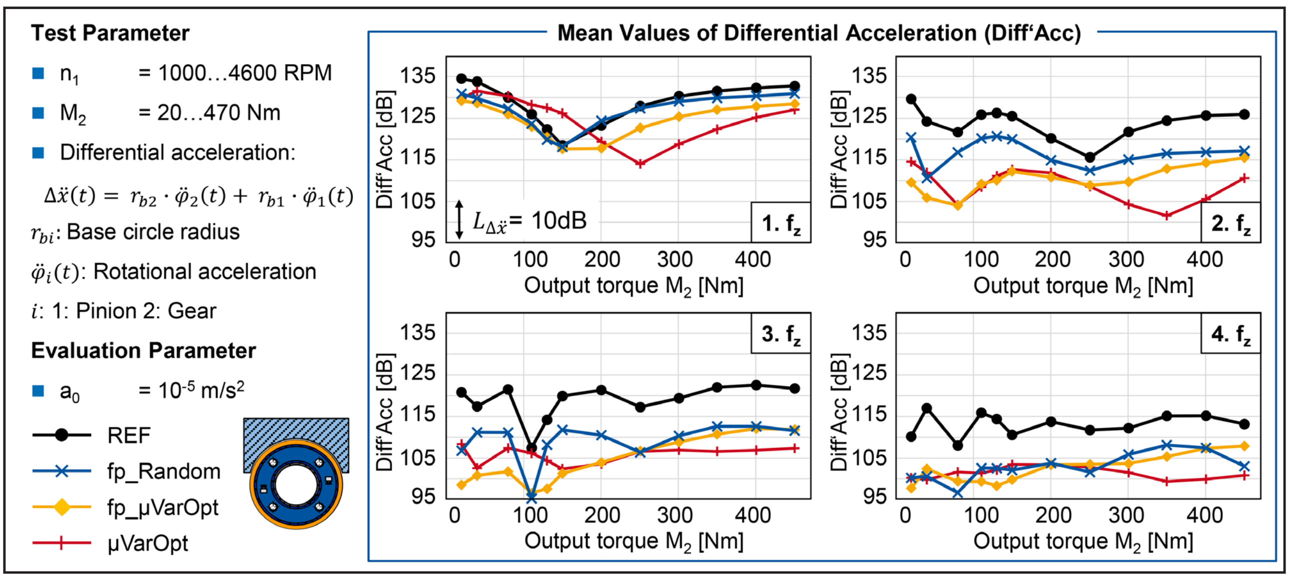

Figure 9 Dynamic excitation behavior under load.

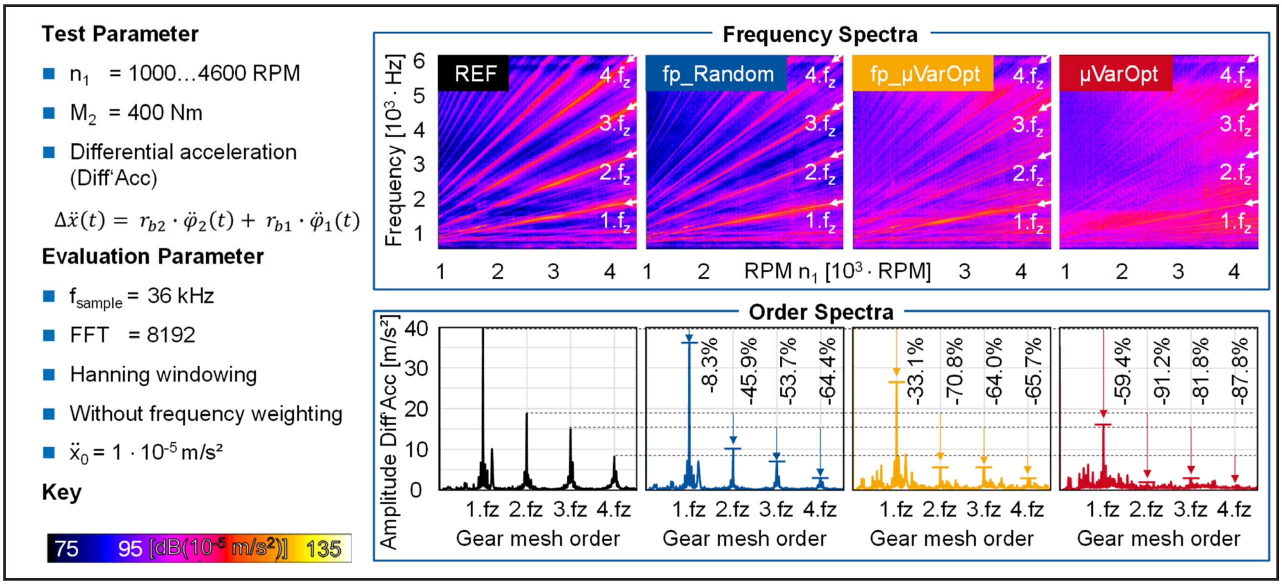

Figure 10 Dynamic excitation behavior at $M_2 = 400$ Nm.

from the environment around the test object (drive and driven machines, pneumatic control of the clamping fields, external oil unit, etc.) are not measured. The upper part of Figure 11 shows the measured airborne noise at $M_2 = 400$ Nm as a frequency spectrum. Similar to the evaluation of the differential acceleration, the airborne noise shows that with an increasing chaotic deviation of the gear geometry from tooth to tooth, the dominant peaks in the form of the amplitude of the gear mesh orders are lowered. At the same time, the background noise increases. For a better evaluation of the change in airborne noise emission, the lower part of Fig. 11 shows the respective order spectra and the percentage change relative to the REF in the amplitudes of the first four gear mesh orders.

The observed characteristics during dynamic excitation are also reflected in the noise behavior. With increasing chaotic gear geometry in the form of the pitch error and the micro geometry, less and less strongly dominant peaks appear in the frequency or order spectrum.

Psychoacoustics

In addition to the physical excitation, a psychoacoustic evaluation was carried out on the basis of the airborne noise measurement with the metrics tonality according to the Sottek hearing model (Ref. 14) and loudness according to DIN 45631/A1 (Ref. 15).

Psychoacoustic Metrics for the Evaluation of Human Noise Perception

The loudness describes the frequency-dependent sensitivity of human noise perception and has the unit sone, see Figure 12. DIN 45631/A1 describes a standardized procedure for determining loudness based on a loudness comparison between sinusoidal tones and noises (Ref. 15). Thus as shown in the audible frequency range according to Zwicker is divided into 24 frequency groups (0 bark to 24 bark) and the respective sound level is weighted according to the human hearing sensitivity. The method is suitable for comparing the loudness of noises with different spectral resolution (Ref. 16).

An essential feature for the characterization of gear noise is the tonality. Noise is perceived as annoying if they are composed of individual, strongly pronounced tones or narrow band frequencies. The Sottek hearing model is used to determine tonality. Previous algorithms for calculating tonality did not take into account or did not take sufficient account of short-term changes in tonality due to the low time resolution. In addition, tonalities below the hearing threshold are considered, although they are irrelevant for the human hearing. The new method according to Sottek includes the human hearing limit and the dependence of noise perception on psychoacoustic loudness. The method determines the loudness of tonal and non-tonal noise components using a permanently performed autocorrelation function. By means of a high temporal resolution, short-term and strongly fluctuating tonalities can be examined. The algorithm also allows the strength and frequency of the tonality

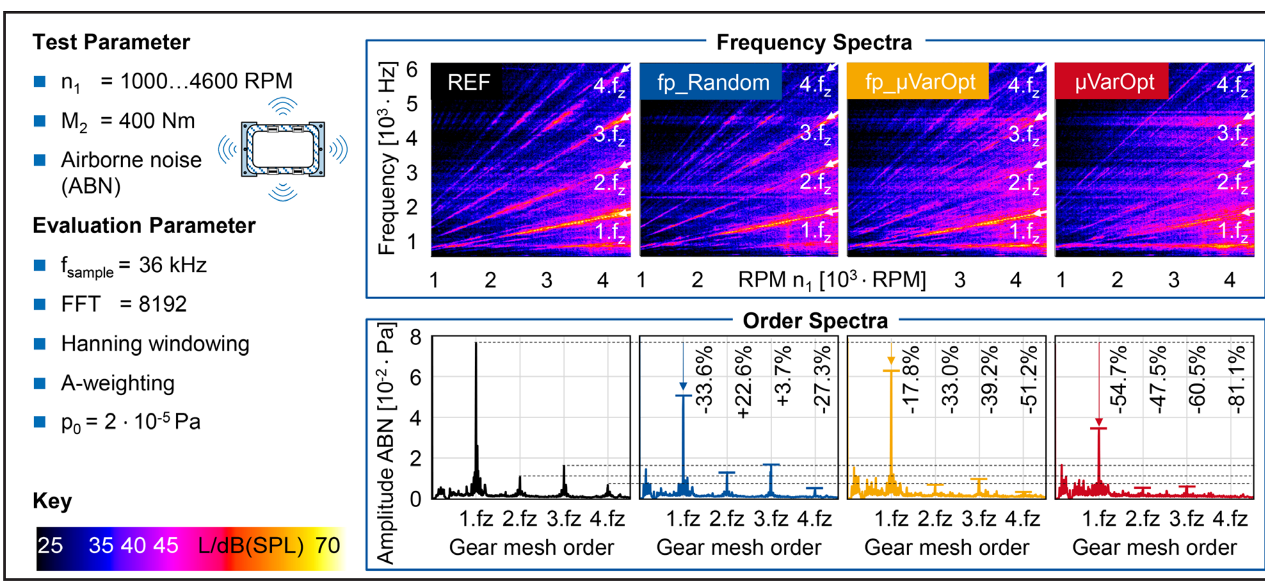

Figure 11 Physical noise behavior at $M_2 = 400$ Nm.

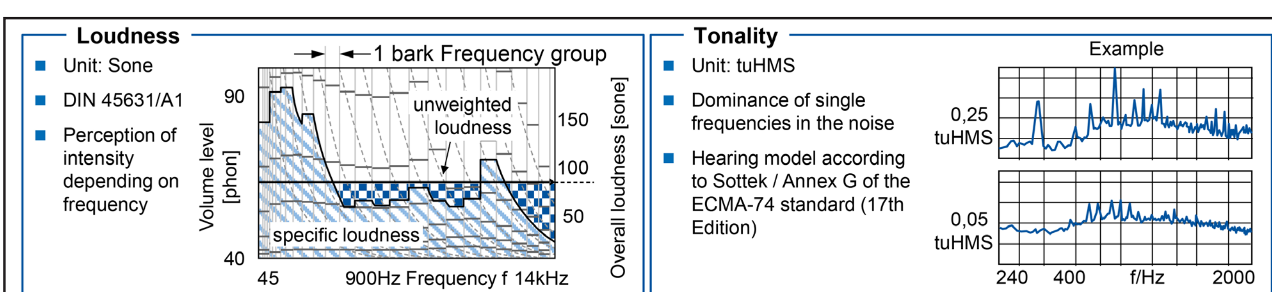

Figure 12 Psychoacoustic metrics: loudness and tonality.

to be determined relative to the time and rotational speed. The tonal value according to the Sottek hearing model is described in the unit tuHMS (Ref. 14).

For this purpose, Annex G of the international standard ECMA-74 (17th Edition) describes a perception-based method developed by HEAD acoustics for the automatic detection and classification of tonal components and their characteristics in noise emissions (Ref. 16). The criterion for prominence of tonalities for the psychoacoustic tonality calculation method according to Sottek is independent of frequency 0.4 tuHMS (Ref. 14). Tonality is hardly perceptible below the value of 0.4 tuHMS (Ref. 16).

Both psychoacoustic metrics loudness and tonality have a linear scale of intensity (Refs. 15, 17). In addition, the metrics were developed and validated in extensive listening tests (Refs. 14–16).

Psychoacoustic Evaluation of the Noise Behavior

For the psychoacoustic evaluation of the variants, the tonality and loudness of the airborne noise signal is evaluated as a single value in each case, see Figure 13, upper part. This allows the load-dependent behavior to be analyzed. In addition, the arithmetic mean was calculated for all load levels.

The lower part of Figure 13 shows the behavior of tonality and loudness as a function of speed for the design torque $M_2 = 400$ Nm. For tonality, the arithmetic mean was always evaluated. For loudness, the 5-% percentile N_5 of the loudness spectrum was calculated. The 5-% percentile as a single number value gives a better impression of the subjective perception of loudness as in the case of transient noises, because human perception focuses on the loudest noise components (Refs. 19, 20).

The evaluation of the tonality shows that already with a stochastic pitch error course the tonality can be reduced by 5.2% with the variant fp_Random and by 7.8% with variant fp_μVarOpt on average. A combination of stochastic pitch error course and a specific design of a micro geometry scattering, as with variant μVarOpt, has significantly reduced the tonality by 36.1% on average. In the design torque $M_2 = 400$ Nm, the tonality could be more than halved by 55.8%. In the course of the tonality over the speed it can be seen that the variant μVarOpt is partly below the limit value of 0.4 tuHMS. Analogous to the evaluation of the quasi-static and dynamic gear excitation, a shift of the significant excitation minimum for μVarOpt is also visible for the psychoacoustic metrics tonality and loudness.

In the case of loudness, similar courses of the 5% percentile N_5 are shown compared to tonality. However, the variants fp_μVarOpt and μVarOpt are partly louder. The variant fp_Random is quieter than the reference at every load level and is on average 8.3% quieter. The variant fp_μVarOpt is on average 2.3% louder and the variant μVarOpt is 1.5% quieter. In the design moment of μVarOpt, the loudness could be reduced by 11.6%.

Summary and Outlook

In this report, a simulation model was generated to model the quasi-static excitation behavior of cylindrical gears with stochastic deviations over the circumference of the pinion and gear. The simulation model is capable of realistically modeling the loaded transmission error (LTE) of cylindrical gears with a stochastic pitch error curve as well as a stochastic scattering of the micro geometry. The simulation results were validated on the basis of tests on the test rig. With this validated simulation model, more in-depth investigations could be carried out to build up an understanding of the effect of stochastically scattered geometric deviations on cylindrical gears on the excitation behavior. It was shown, for example, that for the gearing and a torque range up to $M_2 = 500$ Nm, a stochastic scattering of the pitch error with a maximum amplitude of the IT6 quality class is significantly improved noise characteristics. It was shown that a stochastic pitch error course in low load range up to $M_2 = 60$ Nm generated a stronger reduction of the amplitude of the first gear mesh order 1.fz of the loaded transmission error than that of a micro geometry scattering in the same IT quality class. The positive effect of a stochastic pitch error decreases with increasing load. From a load of $M_2 = 60$ Nm, the variant with a micro geometry scattering shows greater effects for increasing the gear mesh order 1.fz of the loaded transmission error $\Delta\varphi_{LTE,1.fz}$. The combination of stochastic pitch error curve and a micro geometry scattering shows the best results for improving the noise characteristics. This phenomenon was also observed in test rig investigations. The experimental results

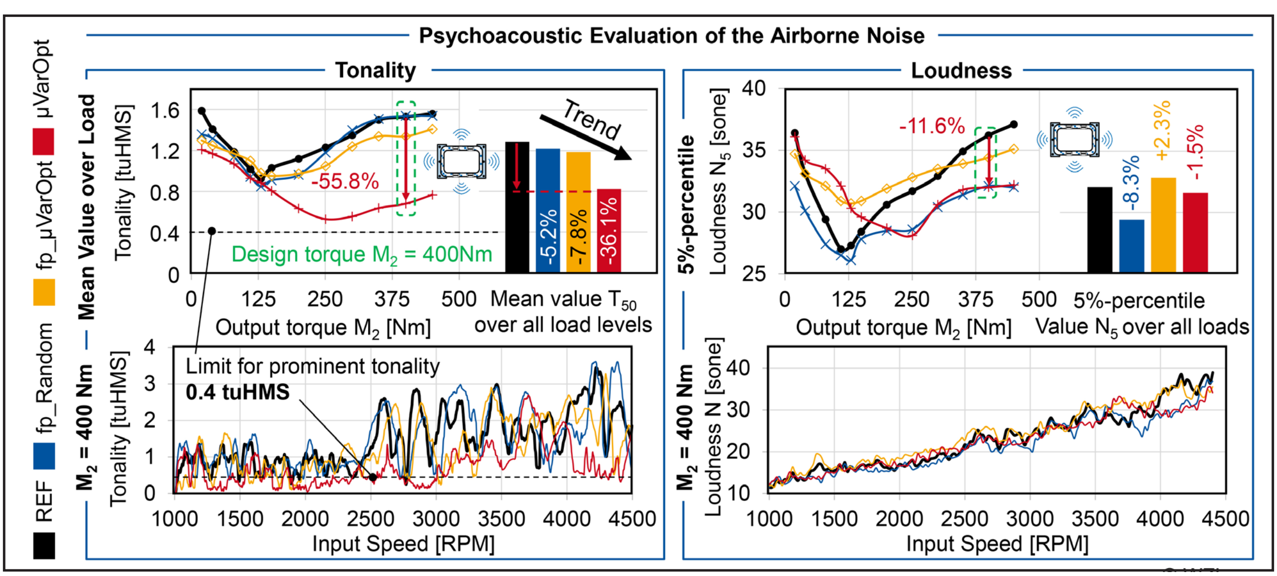

Figure 13 Psychoacoustic evaluation of the airborne noise.

of the noise behavior show that a stochastic pitch error curve can reduce the tonality of the airborne noise by 7.8% on average and the combination of chaotic scattering of the pitch and the micro geometry by up to 36.1% on average. On mean, the loudness increased by 2.3% for the variant with only stochastic pitch error and decreased by 1.5% for the variant with stochastic pitch and microgeometry scattering. "Controlled chaos" can significantly improve the noise characteristics of gears. In general, both the simulation results and the experimental results show that an increase in stochasticity in its expression and amplitude for deviation at the pinion and gear goes is related to with noise-optimized excitation. However, the simulation results also show that an oversized stochastic pitch error curve can also cause a decrease in the amplitude of the first gear mesh order 1.fz of the loaded transmission error $\Delta\varphi_{LTE,1.fz}$. In conclusion, when optimizing the noise characteristics of cylindrical gears by a stochastic scattering of the target geometry, it is important to control the generated chaos. The limits of reliability must be designed precisely so that it leads to an improvement and not to a deterioration of the noise characteristics.

In future work, the possible advantages and disadvantages of micro geometry scattering with regard to tooth flank load capacity must be analyzed in experimental studies. For this purpose, gears with and without targeted micro geometry scattering will be examined in the back-to-back test rig for their pitting load capacity. In addition, future continuous manufacturing processes will be modified so that targeted micro geometry scattering can be produced.

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