# NOISE ANALYSIS FOR E-DRIVE GEARS

## AND IN-PROCESS GEAR INSPECTION

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## It is important to have analysis tools capable to detect potential noise issues and to distinguish between manufacturing and design reasons.

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E-drive gears differentiate from other automotive gears by two essential points: higher quality and the need for an excellent noise behavior.

Gear noise can have many causes. When gear noise issues occur, many people start to look for the causes in the manufacturing process only. However, this is not always the root cause. In order for a gearing system to function quietly, it must first be designed properly according to the load characteristics that will appear later in the real gearbox. Hence, gear design assuming ideal conditions, i.e., parallel axes, is no longer a guarantee for a quiet gear design. A much better approach is to employ loaded tooth contact analysis considering the true gear geometry, realistic loads, and deformations of the gearbox elements.

Even perfectly designed gears are subject to manufacturing errors that can also lead to gear noise often called “ghost noise.” Hence, it is important to have analysis tools capable to detect potential noise issues and to distinguish between manufacturing and design root causes. The gear inspection thus has another important task, namely the reliable detection of potential noise issues.

Typically, in conventional gear manufacturing, quality control is carried out randomly, with only a few parts actually inspected. This is mainly due to the significantly longer measuring times in comparison to the actual production time and limited overall measuring capacity to cope with increased inspection demands. In order to guarantee process reliability, statistics are instead used to validate the process, resulting in a significant reduction of the permissible manufacturing tolerance in comparison to the drawing tolerance.

In addition, constantly increasing power density requirements and the growing importance of excellent noise behavior of transmissions, especially in new e-drive concepts, has resulted in very tight tolerance requirements. Relying on statistical evaluation makes the production of such gears more challenging and expensive.

An inspection concept developed by Gleason called “GRSL” (Gear Rolling System with Integrated Laser Technology) features the possible combination of double flank roll testing and laser scanning. With this completely new approach, inspection now can be performed in parallel at the same speed to the time required for the hard finishing operation. As a result, 100-percent, in-process inspection has become a reality, eliminating the need for statistical process evaluation. In addition, the measured data can be further evaluated concerning waviness in profile, lead and/or line of contact direction, which allows the evaluation of the noise behavior; hence, this new system allows to do an up to 100-percent, in-process noise analysis prediction of the finished gear. And even more, the measured gear deviations can be fed back into the design software to run a loaded tooth contact analysis under real conditions including the gear geometry with manufacturing errors superimposed.

This new revolutionary inspection concept has been integrated with a modern threaded wheel grinding machine and a fast and flexible automation system to create the HFC (Hard Finishing Cell), which features an automated closed-loop correction system.

### 1 GEAR NOISE

Transmissions in e-drive vehicles are more sensitive concerning gear-noise issues than those used with conventional internal combustion engines (ICE) for two main reasons: First, the input RPM of the electric motor, which can go up to 30,000 RPM or even 50,000 RPM [1] is significantly higher than that of a combustion engine, which, depending on the fuel technology (diesel vs. gasoline), goes to max 5,000 to 8,000 RPM. This increases the potential excitation spectrum by a factor of 3 to 10 [2]. Secondly, the masking noise of the combustion engine itself has disappeared, which made noise from the drivetrain not seem so prominent. Hence, understanding and influencing potential gear noise sources is more important than ever.

The noise or sound of a gearbox that we hear starts as a vibration excited in the gear mesh. This vibration is transmitted as a structure borne noise through the mechanical elements such as shafts, bearings, etc., to the housing, which acts as a resonance body or loudspeaker. The generated airborne sound finally reaches the human ear.

Different excitation sources, including the gear mesh, torque ripple from the electro motor, shaft imbalance, or the bearings, are present. In this article, we will focus on the gear mesh as source. The root causes of the excited vibrations in the gear mesh are again manifold. For example, a non-uniform tooth meshing leads to a variable meshing stiffness, which can be influenced positively or negatively by tooth flank modifications in profile and lead, whether they are desired or undesired, such as manufacturing errors. In addition, as a result of the applied load, elastic deformations of the teeth, shafts, and housing can lead to a premature and/or prolonged tooth engagement and thus to a further source of vibration.

Finally, surface structures on the tooth flank itself

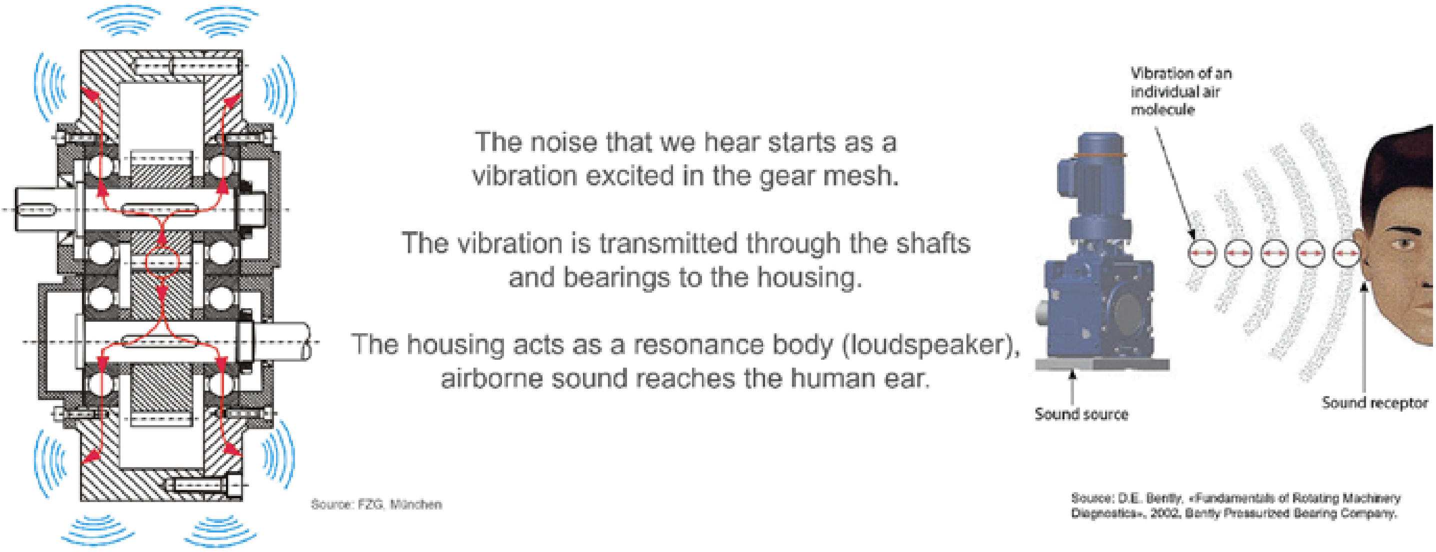

Figure 1: Noise generation and transmission.

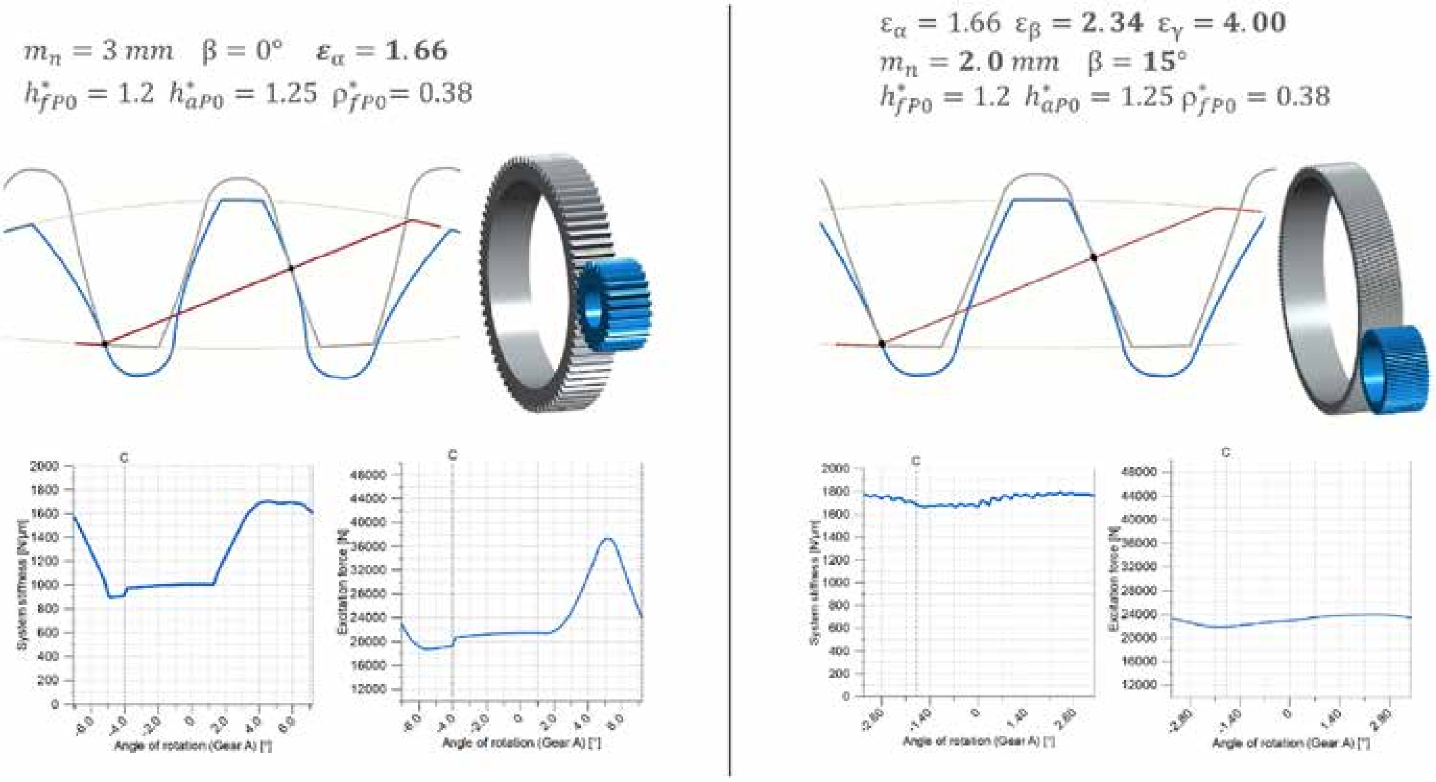

Figure 2: Influence of contact ratio on system stiffness and excitation force.

as well as manufacturing errors/irregularities also lead to small deviations and can have a noise-impacting effect.

## 2 GEAR NOISE OPTIMIZATION IN GEAR DESIGN

In order for a gearing system to function quietly, it must first be designed properly according to the load characteristics, which will appear later in the real gearbox. Today, modern design tools are available for this purpose, with which the gears and other transmission components can be designed for optimum behavior including a quiet noise characteristic.

The KISSsoft® design tool provides a multi-stage process for optimizing the gears. First, the macro geometry of the gears is designed by using the "fine sizing" tool. This tool calculates hundreds of different but possible solutions according to certain design criteria. Often, solutions for the highest possible and integer contact ratios, traverse contact ratio $\varepsilon_\alpha$ and overlap ratio $\varepsilon_\beta$, resulting in total contact ratio $\varepsilon_\gamma$, are sought. As a rule, this leads to fairly constant system stiffnesses during the tooth meshing if the theoretical values as well as the values under load are calculated. This again is desirable because it leads to a constant course of the excitation forces and thus to constant transmissions errors, which are the actual cause of noise emission. Figure 2 compares the effects of two different designs on the system stiffness and the resulting excitation forces. The left part shows a design of a spur gear according to a standard DIN rack profile with tooth height of 2.25 x $m_n$. The traverse contact ratio is only $\varepsilon_\alpha = 1.66$. The resulting system stiffness along the tooth mesh varies greatly from 900 to 1,700 N/µm. Consequently, the excitation force also shows a correspondingly strongly fluctuating behavior. To the right, a helical variant is

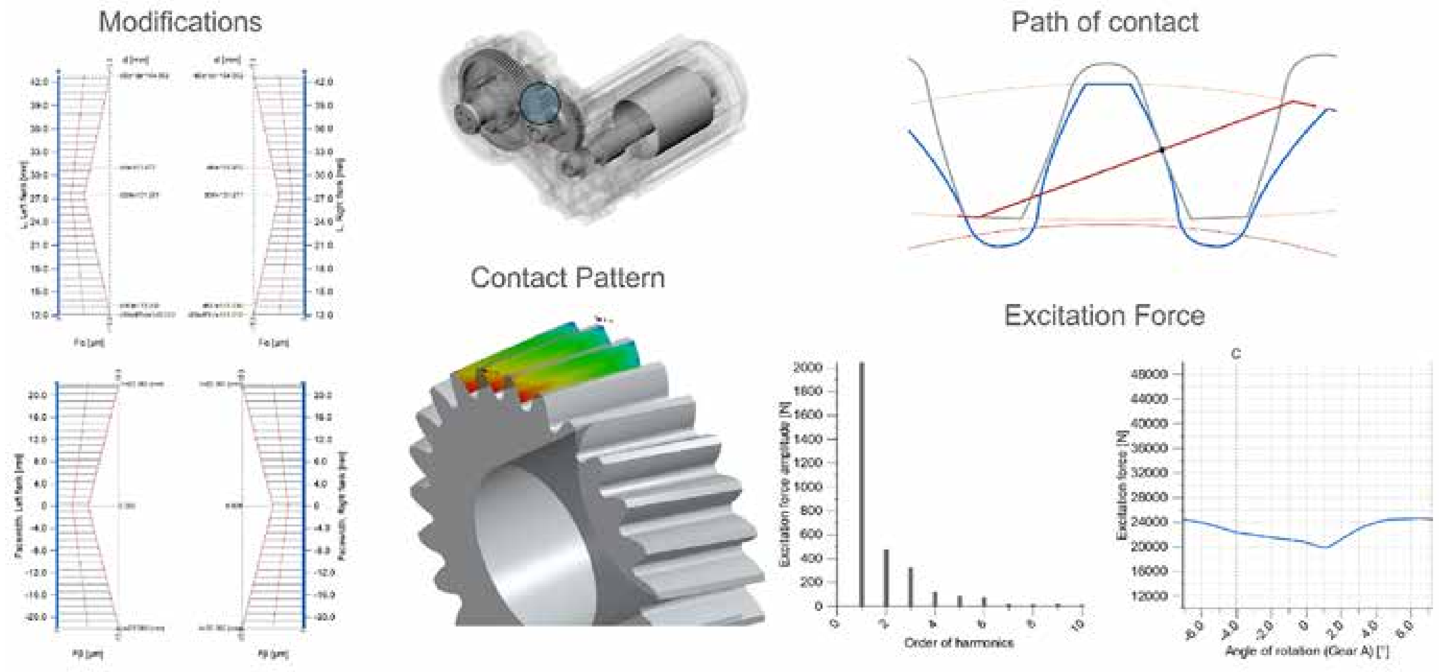

Figure 3: Loaded Tooth Contact Analysis results without modifications.

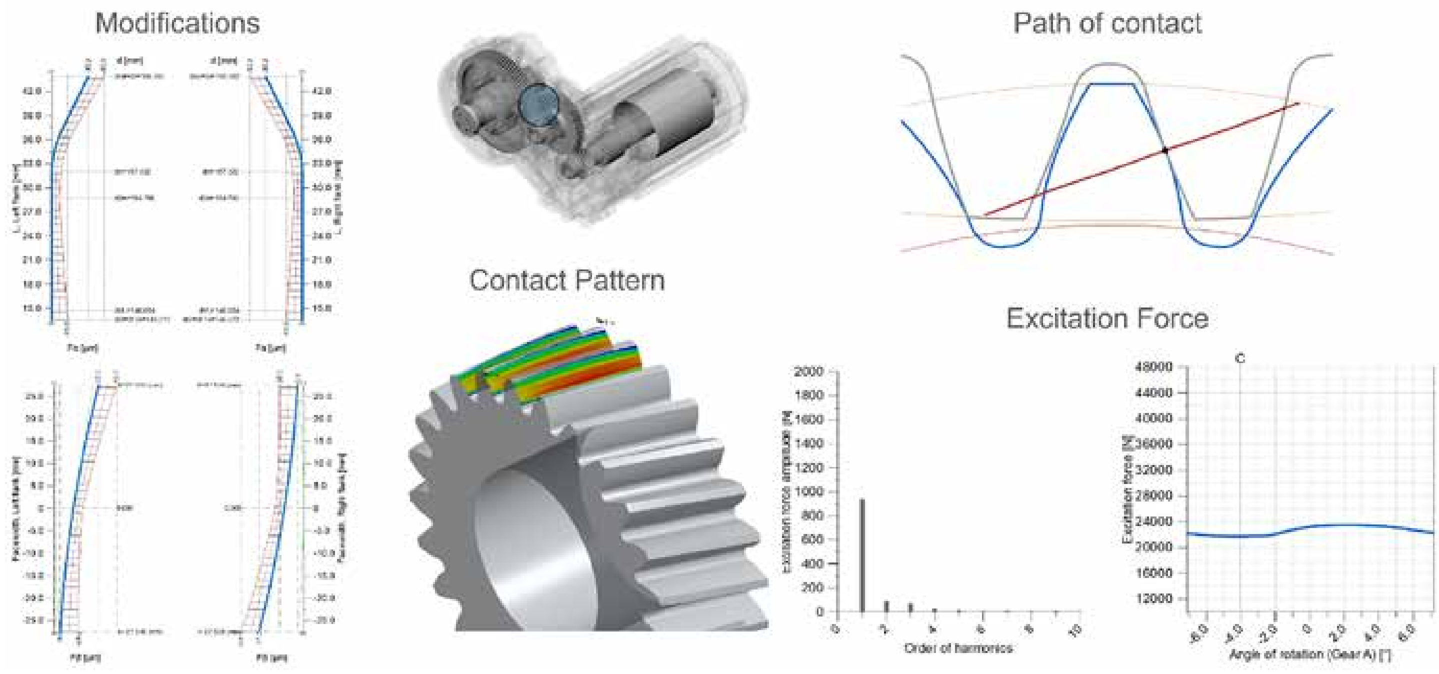

Figure 4: Loaded Tooth Contact Analysis results with lead and profile modifications.

shown, which, with a corresponding overlap ratio of $\varepsilon_\beta = 2.34$, results in a total contact ratio of $\varepsilon_\gamma = 4.00$.

As a result of this change, both the system stiffness and the excitation forces showed a nearly constant trend over the tooth mesh.

However, since this design step does not consider loads and the resulting deformations of the components, the next step is to take them into account. In the loaded tooth contact analysis (LTCA), the deformation of the teeth and the system components are calculated under real loads resulting in changed contact pattern, transmissions error, excitation forces, etc. In this step, the contact pattern is also optimized by selecting suitable modifications. For example, load concentrations in lead direction caused by shaft, housing, gear body, or bearing deformation are usually corrected by applying flank line modifications. Profile modifications, on the other hand, help to correct premature and/or delayed tooth engagement caused by tooth bending. They are also favorable to reach fairly constant transmission error for different torque levels [4]. Profile crowning and/or tip relief with a parabolic smooth transition are often used here. The results of a successfully performed loaded tooth contact analysis are shown in Figure 3 and Figure 4.

Figure 3 initially shows the unmodified case. The calculated contact pattern clearly shows excessive loads on side I (left side), especially in the tooth root area where the radius of curvature is smaller. In addition, the path of contact displayed shows an extended tooth engagement. All this results in the excitation forces shown below right along the angle of gear rotation and as corresponding order harmonics. One can clearly see fluctuating excitation forces during tooth meshing, which are also expressed in very pronounced order harmonics.

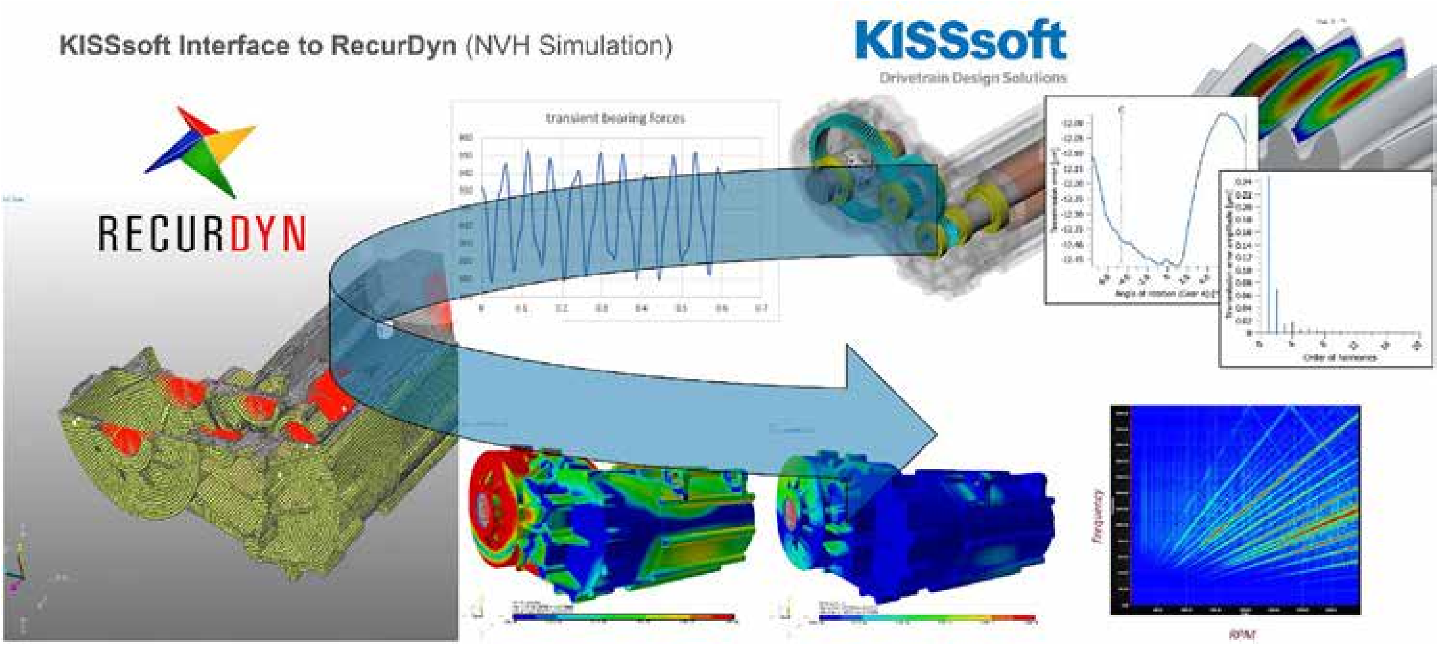

Figure 5: NVH Simulation: Excitation calculation in KISSsoft, response calculation in Recurdyn.

In contrast, Figure 4 shows the situation after an optimization. On the one hand, flank line modifications were selected to avoid the excessive load on side I and, on the other hand, profile modifications (crowning plus tip relief) were selected to achieve a uniform contact pattern. The prolonged tooth engagement has thus been eliminated, which can be seen very clearly in the path of contact. In addition, the graph of the resulting excitation forces now shows a much more constant curve, which is also very clearly reflected in the order harmonics shown next to it. The first order harmonic was halved while the higher harmonics could be reduced even further.

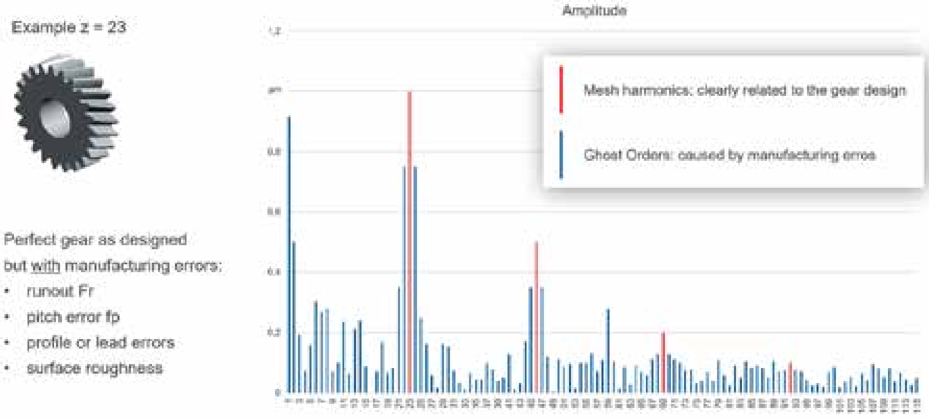

Figure 6: Example of an order analysis of a gear with 23 teeth.

In order to finally determine the effects of these excitation forces on the noise radiation of the gearbox, KISSsoft features an interface to Recurdyn, a multi-body simulation software. The force excitation curves at the corresponding bearing points for different RPMs are calculated in KISSsoft, transferred to the Recurdyn gearbox model, which simulates the sound radiation behavior at each point of the gearbox housing and calculates Campbell diagrams (Figure 5). A very impressive example of such an NVH simulation and optimization was described by Marano et al [3].

Although the advances in the simulation of noise behavior are impressive, they still do not consider manufacturing-related sources of error. It is known from practical experience that the smallest deviations and waviness on the tooth flanks can lead to disturbing influences in the noise behavior. In addition to simulation tools, other analysis methods are therefore used to check the noise behavior. A very well-known and meaningful method is the single flank roll testing (SFT). Here, the gear to be tested with all its manufacturing defects is either rolled against a master gear or against the actual mating gear on one flank, the real rotational deviations are measured and then analyzed. It is common to transform the time signal of the rotational deviations into the frequency domain resulting in an order analysis.

An example of an order analysis of a gear with 23 teeth is shown in Figure 6. First of all, distinct amplitudes at the 23rd order and its multiples can be seen (red amplitudes). These are also referred to the harmonics of the tooth meshing frequency. These also could be simulated and largely influenced in the design phase using KISSsoft. However, numerous other orders also can be seen, which lie between the meshing harmonics. These orders are often also called "ghost orders" because they cannot be clearly traced back to the gear geometry or its number of teeth. What they have in common is that all these orders clearly come from manufacturing errors such as pitch errors, runout deviations, profile and flank line deviations, waviness, etc. A typical radial runout Fr, for example, shows up as first order and typically occurs as sidebands next to the mesh harmonics. The prominent 59th order in this example could be a critical ghost order resulting in a noise issue on that particular gear. This method (SFT) also allows axle misalignments to be set and different loads to be applied and tested as they occur in the real gearbox. The disadvantage is additional testing equipment in the form of a single flank roll testing machine is required. Therefore, methods have been developed in recent years to develop such order analyses from analytical measurements based on standard measurement equipment that is available anyway. A well-known method is the so-called waviness analysis, which is described in more detail in Section 4. The disadvantage of this method is that the real tooth meshing is only simulated based

on measurement data, and the measurement time required for this is very high. Therefore, this method has not been suitable for testing in series production to date.

## 3 TRADITIONAL GEAR INSPECTION – TODAY AND IN THE FUTURE

In conventional gear manufacturing, quality control is carried out for a number of pieces per batch. The majority of parts enter final gearbox assembly without any inspection. Among other things, this approach is based on two facts: Measuring time is significantly longer than the machining time and the limited measuring capacity available. In hard-fine finishing, for example, continuous generating grinding, it is not unusual to measure only one or two workpieces per dressing cycle or directly after the machine setup.

Depending on the dressing cycle, the number of inspected parts corresponds to only about 5 percent of workpieces produced in total (Figure 7). However, in order to guarantee almost 100 percent reliability, statistical evaluation is instead used to validate the gears being produced. Typical measuring characteristics can be represented and statistically evaluated on a Gaussian bell curve. By deliberately narrowing down tolerances on the measured components in particular, it is possible to guarantee compliance with the actually required drawing tolerances with a sufficiently high probability (typically > 99.99994 percent). This method is commonly used for machine and process capability studies and is globally recognized [5]. The machine or process capability values $c_{mk}$ and $c_{pk}$, requently taken as a basis, are usually set above 1.67.

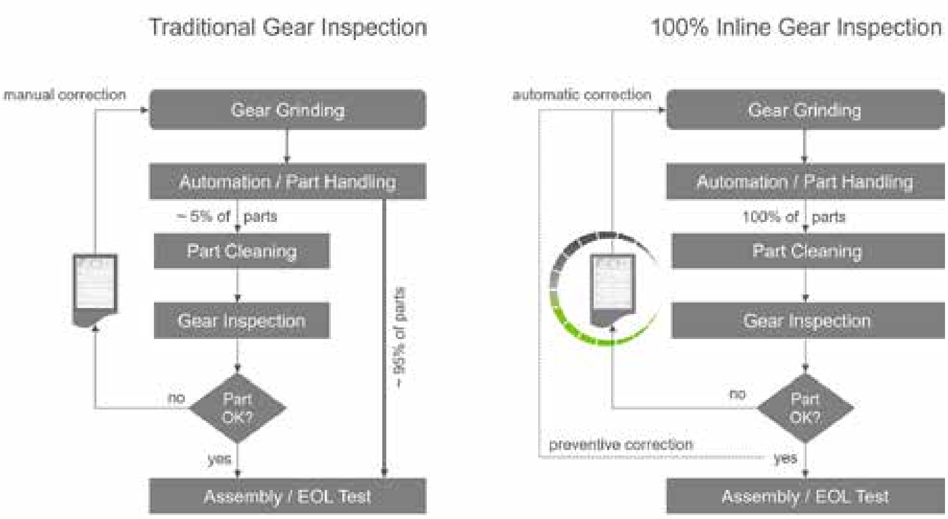

Figure 7: Traditional gear inspection vs. 100 percent in-process gear inspection.

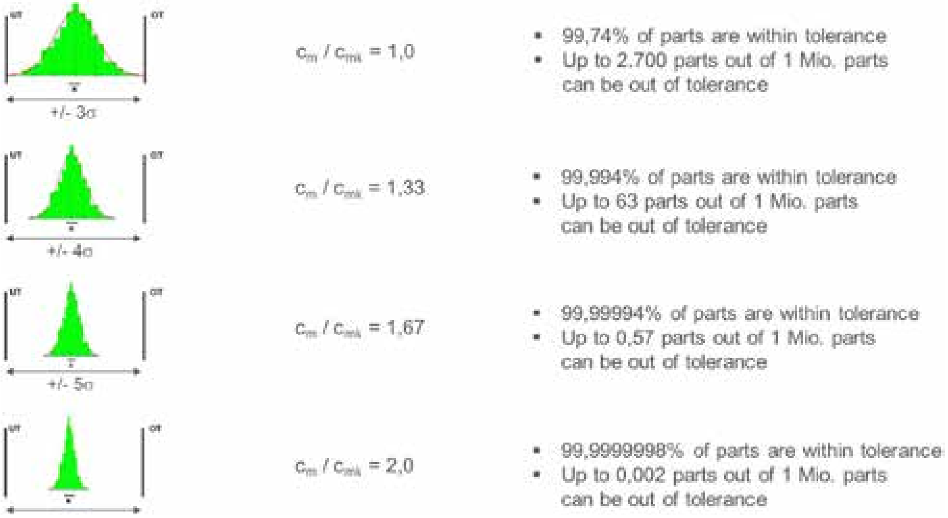

Figure 8: Influence of capability values on probability to match the tolerance.

Statistically, the reject rate is only 0.57 workpieces per 1 million manufactured workpieces, which means that only about 50 percent of the actually intended drawing tolerances are available as manufacturing tolerances (Figure 8.). This situation is aggravated by the fact of increasing quality demands, especially with e-drive gears, due to NVH and other topics leading to increasingly tight tolerances. Clearly, this high dependency on statistics poses a significant challenge to a growing number of gear manufacturers.

Another problem of traditional gear inspection is the long (waiting) time between part removal for inspection and the actual availability of measured results. Waiting and inspection time can easily amount to between 30 to 45 minutes depending on the inspection room capacity. After inspection, a decision must be made as to whether a correction of machine settings is necessary. The implementation of such corrections must be carried out by the machine operator, taking additional time, all while the production is continuously running, good or bad. So far, today, focus has been given to establishing a "closed loop" connection between the metrology system and the production machine, installing the measuring machine in close proximity to the production machine, e.g., by employing so called "shop-hardened" metrology centers.

Now, how would an ideal solution to overcome the described challenges look like? Ideally, all parts could be inspected immediately after they have been produced (Figure 7), bearing various advantages. The quality achieved on each workpiece could be documented. Workpieces out of tolerance could be corrected immediately by a closed loop auto correction system. And even better, by inspecting up to 100 percent of parts, one could also monitor trends and apply preventive corrections before parts are getting out of tolerance. The ultimate goal would result in predicting whether a workpiece could cause noise issues within the gearbox after its assembly.

So, key to creating an ideal situation is a metrology system capable of inspecting gears as fast as they are produced and that can easily be installed close to the production machine.

## 4 IN-PROCESS GEAR INSPECTION – ROLL TESTING AND LASER INSPECTION

In 2018, Gleason introduced a very special metrology system GRSL [5]. The GRSL combines the latest non-contact analytical gear inspection with well-proven, double-flank roll testing of gears applied in most of today's high-volume gear production environments in order to achieve 100 percent inspection of specific variables (Figure 9). But the GRSL is much different than these traditional systems. It measures both the composite functional error by double flank roll testing with a master gear as well as the individual gears characteristics of involute, lead, and index error by applying laser-scanning technology.

During the roll testing cycle, two laser heads move automatically

Figure 9: GRSL – Multiple inspection methods combined in one platform.

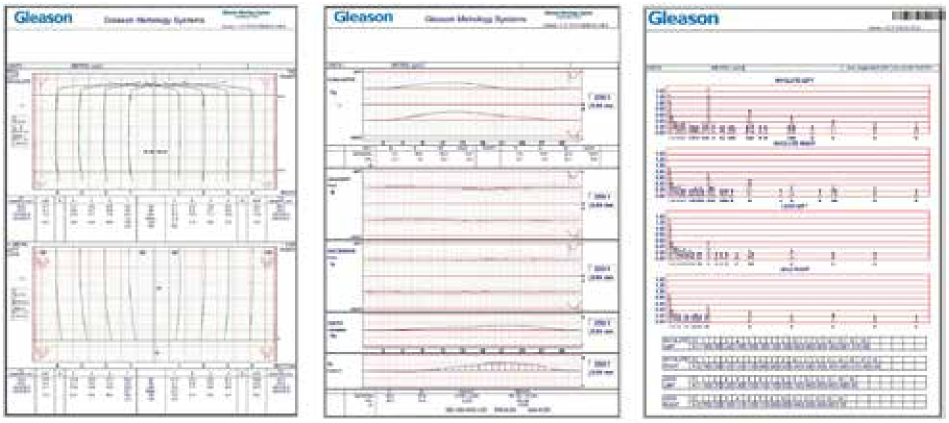

Figure 10: Chart possibilities of a GRSL including advanced waviness analysis.

Figure 11: Hard Finishing Cell (HFC).

into position to scan both gear flanks (left and right) simultaneously. In addition, different sections along the face width of the gear can be scanned to inspect even the lead. With laser technology, the overall inspection time is significantly reduced compared to a standard tactile measuring system. Example: The inspection time required for a typical, automotive planetary pinion can be reduced with laser technology by a factor of 4, from roughly 2.7 minutes down to 39 seconds. With the inspection time being greatly reduced, this process can even add additional value by measuring profile and lead on all gear teeth — not just the usual inspection of only four teeth around the circumference of the gear.

With such comprehensive data available through laser scanning, it is also possible to further evaluate gears beyond standard gear inspection habits such as profile, lead, pitch, runout, and size. In addition, the 3D laser used on the GRSL gather much higher density data at higher speeds than a traditional tactile probe. The gear flank area seen and scanned by the laser probe at any given instance during the measurement is much higher than using a contact probe. The contact probe simply makes a point contact while the laser has a line that is typically upwards of 7mm scanning measurement area at high frequency with sample spacing of microns. This captures a large surface area of gear with higher density at much faster inspection times. Such a high-density measurement of the entire surface is simply not practical to achieve with a tactile probe. For a typical 2D trace such as profile or lead trace used for gear measurement, 3D laser probe captures 10-plus times more data points at much higher speeds than with a conventional tactile contact probe.

Understanding the profile and lead of all teeth makes it possible to calculate a so-called “advanced waviness analysis” resulting in an order analysis of the gear topography (Figure 10). In contrast to the traditional gear measurement technique, where periodic components or waviness are only captured as form errors ffa or ffb in the profile and/or flank line, advances waviness analysis goes far beyond this.

Advanced waviness analysis evaluates periodic errors in the profile, the flank line, or the pitch according to their frequencies/orders and their amplitudes and essentially corresponds to the waviness analysis according to VDI/VDE2612 [7]. Measured profile and/or flank lines of all teeth are first connected to each other along the correct path of contact. The obtained “signal” represents a theoretical transmission error and is then decomposed into its corresponding components (frequencies/orders and amplitudes) either by an FFT or with the aid of a Gaussian least square method.

An example of such an analysis can be seen in Figure 10 on the right. Order analyses are shown for the profiles (involute) and flank lines (lead) on the right and left tooth flanks. The lower section of the chart summarizes the most conspicuous orders and amplitudes in table form. This allows to quickly distinguish between mesh harmonics, mainly influenced by the gear design and other orders, so called ghost orders that typically have their root cause in manufacturing errors.

Whereas, in single flank roll testing, the actual transmission error between gear and master gear is detected and displayed as an order analysis, in advanced waviness analysis, the transmission error is calculated from measured profile data. This method has been put to use for years and provides the advantage of employing existing analytical inspection equipment rather than an additional single flank roll tester. However, this process bears a specific disadvantage: It takes a long time (on a standard metrology system) to determine profile data of all teeth required for calculating the order analysis. With Gleason’s GRSL, it is this very profile data that can be acquired extremely quickly, eliminating the disadvantage of analytical inspection. With the calculated order analysis and its corresponding amplitudes (advanced waviness analysis), it is possible to detect potential noise issues such as ghost orders [6]. These orders are not related to the mesh harmonics of the gear and are typically caused by small irregularities created during the manufacturing process or by the production machine itself. Such ghost orders can cause problems once they exceed a specific amplitude. To date, such order analyses are carried out on a random basis only due to the high inspection effort involved.

With advanced waviness analysis and the possibility to inspect up to 100 percent of the production output, it is now possible to evaluate every produced gear regarding potential noise issues, sorting out nonconforming gears before they are assembled into the gearbox. This is a novelty in the gear industry and a game changer especially for the inspection of e-drive gears, since e-drive applications are particularly noise sensitive.

## 5 INTEGRATING METROLOGY INTO THE PRODUCTION FLOW

Gleason's hard-finishing cell (HFC) seamlessly integrates in-process metrology into the manufacturing process. This fully automatized manufacturing cell features threaded wheel grinding (Figure 11 [8]: Gleason 200/260GX), washing, part marking and a GRSL metrology system, all connected by a robotic loader with a basket-based palletizer system. The integrated automation is made by Gleason's own automation solution provider. The gantry loader is handling the complete workflow within the cell, including part handling between grinding machine, washing and part marking stations, as well as the metrology system.

The stacking cell accommodates baskets of various manufacturers and styles and is ideally suited for the autonomous processing of large lot sizes of gears.

The 200/260GX uses a double spindle concept to bring down nonproductive idle times to an absolute minimum with less than four seconds workpiece change time. Machine setup is extremely easy and fast using Gleason's Quik-Flex® Plus Workholding, just one tool for the exchange of all mechanical components and a menu guided workflow for all necessary setup steps.

In addition to four different dressing systems for highly productive or flexible production, today's quality demands require modern grinding processes. This includes the possibility to grind gears with extremely good surface quality and twist control. A novelty in the industry is that neither grinding nor dressing times are negatively affected by Gleason's twist-controlled grinding process [9].

Gleason's closed loop system connects the grinding machine with the integrated GRSL metrology center. Inspection results are directly returned to the grinding machine without any involvement of the operator. The machine compares the measured values with the target nominal values and automatically performs the necessary corrections. With the GRSL being directly integrated in the hard finishing cell, results are available right after the workpiece has been ground, typically in less than five minutes.

Compared to the traditional approach of gear inspection in a separate inspection room, reaction time is dramatically reduced. And most probably the biggest advantage is that with this new system, for the first time ever it is now possible to evaluate every produced gear for potential gear noise issues by using the advanced waviness analysis.

## 6 SUMMARY

E-drive gears differentiate from other automotive gears by two essential points: higher quality and the need for an excellent noise behavior.

Gear noise can have many causes. When gear noise issues occur, many people start to look for the causes in the manufacturing process only. However, this is not always the root cause. In order for a gearing system to function quietly, it must first be designed properly according to the load characteristics that will appear later in the real gearbox.

Even perfectly designed gears are subject to manufacturing errors that can also lead to gear noise often called "ghost noise." Hence, it is important to have analysis tools capable to detect potential noise issues and to distinguish between manufacturing and design reasons. The gear inspection thus has another important task, namely the reliable detection of potential noise issues.

Gleason's Hard Finishing Cell provides the capability to inspect up to 100 percent of workpieces with a fully integrated GRSL double flank roll tester and laser scanner. The ground gear is transferred to the GRSL for inspection of all relevant gear characteristics including profile, pitch, runout, and — if desired — lead, in real time. In addition, advanced waviness analysis can detect gears with potential noise issues such as ghost orders.

Deviations determined in the hard finishing process are fed back directly into the production machine by means of a closed-correction loop. If deviations are within tolerance, fully automatic correction and real-time adjustment of the corresponding parameters can be automatically achieved. During traditional gear inspection, 45 to 60 minutes may pass between removing the workpiece from the machine, its transfer to the inspection room, waiting in line, the actual inspection process, and the analysis of the measurement result.

Compared to the conventional measuring process, HFC's in-process inspection and closed-loop correction ensure optimum quality in a fraction of the time. With up to 100 percent quality control, statistical evaluation can be eliminated from the manufacturing process, resulting in stringent compliance with tolerances according to original drawings.

## BIBLIOGRAPHY

[1] Mileti, M., Schweigert, D., Pflaum, H., Stahl, K.: "Speed4E: Hyper-High-Speed Driveline and Gearbox for BEVs," CTI Symposium, USA, May 2019.

[2] Stadtfeld, H. J.: eDrive Transmission Guide, The Gleason Works, 2020.

[3] Marano, D., Pascale, L., Langhart, J., Ebrahimi, S., Giese, T.: "NVH Analysis and Simulation of Automotive E-Axles," Gear Technology, January 2021.

[4] Dinner, H., Kissling, U.: "An Algorithm for Robust Gear Modifications Design," Gear Solutions, July 2012.

[5] Deininger, K.: "Combined Functional and Analytical High-Speed In-Line Gear Analysis," GETPRO International Conference, March 2019.

[6] Wagaj, P., Beerck, D.: "Gear Noise Analysis: Design and Manufacturing Challenges Drive New Solutions for Noise Reduction," Gear Technology, July 2019.

[7] VDI/VDE 2612, Measurement and testing of gears – Evaluation of profile and helix measurements on cylindrical gears with involute profile

[8] Türich, A.: "A single system for fast and high-quality production with up to 100 percent gear inspection – long the dream of many customers, and now a reality," Gear Solutions, February 2021.

[9] Kissling, U., Stolz, U., Türich, A.: "Combining Gear Design with Manufacturing process Decisions," Antriebstechnik, November 2009.

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