New Approaches

In Roll Testing Technology of Spiral Bevel and Hypoid Gear Sets

Heinz Eder and Christian Pahud

Introduction

The roll testing of bevel gears has existed as long as bevel gearing itself has existed. A device was required to check and confirm functionality, mounting distances and backlash to suit the future assembly condition of the gear set.

Single-flank and vibration checking have traditionally been widely accepted testing and checking methods for evaluating the quality of spiral bevel and hypoid gear sets. Mainly due to productivity reasons, the methods were limited to laboratory application, spot checks to monitor production and assembled gear sets.

Only the introduction of CNC roll testing equipment combined with PC-based evaluation technology dating back to 1990 enabled the breakthrough of this technology onto workshop floors in mass production applications (Ref. 1). Since then, this process has been automated, so it's now state-of-the-art technology, where the best assembly position for the gear set is evaluated, checking the quality characteristics for different mounting positions. This fulfilled the requirements of the automotive industry regarding the generation, recording and documentation of information about the quality level of its manufactured gear sets. However, the industry later required checking of the gear set characteristics over a wider range of positions. Checking a defined number of positions, though, was jeopardizing productivity. This is where the new continuous approach can be used to provide the required amount of information without compromising productivity.

Methods for Checking Spiral Bevel and Hypoid Gears

There are many reasons for checking spiral bevel gears and hypoid gear sets in production, such as monitoring production and documenting manufactured quality. However, in the pre-assembly stage, the main reason is to predict noise emissions, once the gear set is mounted in the carrier. The requirements for a testing device in a production environment are reproducibility of results, short setup and testing times, best possible simulation of "real" situation once the gear set is assembled, a straightforward good/reject identification and a reliable detection of components that do not fulfill the requested quality standards.

Methods to check individual components. There are numerous ways of checking individual components that will not be listed, as this paper is purely focused on the possible means of detecting and forecasting the noise behavior of spiral bevel and hypoid gear sets in automotive applications.

3-D coordinate measuring machine (CMM). On a suitable three-dimensional coordinate measuring machine that's measuring individual components of pinions and ring gears, pitch checks will indicate the indexing quality. Topography checks will indicate how close the actual microgeometry of the flank form approaches the theoretical nominal data or that of the master gear to be copied. However, these checks will give little indication about the future noise emission to be expected from an assembled gear set because only one component at a time is evaluated. In addition, usually not all teeth are checked for timing reasons and only a sample

Management Summary

This paper presents a new approach in roll testing technology of spiral bevel and hypoid gear sets on a CNC roll tester applying analytical tools, such as vibration noise and single-flank testing technology.

When assembling a spiral bevel or hypoid gear set in a carrier, two variables can usually be adjusted: 1.) ring gear mounting distance, to adjust required backlash and 2.) pinion mounting distance, to adjust contact pattern position and consequently running behavior.

The task is to reduce testing time compared to conventional roll testing while improving the amount of information generated to give indication for the best possible assembly position in the axle carrier.

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Figure 1—Oerlikon T60X tester (2003).

number of teeth is evaluated with the possibility of nonchecked teeth being not OK.

There is, however, a fairly new approach for checking bevel gears on 3-D CMMs. The approach, already realized for parallel-shaft gears (Ref. 2), is to scan the path of contact (POC) to find the possible causes for noise excitement whilst meshing individual teeth. The disadvantage of this method is that POC analysis will be made on the assumption that the matching member is perfect. Real components, however, will deviate from the nominal and will influence the POC.

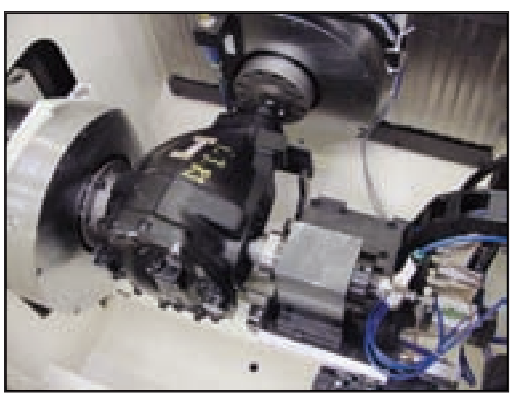

Figure 2—Typical mounting arrangement of bevel or hypoid housing on Oerlikon T60X.

Another possibility is the virtual meshing of a gear set after checking two matching components. After checking the topography of pinion and ring gear teeth, both members are virtually matched and a real "ease-off" can be generated. After evaluating a virtual, reproduced true ease-off, the ease-off condition, the tooth contact pattern (TCP), the POC and the transmission error (TE) can be analyzed, with the latter indicating noise emission capacity.

All of the checks available on a 3-D CMM are extremely accurate. However, testing is rather time intensive. Still, besides the latter method, checking one component only can hardly indicate the running condition of a gear set.

Therefore, the main application of 3-D CMMs in production is to monitor samples from cutting or grinding operations and to control topography when the machines' settings are changed automatically by means of software like KOMET® to ensure manufactured topography is as calculated.

Methods to check running behavior of matched sets. In the past, with the increasing role of finish-ground gear sets, the vast majority of spiral bevel and hypoid gears were lapped after heat treatment, depending on geographic region and application.

The lapping process necessarily involves a pairing of pinion and ring gear. Therefore, the obvious solution was to check the sets in pairs. Simulating the assembly of the gear set on a roll-tester was, and still is, the fastest quality check available in the pre-assembly stage.

Roll testing. What most roll testers have in common is that a gear set is clamped, brought into mesh and backlash is adjusted. After spraying or painting the gear sets, to avoid scoring, speed and torque are applied. The only difference between the numerous amounts of testers is the degree of automation developed over the years, starting from an all-manual tester with mechanical brakes to apply torque to the state-of-the-art testing machine that has fully automatic meshing and applies torques and speeds via electronically controlled drives.

Furthermore, testing as described has a high level of productivity, and typical testing time—not including clamping and unclamping—can be completed in the range of one minute.

A derivative of the T60, the T60X machine (see Fig. 1) was presented to the market in 2003 to meet customer demands, after realizing that meticulous testing of individual gear sets still leaves uncertainty in the assembly stage, where the gear sets are assembled in a carrier. Typically, the manufacturing tolerances of the housing, together with the evaluated best position on the pinion mounting distance, are compensated by shims (see Fig. 2). In production, wrong shimming caused by whatever reason will lead to a condition in which the perfectly evaluated gear set will be subject to potential noise emissions, if assembled incorrectly.

The arrangement of checking the gear set in an already assembled condition takes the detection of potential noise emitting one step further on the assembly line. The obvious nature of this checking arrangement is a purely OK/Not OK filtering before the carrier is released for assembly into the axle.

Another development in the automotive industry in recent years is a growing demand for bevel and hypoid gear sets deviating from shaft angles of 90°, mainly for low-floor, short-distance buses and because of new legislation to allow for softer hoods on motor vehicles, as a precautionary measure in car-to-pedestrian accidents. This requires space between the hood and the engine. This can only be maintained by moving the engine further back into the passenger room. In vehicles equipped with a longitudinal engine and front wheel drive, the space for the front passengers will then be sacrificed to move the gearbox back. To maintain the space for the front passengers, "slim line" gearboxes have been developed using a shaft angle smaller than 90° for the bevel gear set.

To satisfy that market requirement, the T60A machine was developed and presented in 2004. The T60A accommodates a shaft angle range of 90° +/– 11°.

Tooth contact pattern (TCP) analysis, conventional. After finishing the roll test of a gear set that has been sprayed or brushed with contact pattern paint, the contact pattern is visibly marked on the teeth. The created tooth contact pattern, is compared to a "master contact pattern" and judged by a trained individual. This check is performed on a "subjective" basis using the human eye as a measuring instrument. This process, involving the human factor, has disadvantages in repeatability and reproducibility and therefore creates difficulties in meeting modern quality control requirements. Consequently the clear choice is to replace it with "objective" checks.

To eliminate the human influence when judging the TCP, a camera-based TCP recognition system can identify and evaluate a contact pattern. This system compares a nominal TCP with the recorded TCP and supplies a straightforward Good/Reject message. Typical characteristics that are evaluated and toleranced are length, height, center of gravity, as well as area and orientation of the recorded TCP. Besides the elimination of subjectivity, such a device also enables the collection of statistical data and digital recordings of the TCPs on a fully automatic basis.

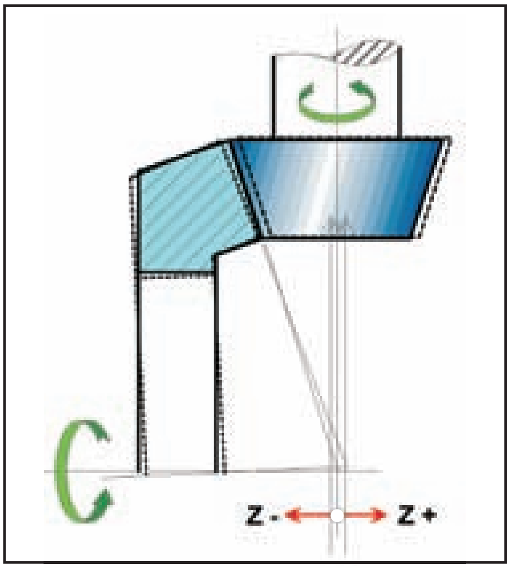

Figure 3—Principle of double-flank check on Oerlikon T60/L60.

Noise check, conventional. While running the roll test of a gear set, which has been sprayed or brushed with contact pattern paint or oil to avoid scoring, the running behavior is judged by a trained individual. As all checks involving the human factor, this check is performed on a "subjective" basis using the human ear as a measuring device. Besides lacking repeatability and reproducibility, this check has historically had a wide spread. Also users claim a reasonable ability of forecasting and correlation to vehicle noise. Nevertheless, this testing method as a final check is replaced by "objective" means of checking and evaluating.

Noise check, automatic (air noise). An air noise check is historically the logical step from judging the gear noise by listening to it with the human ear to judging it by using a microphone and setting the tolerance at a predefined noise level, typically a dB(A) rating. This evaluation method has not made a real breakthrough and has no real significance in testing and evaluating the running behavior of spiral bevel and hypoid gear sets.

Double-flank check. Double-flank checks in parallel shaft gear applications are usually performed by mating a member with a master gear or pinion and recording the axial deviations while running the set in a no-backlash situation. With spiral bevel gears, which are typically mated during the lapping process, this opportunity is not available. Instead the sets are double-flank tested in pairs as they are assembled (see Fig. 3).

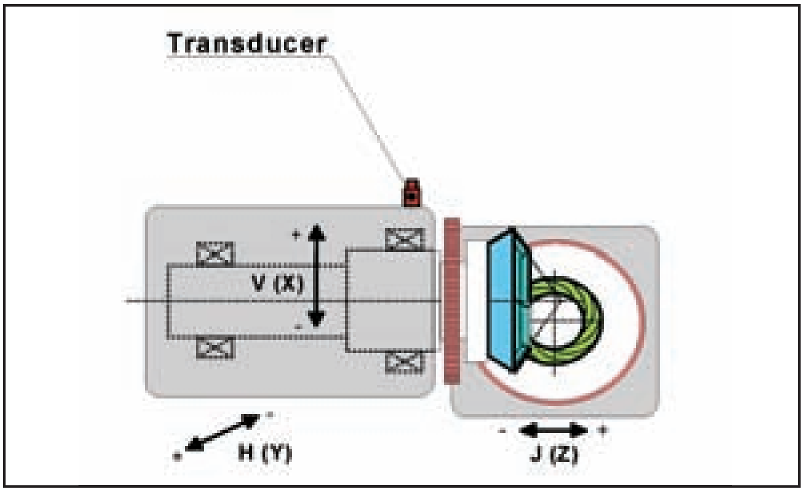

Figure 4—Typical arrangement of a vibration noise sensor on a bevel gear rolling tester.

Figure 5—Typical result of a vibration noise check referenced to pinion.

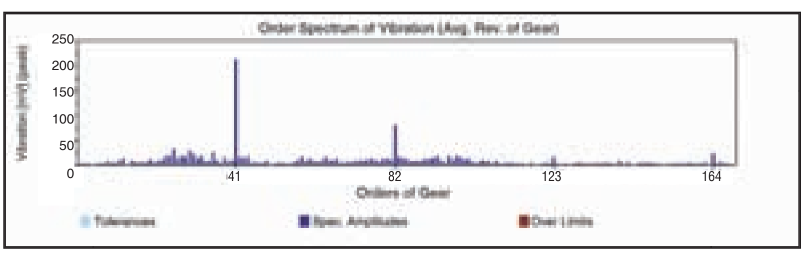

Figure 6—Typical result of a vibration noise check referenced to ring gear.

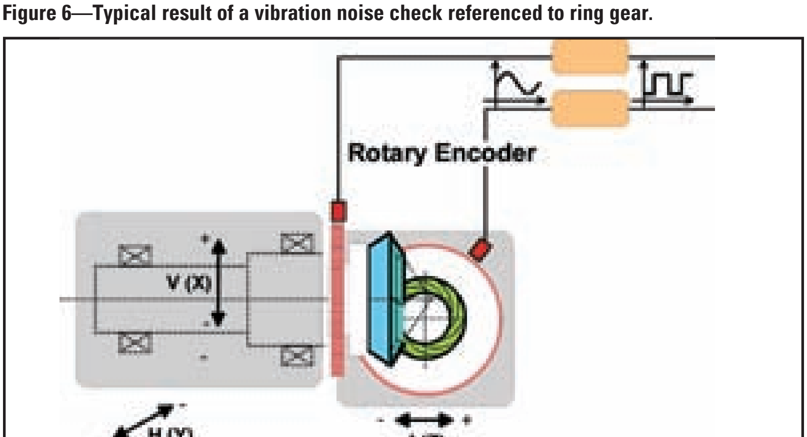

Figure 7—Principle of single-flank check on Oerlikon T60.

The test is performed in a no-backlash condition. While the ring gear is making one revolution, deviation of the pinion in ring gear mounting distance (deviation Z) is recorded. A fast Fourier analysis then evaluates rotary pinion and ring gear deviations separately. This test is usually performed in very little time. As this test does not represent the final assembled condition, which will have backlash, the test result cannot make a significant statement regarding running behavior.

However this test has established itself as a quick pre-check for CNC lapping and CNC testing to recognize runout errors on pinions and ring gears and clamping errors of mainly ring gears. Clamping errors will have an effect on runout qualities. This test avoids the possibility of pairs of gears being lapped or tested in an incorrect clamping position, thereby avoiding damage during lapping or misreading of testing results due to incorrect clamping.

Vibration noise check (VN). Typically a vibration noise sensor is mounted on a gear tester as close as possible to the meshing gear set to be tested (see Fig. 4). Preferably a CNC roll tester is used to apply torque and speed, to minimize influences of the roll testing machine itself, such as temperature deviations caused by mechanical brakes, torque variations due to manual application of torque, and speed variations due to influences of the applied torque—just to name a few.

The measured signal will then be amplified, synchronized with the spindle rpm and evaluated on a separate evaluation unit where typically a fast Fourier analysis will be carried out to divide the signal into the harmonic contents.

An advantage of this measuring principle is short measuring times due to the fact that comparatively high spindle speeds can be applied, typically allowing achievement of tooth mesh frequencies in the area of 300 Hz. Another advantage is the reduction of unproductive acceleration and deceleration times. Forecasting noise emission in the vehicle is reasonably good in the range of mesh frequencies. However rotational harmonic contents of pinion and ring gear can cause side band effects that cover or shift mesh frequencies, challenging their definite identification. Because vibration noise checking is a dynamic testing method, resolution for rotational harmonic contents is poor to nonexistent. Generating usable information for reliable forecasting of noise behavior is limited to the mesh harmonic contents of lower orders (see Figs. 5 and 6). The sum of its disadvantages compared with its directly competing measuring method, single-flank testing, has led to a decreasing application of vibration noise testing in the industry.

Single-flank transmission error check (SFT). For single-flank checking, high-resolution rotary sensors are mounted on pinion and gear spindle, typically as close as possible to the components to be analyzed (see Fig. 7). It is highly recommended that an NC control be used to apply torque and speed.

The digitized signal collected from the rotary encoders is recorded and fed into a PC-based analyzing system. By definition (DIN 3965), single-flank checking is a quasi-static checking method, hence it is basically free from dynamic influences. As a consequence, the equipment used, assuming measuring itself reaches an acceptable level, has no influence on the result itself. Due to the lack of dynamic influences, repeatability of SFT results is usually very good. In addition to the mesh transmission errors, which clearly correlate to vehicle noise behavior, rotational harmonic contents of the checked components can be obtained. A positive side effect of low checking speeds is fast acceleration and deceleration times for the checking procedure itself.

Due to the increased quality and quantity of characteristics and information provided by single-flank testing in comparison with vibration noise analysis, the former has reached a stage where it can be clearly called the "industrial standard" for pre-assembly running behavior checking of spiral bevel and hypoid gears.

Best position evaluation strategy, successively. All evaluation strategies named hereafter apply for both checking methods, vibration noise and single-flank transmission error, with all preconditions and characteristics mentioned in the sections *Vibration noise check (VN)* and *Single-flank transmission error check (SFT).*

The vast majority of bevel and hypoid gears end up in vehicle applications. Typically the pinion cone distance (by shimming the pinion backface) and the backlash (by adjusting the ring gear mounting distance) are the two variables that can be adjusted in the assembly stage.

To ensure proper running behavior in the assembled stage, the set will be tested on a bevel gear roll test stand to evaluate the best running position, which will be set in the assembled carrier. Alternatively a known carrier displacement

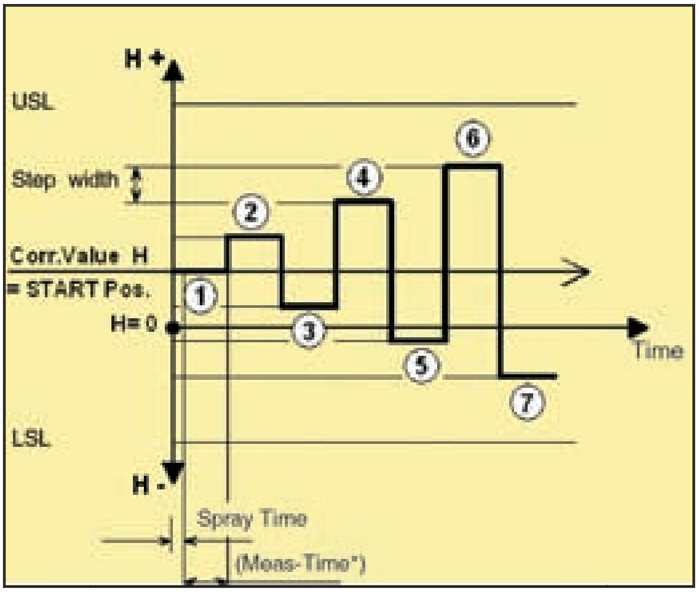

Figure 8—Classic best position evaluation procedure.

range will be imposed on the set and the transmission error tolerances will have to be kept over the entire range of displacement to ensure proper running behavior in the axle over the whole range of running conditions.

The typical approach to check the running position plus a wider range of possible assembly positions is to successively check a set number of individual positions for the pinion cone setting, followed by an individual evaluation of each position (see Fig. 8). The result for each individual setting position is an evaluation as mentioned in Figure 3. Application of this strategy is increasing the checking times for each individual position. Trying to optimize checking times consequently means reducing the amount of positions to be checked and thereby sacrificing the resolution over the entire range.

Best position evaluation, continuous. As the request was to get much more complete information of running behavior over an entire range of possible deflections in the gear carrier under load and temperature influences, the pre-evaluated and known gear housing deflections are simulated in the roll testing machine. Also, different from the incremental/successive approach, as explained in the section *Best position evaluation strategy, successively*, the deflections are now simulated on a continuous basis, thereby generating a wider range of possible information about the running behavior in only a fraction of the time previously required.

The result of a continuous measurement along a range of pinion cone settings deviating from the nominal mounting distance by +/–0.09 mm: the mounting distance is continuously increased, while data for either single-flank transmission error or vibration noise is collected (see Fig. 9). This data is evaluated by means of a fast Fourier Transformation evaluation.

In an example evaluation, a gear set ratio of 14:41 is evaluated, and an order analysis referenced to the pinion is displayed. Pinion orders along pinion cone setting, in this case single-flank transmission error for drive, are visible. Cross-referencing by pinion orders, the sample shows pinion rotational order: The 14th pinion rotational order equals the 1st mesh order, the 28th pinion rotational order equals the 2nd mesh order and so forth (see Fig. 10).

The displacement characteristic for each individual single-flank transmission error component can be extracted. The sum of information gained

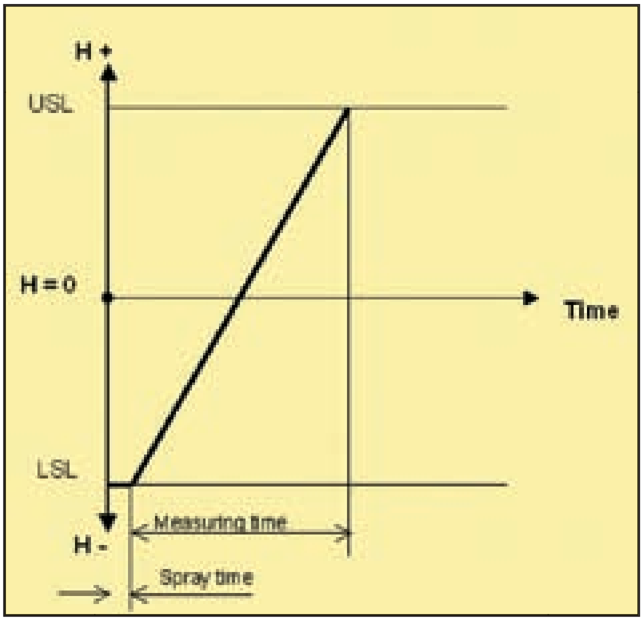

Figure 9—Continuous best position evaluation procedure.

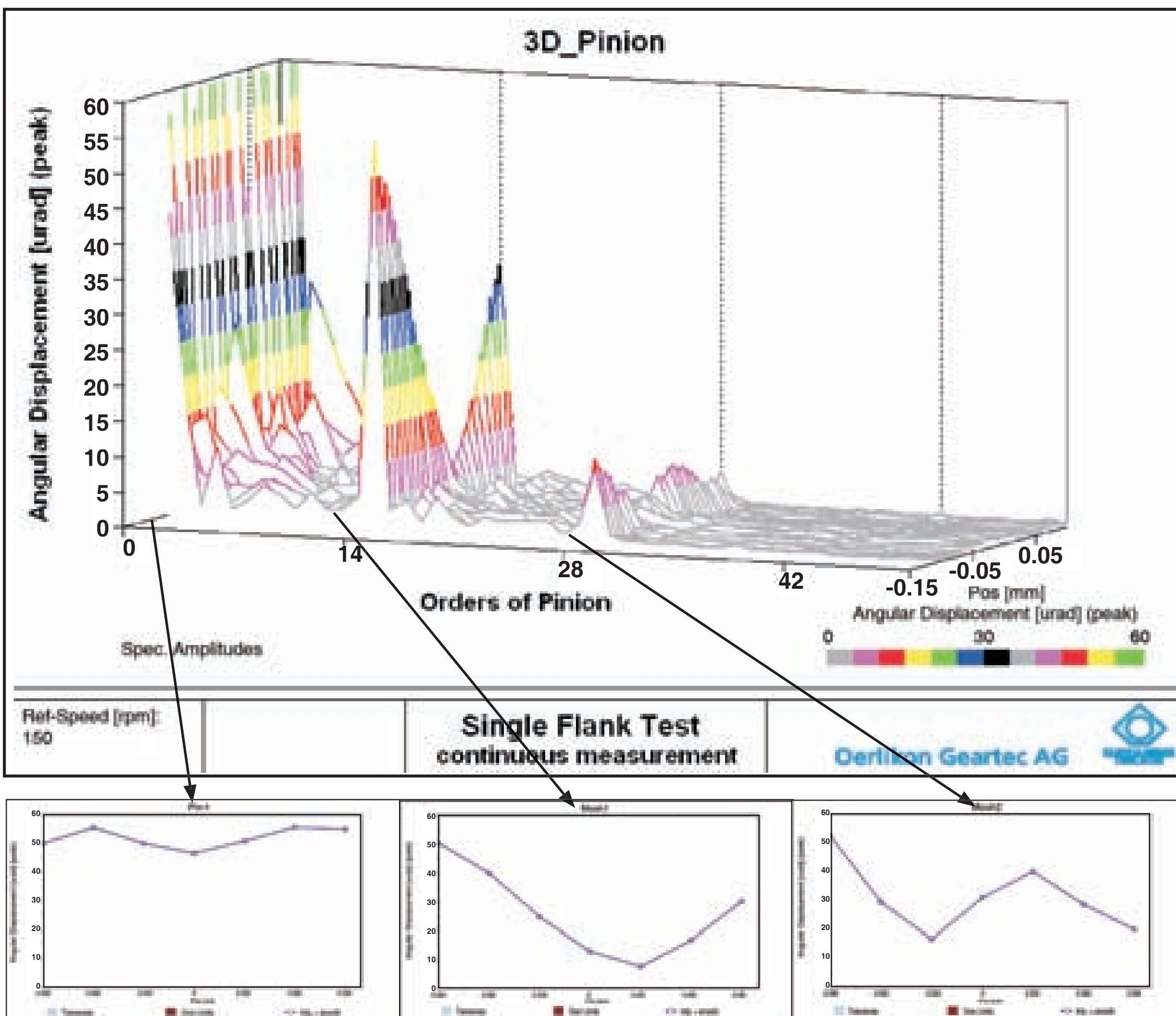

Figure 10—Continuous measurement evaluation result and extracts of pinion rotational orders 1, 14 & 28.

can then be used for evaluation, so different attachments of importance can be applied to different characteristics. This result will then be a clear indication of which pinion cone setting is the position having the desired transmission error characteristic. Alternatively the achievement of a desired transmission error characteristic can be checked and confirmed.

The application aspect of this new approach is as wide as the approach itself and can be applied in mass production using all evaluation tools with a simple Good/Reject result and the output of the best pinion mounting position. On the other hand, it is an ideal tool for the gear engineer to evaluate all possible means of bevel and hypoid gear characteristics in the development stage whilst gaining information for later application in mass production.

Test Series

A test series (see Table 1 for parameters) was conducted to show the capabilities of this new continuous approach.

All tests were conducted on an Oerlikon T60 gear testing machine equipped with capabilities for checking vibration noise and single-flank transmission error in both modes, the successive and continuous evaluation strategies. One set of ground hypoid gears was checked five consecutive times without clamping and unclamping in each method. Vibration noise and single-flank checks were also performed using both evaluation strategies, successive and continuous. All results and graphs in this paper represent averaged figures of five consecutive measurements. The range markers show the range of these five consecutive measurements to indicate the quality of repeatability for each characteristic.

Vibration noise checking results, successive. Analyzing the mesh harmonic contents of vibration noise, we get a result as shown in Figure 11. The amplitude of mesh 1 decreases from position 1 at 315 mV (pinion cone setting –0.09 mm) to position 5 at 45 mV (pinion cone setting +0.03 mm). This indicates that shifting the pinion cone position by 0.12 mm can reduce the significant amplitude for mesh 1 by 86%. A similar potential of improvement can be identified for mesh 2.

However, best positions for mesh 1 and mesh 2 do not coincide. Also, depending on the best position evaluation strategy, which has to be correlated with actual noise emission in the vehicle, the "correct" best position can vary from application to application. Repeatability for meshes 1–4 is at an acceptable level. For meshes 5 and 6, the range of measurement results is in the area of the signal size itself and therefore is not suitable for further evaluation.

Table 1—Parameters for Test Series.

Ratio	14:41
Axial Offset	30 mm
Axial Backlash	0.16 mm
Checking Speed for Vibration Noise (Pinion Spindle)	1,100 min^{-1}
Checking Speed for Single-Flank Test (Pinion Spindle)	150 min^{-1}
Torque	15 Nm
Increments of Pinion Cone Settings Referenced to Nominal Pinion Mounting Distance (7 positions)	Pos.1–7: –0.09 mm; –0.06 mm; –0.03 mm; 0 mm; 0.03 mm; 0.06 mm; 0.09 mm
Checking Duration per Increment, Successive	5 Ring Gear Revolutions
Checking Duration per "Increment," Continuous	2 Ring Gear Revolutions

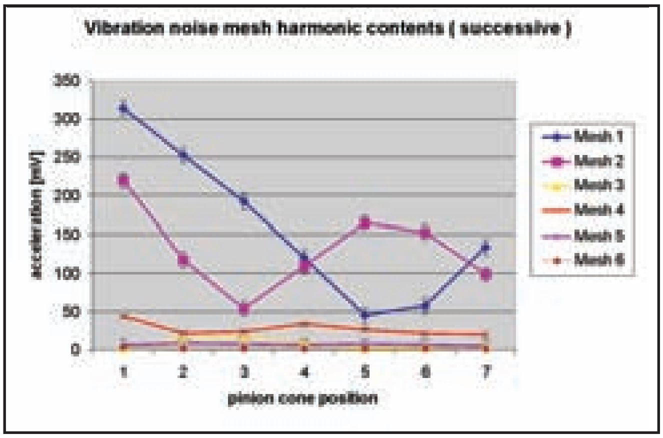

Figure 11—Mesh harmonic contents of vibration noise signal; checking method successive.

It has to be emphasized that, for this study, ground gear sets have been used. As these sets fulfill high quality standards, as all heat treatment distortions are removed by this process, there are no sideband effects. Consequently, mesh harmonics can clearly be identified.

To prove the known fact, that vibration noise analysis is not a feasible method to detect the rotational harmonic contents in reference to the gear, gear rotational harmonics were extracted from the measured signal by FFT detection. As expected, the quality and repeatability of the result was not suitable to give any indication because the range of the measured signals (see Fig. 12) was wider than the averaged signal itself. This is mainly due to factors as explained in the section *Vibration noise check (VN)*.

Vibration noise checking results, continuous. The continuous vibration noise measurement (Fig. 13) shows almost identical results to

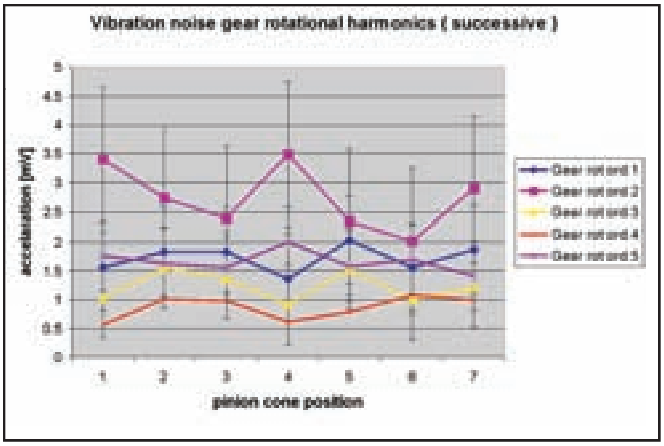

Figure 12—Gear rotational harmonic analysis of vibration noise signal; checking method successive.

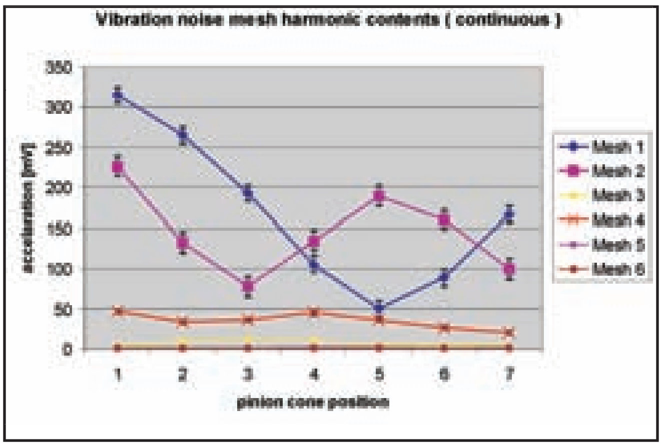

Figure 13—Mesh harmonic contents of vibration noise signal; checking method continuous.

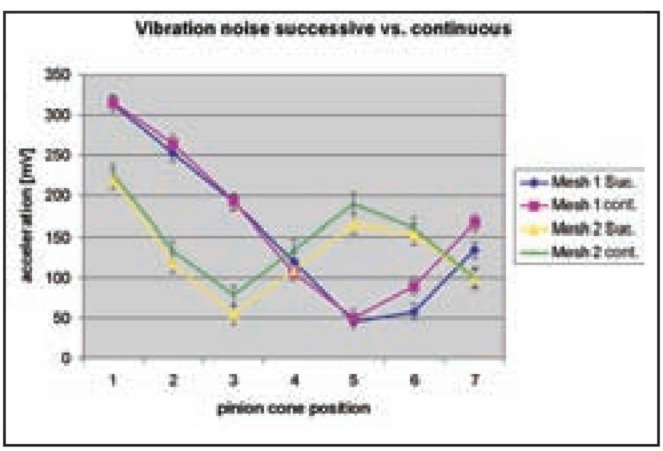

Figure 14—Vibration noise successive checking vs. continuous checking.

Table 2—Correlation Coefficient Vibration Noise, Successive Method vs. Continuous Method.	
Characteristic	**Correlation Coefficient VN, Successive vs. Continuous**
Mesh 1	**98.49%**
Mesh 2	**98.34%**
Mesh 3	**89.87%**
Mesh 4	**86.22%**

the successive measuring (Fig. 11). It has to be noted, though, that the checking time could be reduced by 35% using the continuous checking approach.

Correlation of successive check with continuous checks of vibration noise. Visualized for mesh 1 and mesh 2 (see Fig. 14), the correlation of both checking methods can be recognized.

Correlating the successive and continuous checks and performing a correlation study, the results shown in Table 2 can be obtained.

Correlation coefficients for meshes 1–4 reach a satisfying level that proves: Using the new continuous approach, an identical level of quality for results can be obtained, with checking times simultaneously reduced by 35%. Consequently the new continuous approach is qualified for replacing the successive approach in applications where vibration noise is an indicator for future vehicle noise emissions.

The reduction in checking time allows for obtaining a wider range of information without a reduction in productivity. Alternatively productivity can be raised while obtaining a similar amount of information at a similar quality level.

Single-flank checking results, successive. Evaluating the single-flank transmission error in successive mode, a result, as displayed in Figure 15, was obtained. Repeatability reaches an acceptable level for meshes 1–6. The pinion cone position with the highest figure for mesh 1 is position 1 at 49 µrad. The lowest mesh 1 figure is position 5 at 7 µrad. Very similar to the vibration noise evaluation, this difference indicates that by shifting the pinion cone position from position 1 to position 5, the significant amplitude for mesh 1 can be reduced by 86%.

The best position for mesh 2 is position 2 at 4.8 µrad whereas the highest output position for mesh 2 is position 1 at 9.3 µrad, followed by position 5 at 8.4 µrad. Depending on the best position evaluation strategy—which has to be correlated with actual noise emission in the vehicle—and attaching different importances to the obtained results, a "best position" for the assembly of this particular gear set can be determined.

Different from the vibration noise evaluation, the repeatability of single-flank checking results for the rotational orders is acceptable (see Fig. 16). Therefore analyzing the rotational harmonic contents of single-flank transmission error in reference to the ring gear indicates rotational harmonic behavior, like runout, ovality, triangularity, squareness and other rotational harmonic influences. Gear rotational harmonics can be extracted from the measured signal by FFT. Applying single-flank transmission error evaluation, side effects from rotational harmonic components moving mesh harmonic components into sidebands are non-existent. Consequently there is nothing to challenge their clear identification from vibration noise.

The sum of advantages for SFT evaluation, as intimated in the section *Vibration noise check (VN)*, has led to SFT's increasing application in mass production of spiral bevel and hypoid gears.

Single-flank checking results, continuous checking. The continuous single-flank measurement shows a pattern of harmonic mesh content results identical to that of successive measurement (see Figs. 15 and 17). However, checking time using the continuous method was approximately 65% of that using the successive checking method.

Correlation of successive with continuous check of single-flank evaluation. In Figure 18, the correlation of both checking methods is visualized. Displayed are the results for mesh 1 and mesh 2, for both cases.

No significant difference in the two approaches can be identified. The corresponding curves have a good correlation in both absolute amplitudes and patterns along the pinion cone positions, leading to the conclusion that applying the continuous method leads to identical results compared with the successive approach and can be qualified as a suitable replacement. Advantageous is the time reduction while gaining identical output.

Carrying out a correlation study for all mesh harmonic components from meshes 1–5, the results in Table 3 can be obtained. The entire range of meshes 1–5 shows acceptable correlation between the two checking methods.

Correlation between vibration noise & single-flank checking results. As in many applications with lower mesh harmonic contents, meshes 1–3 are the primary indicators for future vehicle noise emissions. Also, checking vibration noise can be a reasonable approach for testing bevel gears to predict vehicle noise.

However, higher mesh orders can indicate surface finish problems caused by surface roughness itself or feedmarks produced when generating a pinion. Also, higher rotational harmonic contents can indicate "wow-wow" sounds. Consequently, not recording and evaluating these higher orders and contents leaves a significant risk of overlooking these problems.

To show that single-flank transmission error can provide similar information compared to vibration noise, a correlation study between the two checking methods was undertaken and is shown in Figure 19.

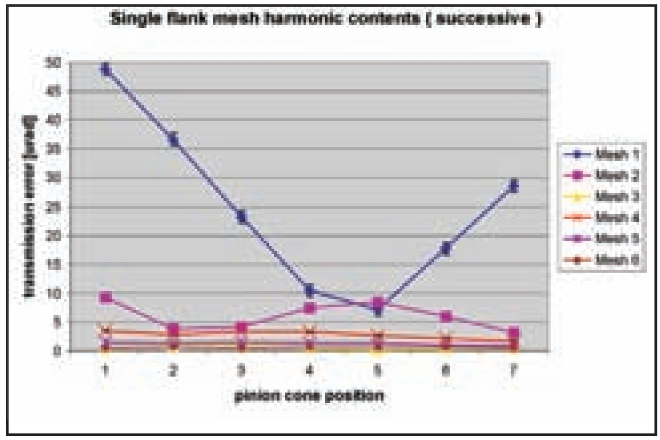

Figure 15—Mesh harmonic contents of single-flank transmission error; successive checks.

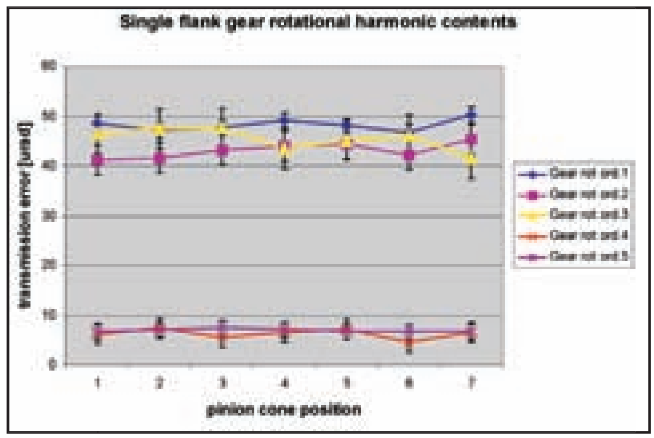

Figure 16—Gear rotational harmonic contents of single-flank transmission error; successive checks.

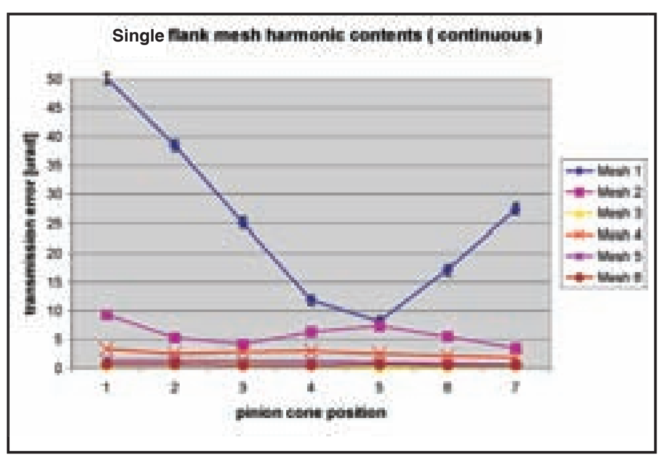

Figure 17—Mesh harmonic contents of single-flank transmission error; continuous checks.

Visualizing the mesh harmonic contents of meshes 1–3 on a logarithmic scale, the pattern of the behavior along pinion cone setting is similar, proving that single-flank transmission error checks are able to replace vibration noise checks.

Conclusion

The continuous evaluation process fulfills two different demands for the manufacturers of spiral bevel and hypoid gears, demands that—until today—were contradictory: short cycle times and full information on running behavior.

Fulfilling these demands ensures reliable statements about the noise behavior that can be expected. Applying the continuous method, which provides information identical in quality to that of the non–continuous checking method, helps manufacturers avoid assembling gear sets that are likely to fail due to unwanted noise emissions in the vehicle. Also, the continuous approach helps them in less time than the successive method, thereby reducing costs.

Recent development of roll testing after gear set assembly helps to further reduce the number of noise failures of assembled carriers by evaluating the quality of transmission, thus allowing manufacturers to filter inaccuracies in the gear set assembly stage.

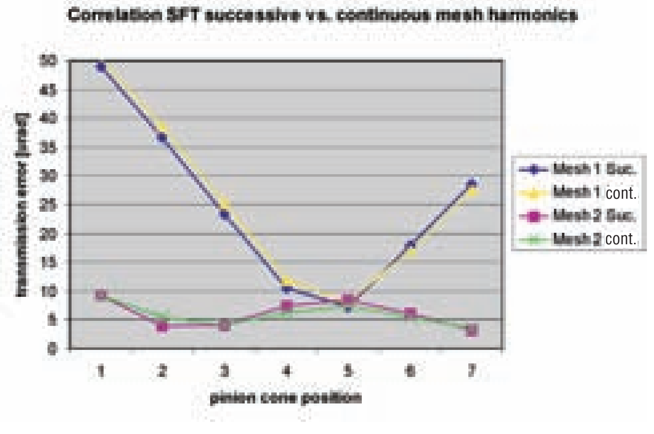

Figure 18—Single-flank transmission error successive checking vs. continuous checking.

Table 3—Correlation Coefficient Single-Flank Check, Successive Method vs. Continuous Method.	
Characteristic	Correlation Coefficient Single Flank, Successive vs. Continuous
Mesh 1	99.68%
Mesh 2	93.57%
Mesh 3	94.64%
Mesh 4	96.93%
Mesh 5	95.08%

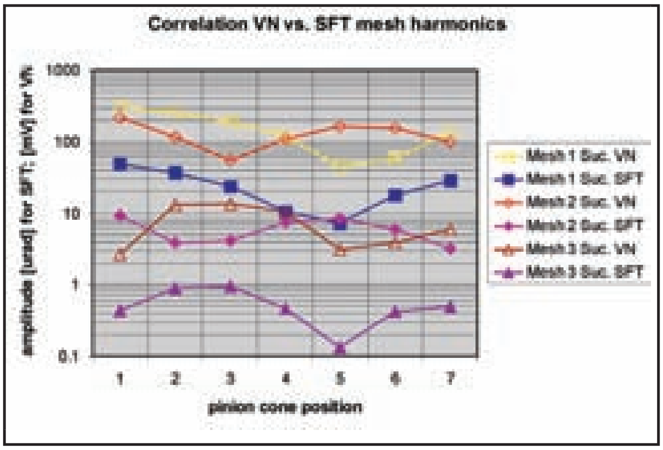

Figure 19—Vibration noise successive checking vs. single-flank successive checking.

Outlook

The new approach, enabling continuous collection of measurement data, offers options for further developments and additional analytical approaches by varying characteristics other than pinion cone setting only. The options include scans with continuously variable amounts of backlash and vertical offset. Furthermore torque- and speed-scans measuring the continuous variation of SFT and/or VN will improve the analytical capabilities of gear engineers both in the development stage and in production. With an angular tester with V, H and J deviations, angular displacements—which will necessarily occur on a bevel gear set under load—can now be simulated, opening up another variable for better research and development.

An earlier version of this paper was presented at the International Conference on Gears, held March 13–15, 2002, in Munich, Germany. It was also published by VDI Verlag GmbH in the conference's proceedings, VDI report 1665. It has been updated by the authors and is republished here with VDI's permission.

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