

Gear Noise Analysis: Design and Manufacturing Challenges Drive New Solutions for Noise Reduction

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Gear noise is among the issues of greatest concern in today's modern gearboxes. Significant research has resulted in the application of enhancements in all phases of gear manufacturing, and the work is ongoing. With the introduction of Electric Vehicles (EV), research and development in this area has surged in recent years. Most importantly, powerful new noise analysis solutions are fast becoming available.

Overview

Noise in a gearbox may be traced to various causes — to name a few:

- Gearbox design errors
- Gear pair transmission error
- Gear dimensional and surface quality
- Bearing and bearing journal quality
- Manufacturing and assembly variances
- External influences, such as radial and axial loads, and varying torques

In the design phase, proper kinematic and geometric gear design, along with mathematical modeling of gear systems, is done using state-of-the-art software tools to minimize gear noise at a later stage. In the manufacturing phase, tolerances of many gear characteristics such as index, lead and profile errors, along with other non-gear characteristics such as bearing surfaces and gearbox housing dimensions, are controlled to minimize noise.

In the final testing phase, traditional methods have been widely used to measure and study gear noise such as single-flank testers to test subassemblies (mating gear pairs under varying loads and/or speeds) and dedicated test rigs to test entire gearbox assemblies. These end-of-line testing systems have helped the gear industry capture and control valuable noise-related data. However, the downside here is the final noise

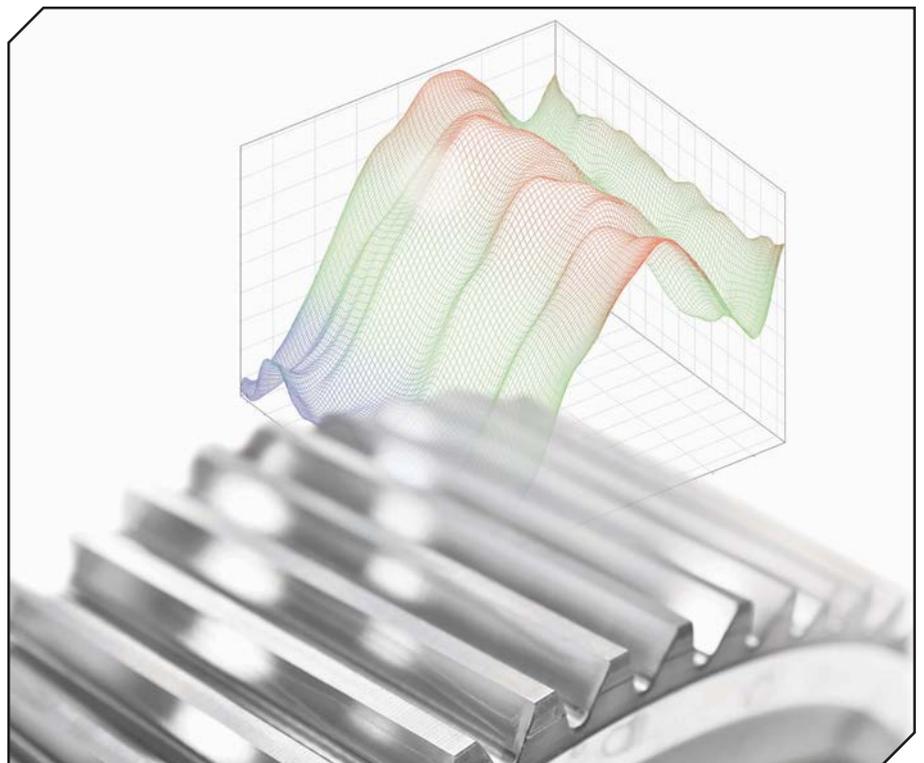
quality is determined at or near the end of the manufacturing process, with most of the manufacturing costs already incurred. Today's throughput targets require understanding what causes this phenomenon much earlier in the design and manufacturing process.

This article presents some of metrology tools Gleason has developed over the years to identify and control many of these noise sources. Its analytical machines (GMS, GMSP and GMSL series) provide a single platform from which users can measure, control and provide data to optimize gear manufacturing processes. All GMS series machines use Windows-based GAMA (Gleason Automated Measurement and Analysis) software. Many proven analysis tools are built into the GAMA software. Though the methods described in this article are mainly related to cylindrical gears, Gleason also provides similar solutions for bevel gears.

Traditional Methods and Analysis

Traditionally, gear measurement machines are used to inspect a few main characteristics on cylindrical gears: index, tooth size, lead and profile deviations. Many industry standards, such as ISO 1328, DIN 3960/62, China GB 10095, AGMA 2015 and JIS 1702, explain how to measure these characteristics, as well as providing tolerances based on the class of gears. Figure 1 and Figure 2 show typical chart output, displaying GMS GAMA measurement results with tolerances and gear class information.

These traditional measurements (index, lead and profile (involute)), assessed by comparison with published tolerances, provide quality information for a single gear. This is very useful in adjusting the manufacturing process for one gear type. In addition, they determine the quality class of a gear, which is required for commercial purposes in many cases.



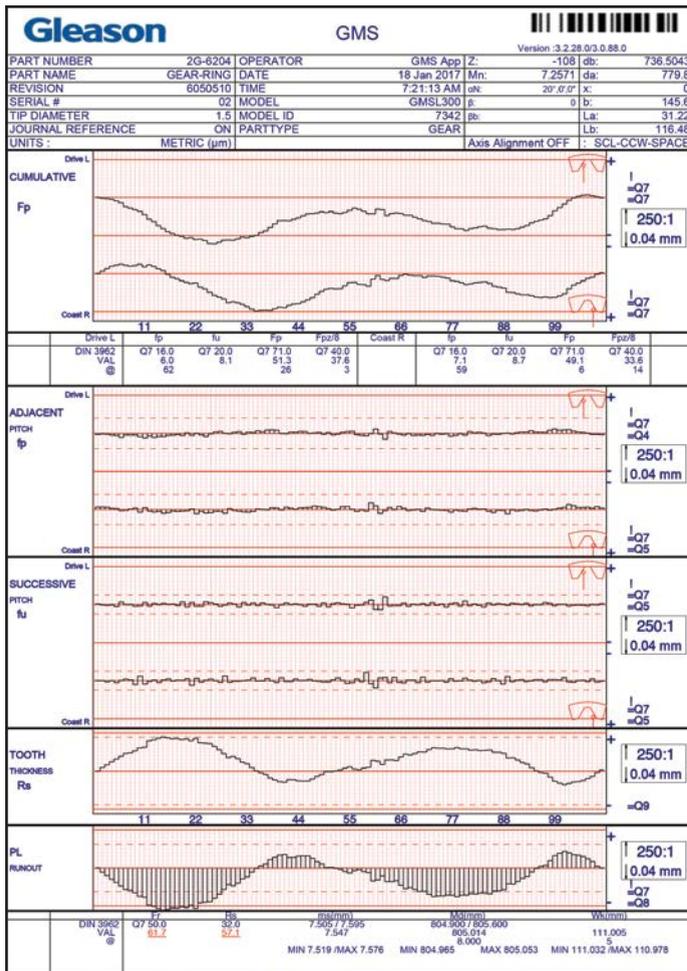


Figure 1 ISO 1328-2013 index analysis chart on GMS analytical machine.

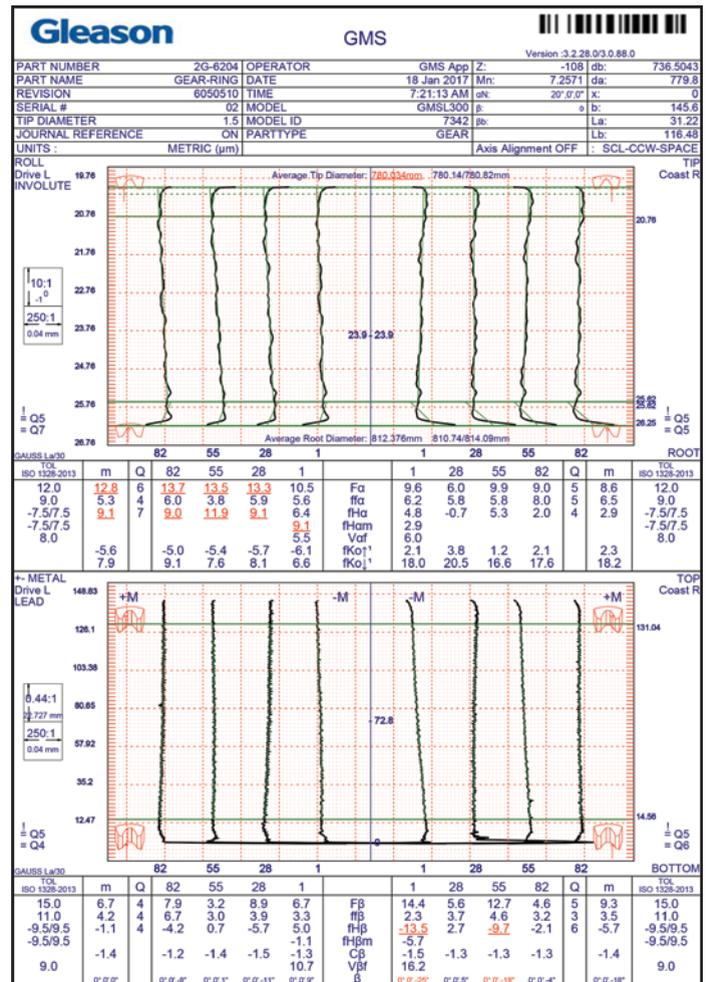


Figure 2 ISO 1328-2013 involute and lead analysis chart on GMS analytical machine.

While traditional measurements and analysis outputs are very useful in maintaining gear quality, they do not provide in-depth, easy-to-analyze data for noise analysis. For this reason, GAMA is equipped with multiple analysis tools to help identify the root cause of gear noise. The input to these tools is measurement data collected during the inspection of a gear. These tools are based on proven test results and save the GAMA user time with extremely user-friendly input requirements and mathematically optimized outputs for ease of interpretation. The output of many of these tools is correlated with noise signatures found during final testing of gearboxes or gear assemblies over the years.

New Analysis Tools

Several enhancements and additions have been made to these GAMA analysis tools, to take them to the next level, addressing the ever-changing needs of

the gear industry and Gleason's customers. They include:

1. Fourier Analysis:
 - Waviness Analysis of Gear Measurements using Fourier transform technique
 - Waviness Analysis of Bearing Surfaces using Fourier transform technique
2. Tooth Contact Analysis
 - Transmission Error Plotting
 - Ease-Off Plotting
3. Surface Finish Analysis
4. GAMA and KTEPS
5. Loaded Contact Analysis with OSU LDP or Gleason KISSsoft

1. Fourier Analysis of Gear Measurements

Fourier analysis is the analysis of a complex waveform expressed as a series of sinusoidal functions, the frequencies of which form a harmonic series. Figure 3 shows Fourier analysis of index, lead and profile traces on the same gear pair shown in Figure 1. By studying the harmonic values of standard traces, the

noise behavior of the same gear can be controlled. While Figure 1 qualifies the gear to pass traditional analysis, Figure 3 clearly shows significant issues with index harmonics. Amplitudes of lower harmonics (1st and 3rd) for index test are clearly beyond the tolerance curve. Comparing individual harmonics values of a production gear with a proven reference gear, the quality of produced gears is easily controlled. Such an analysis is combined with traditional gear inspection data already provided. This saves significant time, since no extra testing time is added, only analysis. By catching gears with higher harmonic values before any assembly takes place, significant cost savings is achieved.

Fourier Analysis of Bearing Surfaces

In recent years, Fourier analysis of bearing surface waviness has proven to be a very powerful tool in determining one of the main causes of low-frequency noise

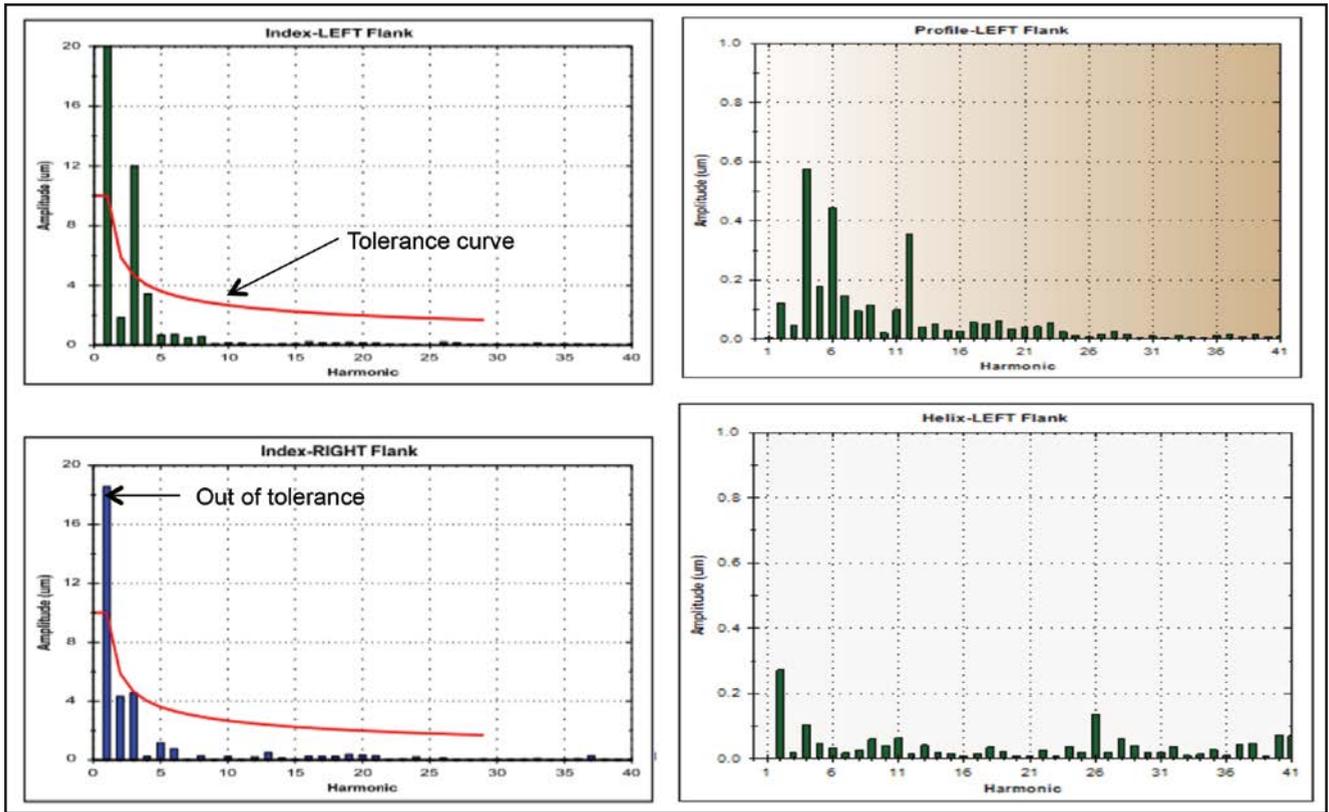


Figure 3 Fourier analysis of index, profile (involute) and helix (lead).

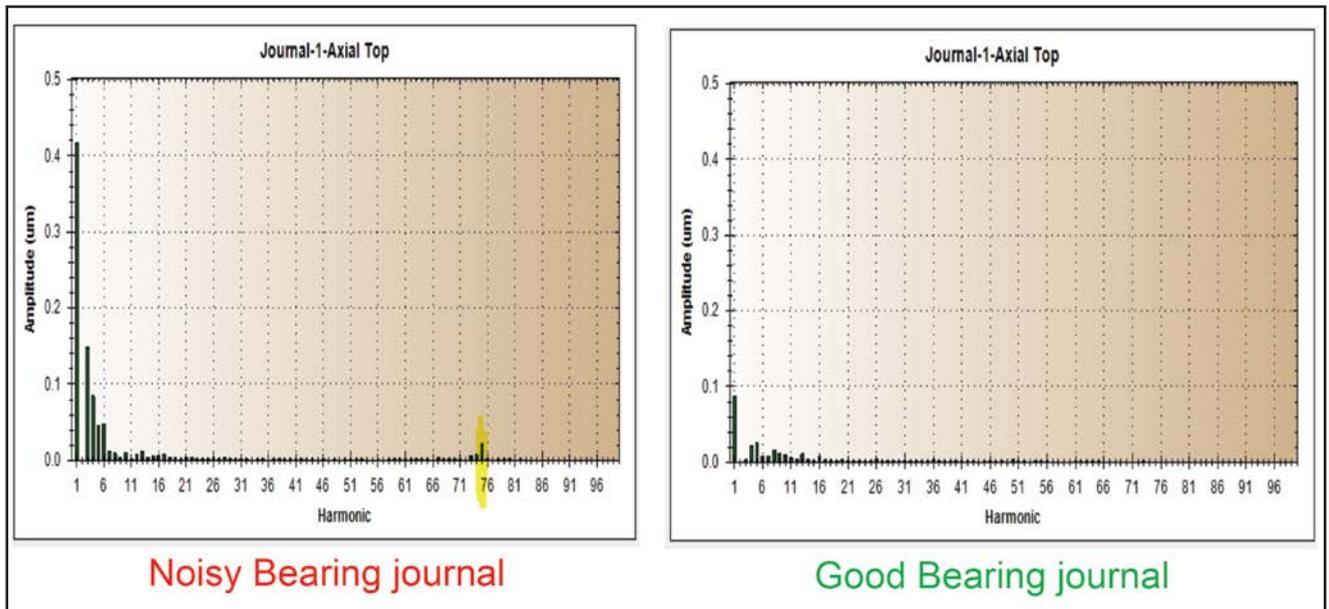


Figure 4 Fourier analysis of noisy and bad bearing journals.

in a gearbox. *GAMA* is equipped with Fourier analysis of bearing surfaces as well. Figure 4 compares Fourier analysis of a noisy and good journal measurement. This example shows that the 75th harmonic amplitude value is much higher on the first bearing journal. Upon careful analysis, it was found to be directly related to a manufacturing issue with the rotary table of the grinder used in the

finishing operation of the measured bearing surface. Typically standard journal measurement charts can only assist with finding lower harmonic issues caused due to eccentricity. By applying Fourier analysis to measured journals, one can focus on higher harmonics as well. This example shows how *GAMA* can help control manufacturing of non-gear related features along with traditional gear features.

2. Tooth Contact Analysis

While waviness analyses as explained above are very useful for analyzing individual gears for quality control, in real life, gears are always meshed in pairs to transmit motion. The true performance of a gear is determined when it meshes with a pinion.

Over the years, many gear researchers

around the world have developed mathematical models to analyze the meshing of gear pairs. These models assist in the design phase of a gear pair, which is targeted to minimize transmission error and improve contact pattern on the gear surface. Transmission error is the difference between the actual position of the output gear and the position it would occupy if the gears were perfectly conjugate.

GAMA can also provide contact analysis. It provides valuable information to the user by mathematically meshing the surfaces of the gear and pinion, which is extremely useful in design as well as in all production phases of the gear. A topological inspection of the mating area of the gear and pinion is performed. This data is then input into the GAMA contact analysis software to compute transmission error along the meshing path and generate ease-off topographical charts. The software is capable of reviewing the effect of misalignments in the axial and radial directions. This allows design engineers to modify gear surface geometry such as amount and length of tip relief. The mathematical algorithms are optimized to give these results in a few seconds on GMS machines.

Figure 5 shows the interface for GAMA Tooth Contact Analysis. The user can select inspection data from a previously inspected gear and mating pinion, and analyze them with a single click.

Figure 6 shows transmission error plots with color codes. The user can see the distribution of transmission error over multiple mesh cycles and their overlap. Fourier analysis of these traces is available, which allows the user to perform harmonic analysis and determine the frequencies of higher amplitude.

Figure 7 shows an ease-off plot. Ease-off plots combine surface modifications (i.e. flank form corrections) from both gear and pinion. Lead crown, tip and root relief are some of the planned flank form corrections to keep contact in the desired region of the gear and pinion mating surface. A contact path is then plotted on this surface. As the figure shows, the contact pattern is shifted toward the root of the gear. It needs to be moved to the center of the gear, which can be done by increasing the tip relief amount of the mating pinion.

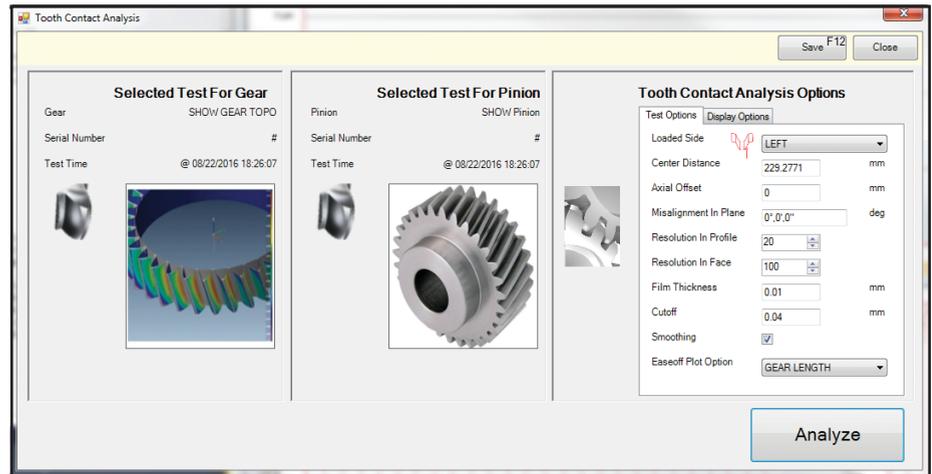


Figure 5 GAMA Tooth Contact Analysis interface.

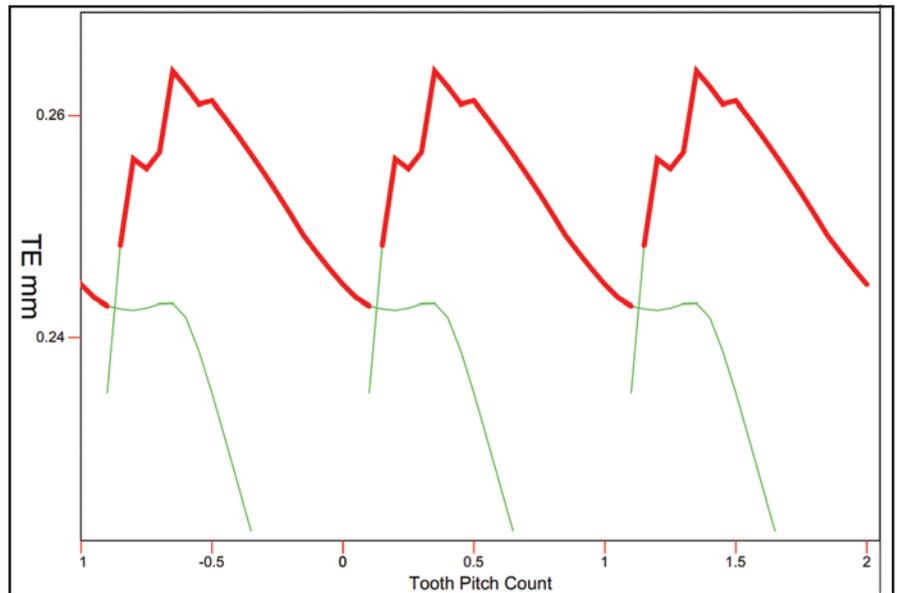


Figure 6 Transmission error (TE) plot.

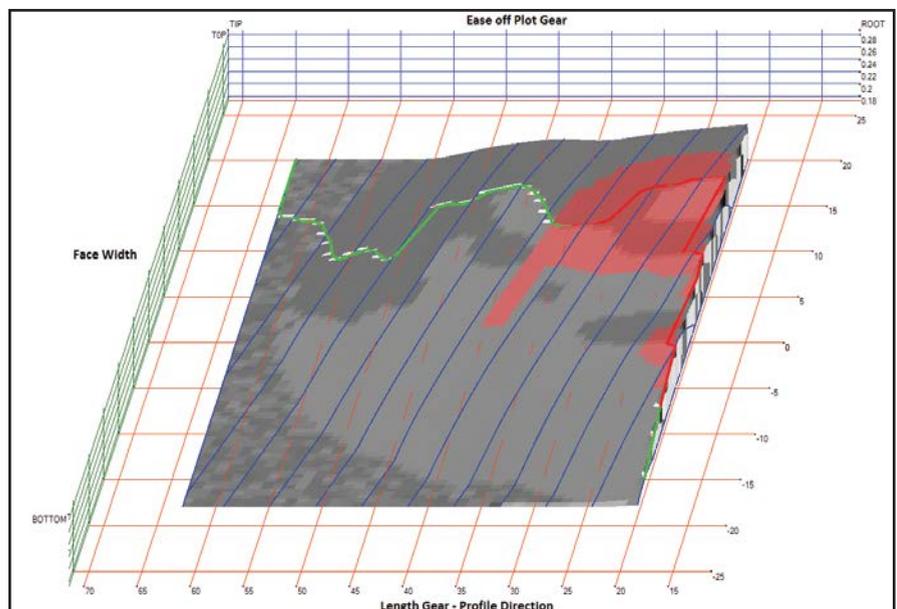


Figure 7 Ease-off topographical charts.

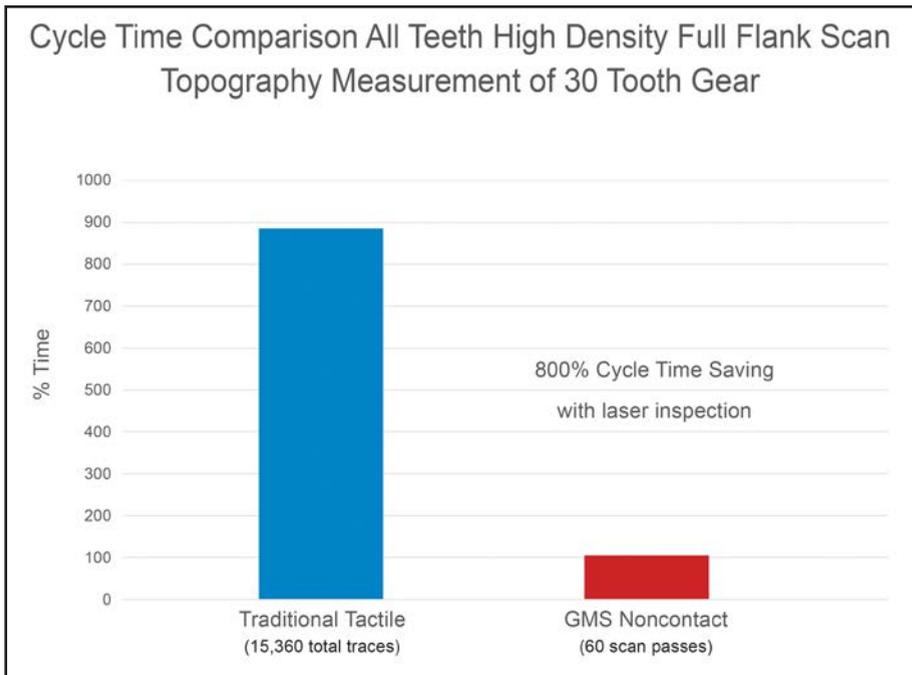


Figure 8 GMSL cycle time advantage.

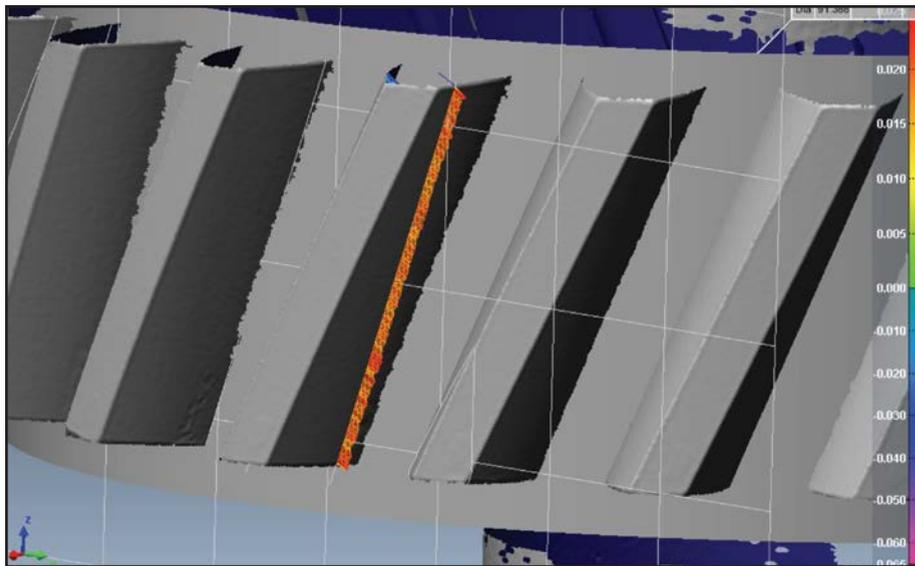


Figure 9 GMSL advantages – multiple sections from point cloud, including line of action.

The GMS, GMSP and GMSL series of machines are capable of performing contact analysis, since all use the same GAMA software. However, the GMSL series offers a significant advantage, due to the non-contact sensor’s ability to capture high-density data at fast speeds, as explained below:

- Contact analysis of a gear pair requires significantly higher density points on gear flanks for accurate analysis. More data is better for accurate predictions and control.
- Collecting high-density data using a traditional contact probe is a very slow process. The contact probe simply cannot provide the high-density data that a non-contact probe can provide.
- Figure 8 shows an 800% cycle time reduction on a GMSL machine with laser sensor, compared to inspecting the same gear with a traditional touch probe.
- Figure 9 shows the ability to take multiple complex sections on a 3D point cloud generated by a non-contact sensor. GAMA can take these sections along the path of contact, and export them for transmission error analysis.

3. Surface Finish Analysis

While waviness and contact analysis are very useful in controlling gear pair-related noise issues, surface finish inspection has a direct impact on the higher frequency noise behavior of gear sets. Surface finish also has a proven impact on the life of a gear. Surface finish measurement of a gear on traditional, manual surface finish inspection machines is a very complex and time-consuming process. This has been made easier on GMS series machines with available integrated, surface finish, probing technologies and GAMA software. Figure 10 shows a surface finish chart produced by GAMA. Traditionally, Ra and Rz output is used to qualify the surface finish of gears. However, GAMA provides a powerful analysis package, which can measure up to 72 different surface finish characteristics with advanced filter methods to analyze high-frequency noise. The same software is available to measure the surface finish of non-gear features such as bearing surfaces.

4. GAMA and Kinematic Transmission Error Prediction Software (KTEPS).

KTEPS uses an analysis approach for determining and diagnosing gear noise especially related to ghost noise. Ghost noise in a gear pair is much more complex to analyze than mesh harmonic noise. The unique one-to-one correlation of gear performance in the time and frequency domains to the geometric and kinematic contributions to transmission error from the tooth face geometry of a single gear allows the software to break out tones and the harmonic nature of gear noise in ways that no other analyses can match. Simple error amplitude metrics do not correlate well with the noise generating properties of harmonic errors, but KTEPS is able to generate the unique error pattern on any portion of any gear tooth responsible for a particular noise harmonic, whether or not it is associated with a mesh harmonic.

The GAMA interface directly communicates with KTEPS in a much-simplified user interface as shown in Figure 11. All programmed geometrical and test data such as inspection locations are transferred automatically from GAMA to KTEPS at the end of test. GAMA's ability to communicate with KTEPS in the background puts this interface at your fingertips on GMS machines.

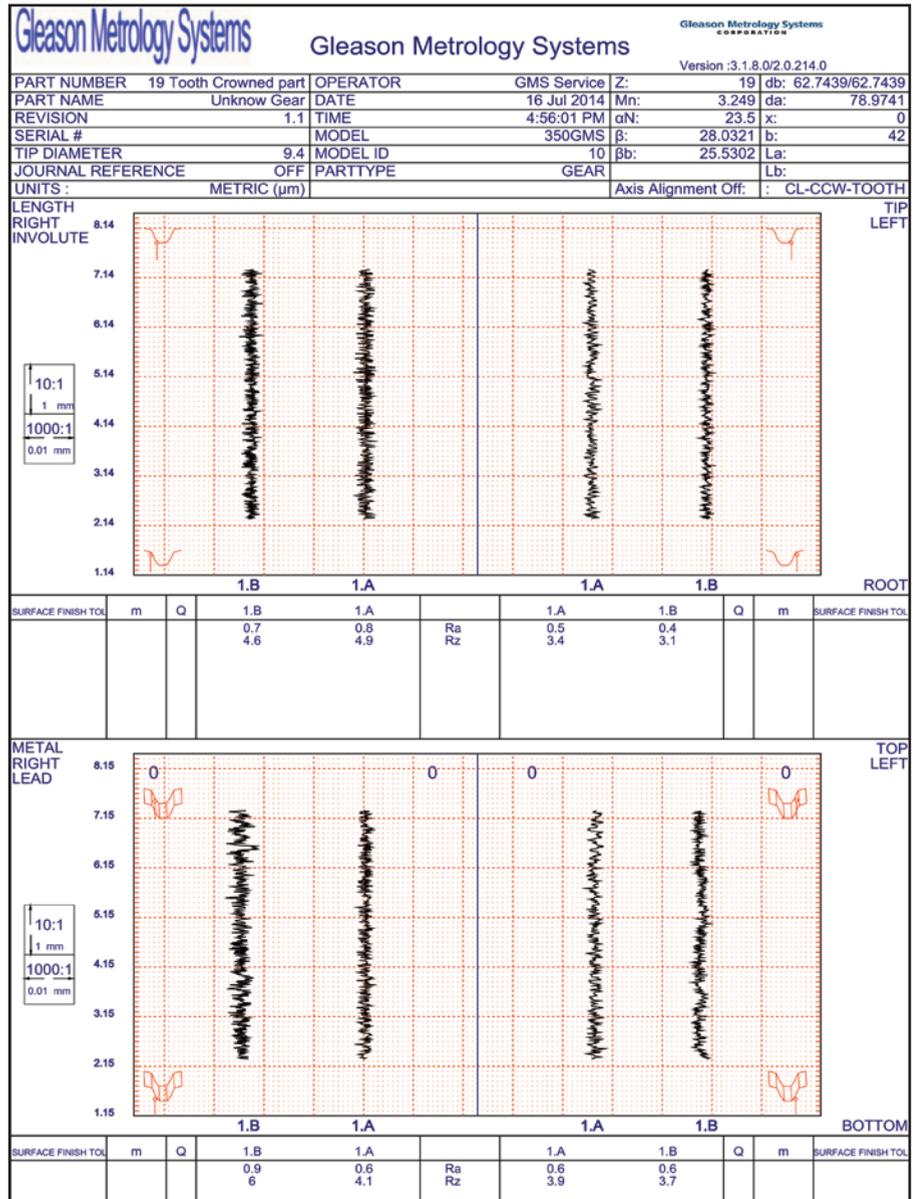


Figure 10 GAMA Surface Finish inspection chart.

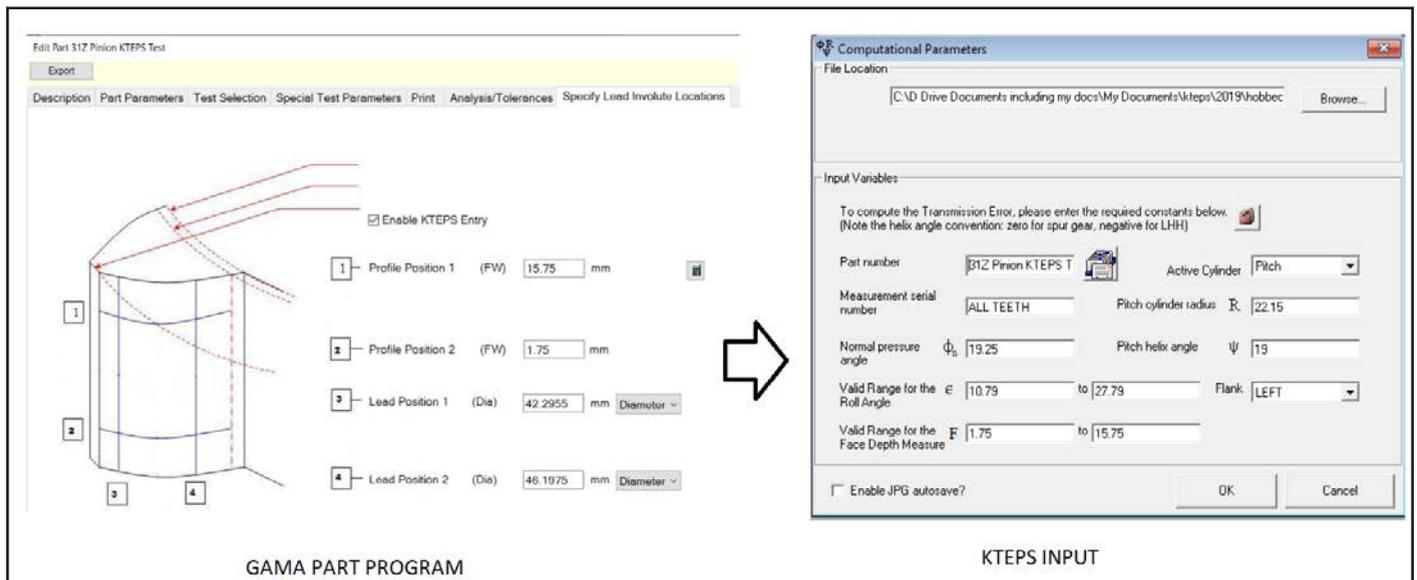


Figure 11 GAMA-KTEPS Integration.

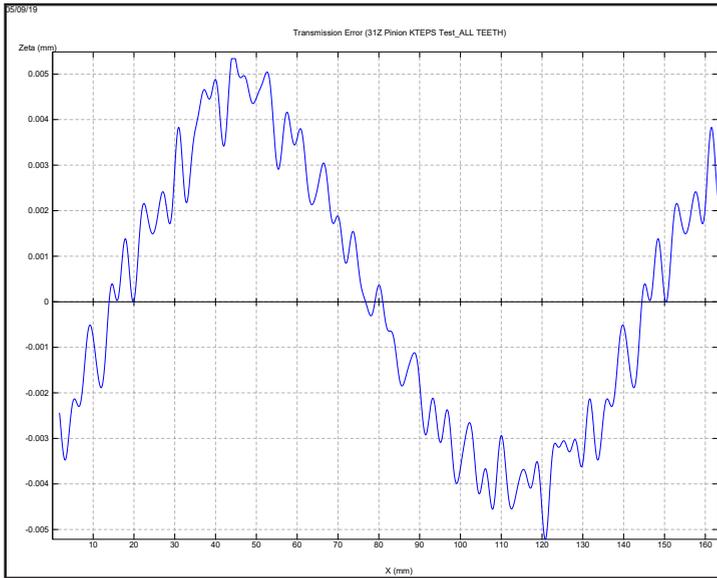


Figure 12 Transmission error of ALL teeth inspection.

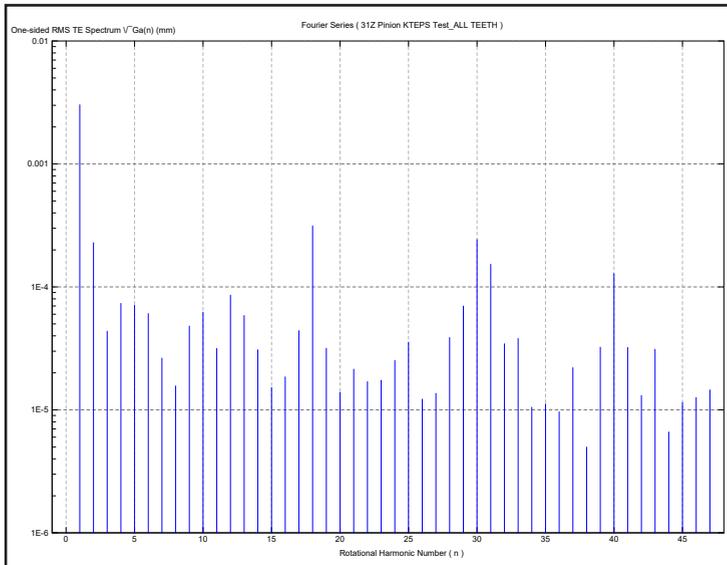


Figure 13 Fourier analysis of transmission error.

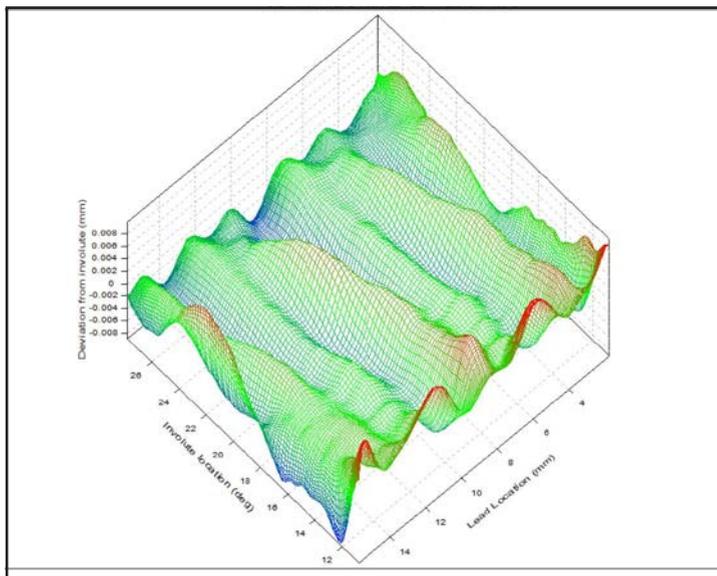


Figure 14a Reconstruction of tooth topological form for 1st harmonic.

Figures 12 to 14 show example analysis of a 31-tooth pinion in *KTEPS*. All teeth of the example gear are inspected at multiple lead and profile locations. Figure 12 shows transmission error analysis for one full rotation of the gear. Since the example gear has index error, the chart shows a large sinusoidal error for one full rotation of the gear. Each gear tooth shows varying transmission error as well. Figure 13 shows Fourier analysis of the transmission error for the same gear. Since this gear has 31 teeth, large transmission error amplitude is observed at the 31st rotational harmonic. The 1st rotational harmonic also shows large transmission error amplitude, which correlated with the large sinusoidal error generated due to index error shown in figure 12. The example gear has form error in the lead direction generated due to the hobbing operation. This has resulted in large errors around the 19th rotational harmonic. One of the major strengths of *KTEPS* is its ability to swap between spatial and time domains with no approximations. Figure 14 shows reconstruction of tooth topological forms at different harmonics. Studying topographical charts at required rotational harmonics based on Fourier analysis gives users the ability to relate gear noise with topological errors.

KTEPS also has advanced analysis abilities such as programmable misalignment errors and ability to create transmission error induced audio clips at programmable RPM for analyzed gear sets.

5. Loaded Contact Analysis

For complete design, an engineer has to consider the effect of tooth bending under varying load. More research has been done to understand the behavior of a gear pair under varying torques or loaded conditions. This is also known as loaded contact analysis.

Both the *Loaded Distribution Package (LDP)* developed by Ohio State University as well as Gleason *KISSsoft* software have the ability to perform this analysis. *GAMA* is capable of writing gear inspection output files in a format that can be easily imported into *OSU LDP*. This is achieved by topographical inspection in *GAMA*, with a simple checkbox on the

user interface. Using GAMA's Gearnet ability, the user can control the storage location of such files for ease of use by a design expert at his offline workstation. GAMA is also capable of writing gear part parameters including tolerances and inspection test data in xml file format published by VDI/VDE 2610 GDE standard. This data then can be shared with KISSsoft for both gear and gearbox design optimization purposes.

As explained in this article, gear noise has multiple causes, and no one solution or analysis package can solve them all. It has been proven over the years that multiple areas of the gearbox assembly need to be controlled during the production phase. Gleason brings a significant advantage to its customers by combining multiple analysis tools on one platform. Figure 15 shows work flow using the GAMA interface. The single GAMA software interface can provide multiple analysis outputs. 

For more information:
Gleason Corporation
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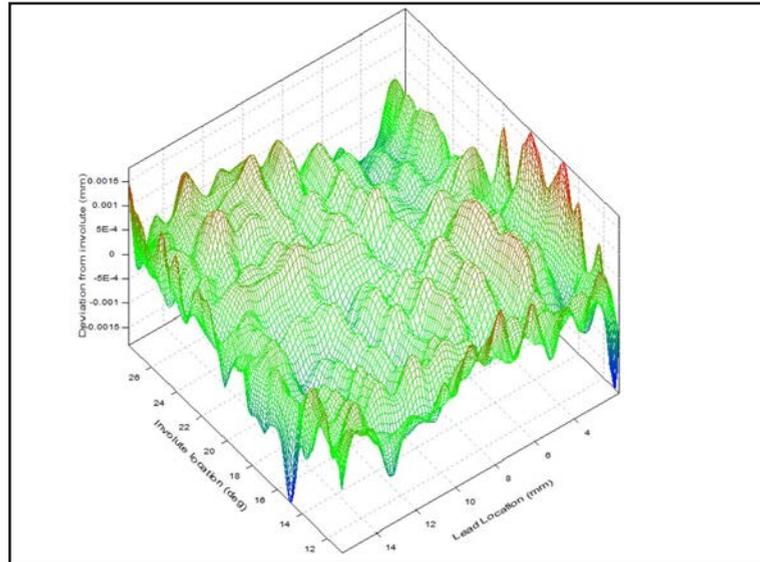


Figure 14b Reconstruction of tooth topological form for 19th harmonic.

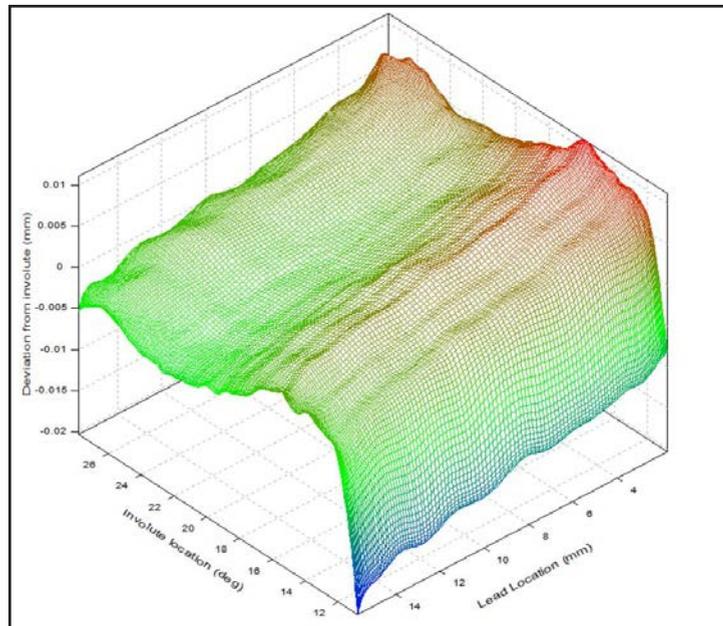


Figure 14c Reconstruction of tooth topological form for 31st harmonic.

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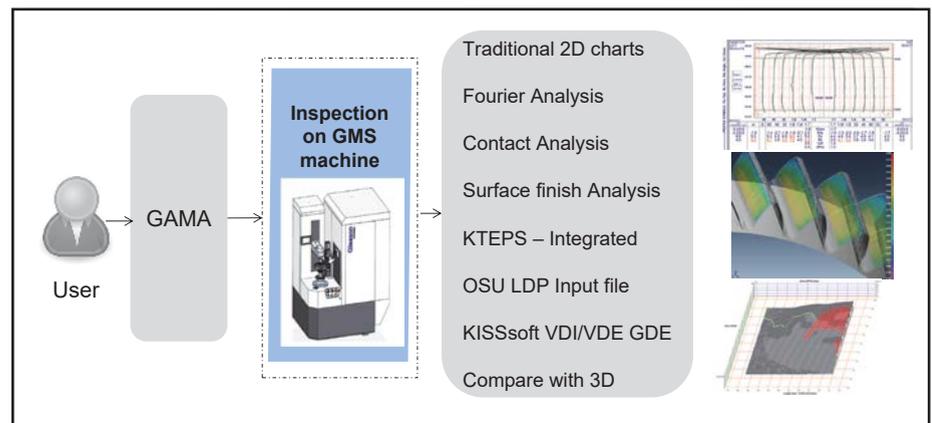


Figure 15 User interface – flow diagram.