Surface Structure Shift for Ground Bevel Gears

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Ground bevel and hypoid gears have a designed motion error that defines parts of their NVH-behavior. Besides others, the surface structure has an effect on the excitation behavior. This surface structure is defined by the hard finishing process. Grinding shows the advantage of high repeatability, defined flank forms with closed-loop corrections, and subsequently very low reject rates. However, it is known that for example lapped gear sets show, at least at low loads, a lower excitation level, including the lower as well as the higher mesh harmonics. The generation of a ground pinion is realized with a generating motion of a cup-shaped grinding wheel that follows a path given by the axis position table. Machine motions itself in combination with resulting machine vibrations, and imperfect grinding wheel roundness during a standard grinding process can lead to a distinct surface structure with facets parallel to the contacting lines. These lines, including their waviness, are crossed while the contacting zone passes along the path of contact and leads to excitations when rolling the bevel gear set. The MicroPulse process (Refs. 1–2), as it is implemented at present, gives the possibility to influence each axis position in each line of the axis position table with small, predetermined or random amounts. The presented development is a process which improves the excitation behavior of a ground bevel gear set by altering the surface structure of a generated member along the path of contact from slot to slot. This process can include the use of the MicroPulse motions, but it is not required. Rather than using the same axis-position-table for every ground slot — the current state of the art — every slot receives changes to its specific axis-position-table. The changes from slot to slot are calculated to address the objectionable harmonic excitation. For this reason the objected harmonic excitation is predictably addressable based on a closed-loop iteration calibrating the chosen process parameters.

Introduction / State of the Art

Ground bevel and hypoid gears have a designed motion error that defines parts of their NVH-behavior. In addition to other dynamic effects, the surface structure has an effect on excitation behavior. This surface structure is defined via the hard finishing process. The most common hard finishing processes are, for example, lapping, grinding, and skiving. Grinding shows the advantage of high repeatability, defined flank forms with closed-loop corrections, and, subsequently, has very low reject rates (Ref. 3). However, it is known that lapped gear sets show — at least at low loads — a lower excitation level at lower and higher mesh harmonics.

Originally, the motions between tool and work gear are derived from a rolling process of the work gear and the generating gear. After the transformation of the rolling motion into a five- or six-axis free form machine, the motions of the single axes are basically third order functions with a dominating first order content. The coordinates for all axes are written into an axis position table that is read in by the machine controller of the free form machine.

The generation of a ground pinion is realized via the rolling motion of a cup-shaped grinding wheel that follows a path given by the axis position table. Some excitations in ground gear sets are caused by the production process itself. The machine follows each line in this axis position table and interpolates between the lines. At low roll rates, a high number of lines are given in the axis position table, and the machine can follow these lines very accurately because of the slow motions and their continuous functions. With low roll rates the machine inertia also contributes to smooth transitions between the lines in the axis position table.

At high roll rates, fewer lines are generated in the axis-position-table. The machine has to follow these lines at a higher speed while the grinding wheel RPM, determined from a given surface speed, remains the same. This results in fewer revolutions of the grinding wheel between the axis positions of the part program, creating surface pattern similar to generating flats. The minimal time increment between two axis positions is limited by the controller-specific block time, which presents the upper limit of axis positions for each given roll rate. An additional cause of certain surface pattern at high roll rates is the degrading synchronization accuracy between the three linear and two rotational axes.

The above described effects can basically be summarized as influences where machine motion, in combination with resulting machine vibration and imperfect grinding wheel roundness during a standard grinding process, will lead to a distinct surface structure with facets parallel to the contacting lines. These lines, including their waviness, are crossed while rolling along the path of contact and lead to excitations when rolling the bevel gear set. Depending on roll rate and machine dynamics, these effects can be found at lower mesh harmonics (fast roll-rates) or at higher mesh harmonics (slow roll-rates).

The MicroPulse process (Ref. 2), as implemented at present, offers the possibility to influence each axis position in each line of the axis position table with some small predetermined

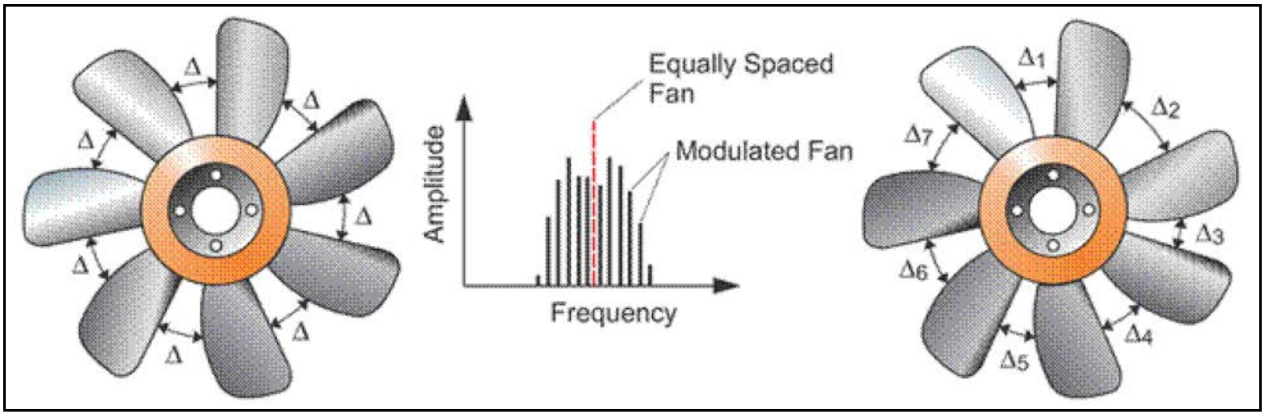

Figure 1 **Cooling fan with unequally spaced blades.**

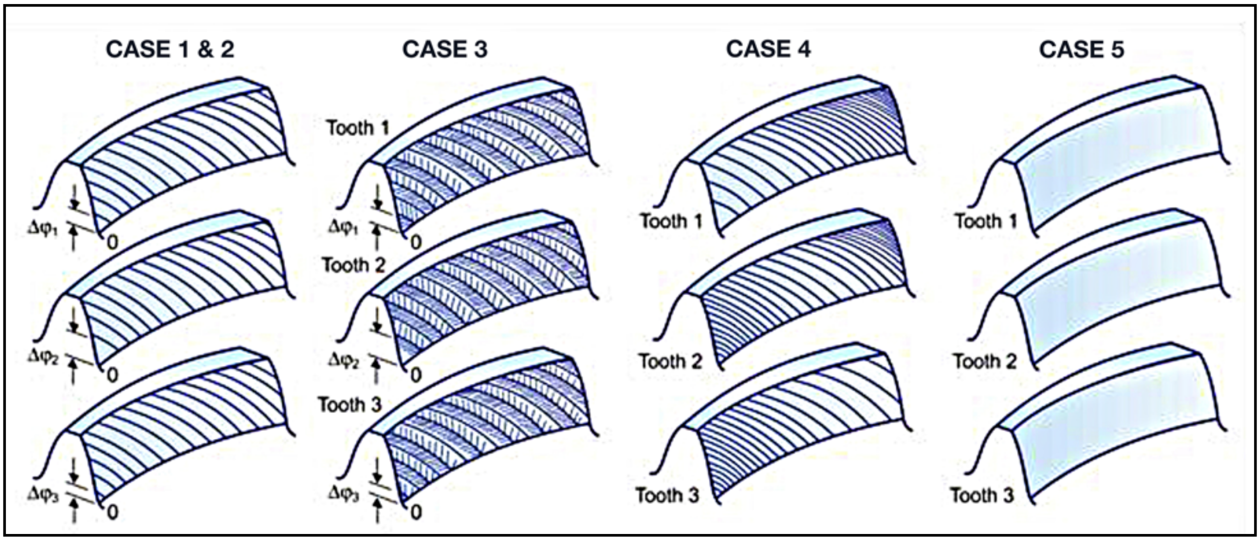

Figure 2 **Tooth mesh surface structure and excitation change.**

or random axis motion amount. In previous research (Ref. 2) MicroPulse was used to introduce a predictable and/or random surface structure on the flank to influence the NVH behavior of the ground gear set. In the standard grinding process the same axis-position-table is used for every tooth slot, leading to a similar appearance of the surface structure for every flank, if the process affected wear of the grinding wheel from the first to last slot is neglected.

Additional literature research in the field of application and inventions utilizing principles of (frequency-) modulation in the field of mechanical engineering present the separation to the inventive idea. For example, in fans (U.S. 3006603 A) (Ref. 4), torque converters (U.S.20110289909 A1) (Ref. 5), and turbines (U.S. 1502903 A) (Ref. 6), an unequal spacing of the blades leads to a changed excitation behavior. Figure 1 shows the exaggerated example of a cooling fan with unequally spaced blades. The results of these spacing variations lower the peak harmonics (e.g. — blade impact frequency of a fan) and introduce additional sidebands. The energy of the peak harmonic is distributed from the peak to the sidebands, leading to a lowering of the peak harmonic. This idea applied to the spacing of gear teeth has been part of several research projects, but showed only limited success (Ref. 7).

The above stated properties of the standard grinding process including the MicroPulse repeat precisely from one tooth to the next and lead to excitations of discrete harmonics that correlate to the machined existing surface structure, including the surface waviness, leading to measured NVH-behaviors that are not acceptable in the final application of the ground gear sets.

Theoretical and Practical Background

The idea behind the "surface structure shift" was the development of a process that improves the excitation behavior of a ground bevel gear set by altering the surface structure of a generated member from slot to slot. This process can include the use of the MicroPulse motions, but it can also be applied without MicroPulse. Instead of using the same axis-position-table for every ground slot — today's state of the art — every slot receives changes to its specific axis-position-table. The changes from slot to slot are calculated to address the objectionable harmonic excitation. For this reason, the objected harmonic excitation is predictably addressable based on a closed-loop iteration calibrating the chosen process parameters.

The following general cases (Fig. 2) are possible to change the excitation behavior using this process:

1. Shifting the roll-positions so that not every facet (waviness) is positioned the same way on each flank combined *with* a MicroPulse-motion.
2. Shifting the roll-positions so that not every facet (waviness) is positioned the same way on each flank *without* additional MicroPulse-motion.

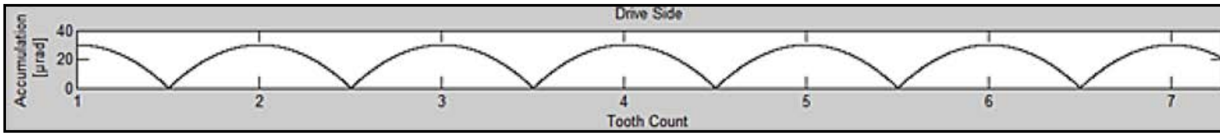

Figure 3 Simulated transmission error without any surface structure and waviness.

3. Changing the position of every facet (waviness) on every flank *only* by applying the MicroPulse motions.
4. Changing the distances of the roll angle increments in the axis position table along a slot (from start-roll position to end-roll position) with and without a different function from slot to slot.
   - Changing the position for every facet/waviness for every flank with the same amount of shift (every flank has the same pattern, only shifted versus the original pattern), utilizing roll-position shift and/or MicroPulse. This change is targeted to counteract dynamic events during the grinding process, leaving a surface without significant surface effects, eliminating higher harmonic excitations.

The amount of roll-position shift in cases 1) and 2) is a result of a calculation based on:

- An analysis of the results of a single flank test (SFT) of the evaluated gear set.
- An analysis of the original axis position table (within the part program) that would be used in a standard grinding process for a particular part, especially the relation between the number of lines in the axis position table and the roll angle.
- An analysis of the existing contact pattern.

The simulation in Figure 3 shows the transmission error caused by a designed motion error, without any surface structure influence. Desirable is a low transmission error leading to a low excitation level, by means of low motion error amplitudes. Note that a certain amount of crowning in profile and face width direction of the flanks is required in order to maintain a good contact pattern under high load situations. Crowning is a deviation from conjugate flank surfaces and will cause correlating amplitudes of motion error.

A fast Fourier transformation (FFT) of this transmission error (Fig. 3) leads to the results in Figure 4. This figure shows the most desired result of an FFT of a single-flank test (SFT) of a gear set showing only an excitation due to the designed motion error.

The FFT of an SFT of a measured real gear set (Fig. 5) shows a different behavior than the analysis of the theoretical gear set (Fig. 3), especially in the higher mesh harmonic range.

The amplitude of the 6th mesh harmonic is pronounced, which is not obvious in the analysis of the designed motion-error. In this case the amplitude of the sixth mesh harmonic is at 9.4 µrad. It is assumed that surface structure effects/waviness on the standard ground flank lead to the effects of a higher sixth mesh harmonic. To trace back these effects, they are replicated via simulation with a purposely introduced surface structure (Fig. 6). Here the simulated transmission error does not only consist of the designed motion error, but also of a surface structure with a pattern of six-grooves-per-motion error parabola.

An FFT of the transmission error (Fig. 6) leads to the results in Figure 7; Figure 7 shows the result of an FFT of a simulated SFT of a gear set, including an additional surface structure (waviness); and due to that, an additional excitation of the sixth mesh harmonic, correlating to the measurement of the real gear set.

The simulation including the surface structure represents a simple model leading to the wanted replication of the effects of a higher sixth mesh harmonic measured during an SFT of the real gear set.

The most efficient way to lower the amplified excitations in Figure 7 would be the elimination or reduction of the effects that take place during the standard grinding process itself. This is desirable, but the possibilities are generally limited by machine stiffness and dynamic behavior in the grinding process.

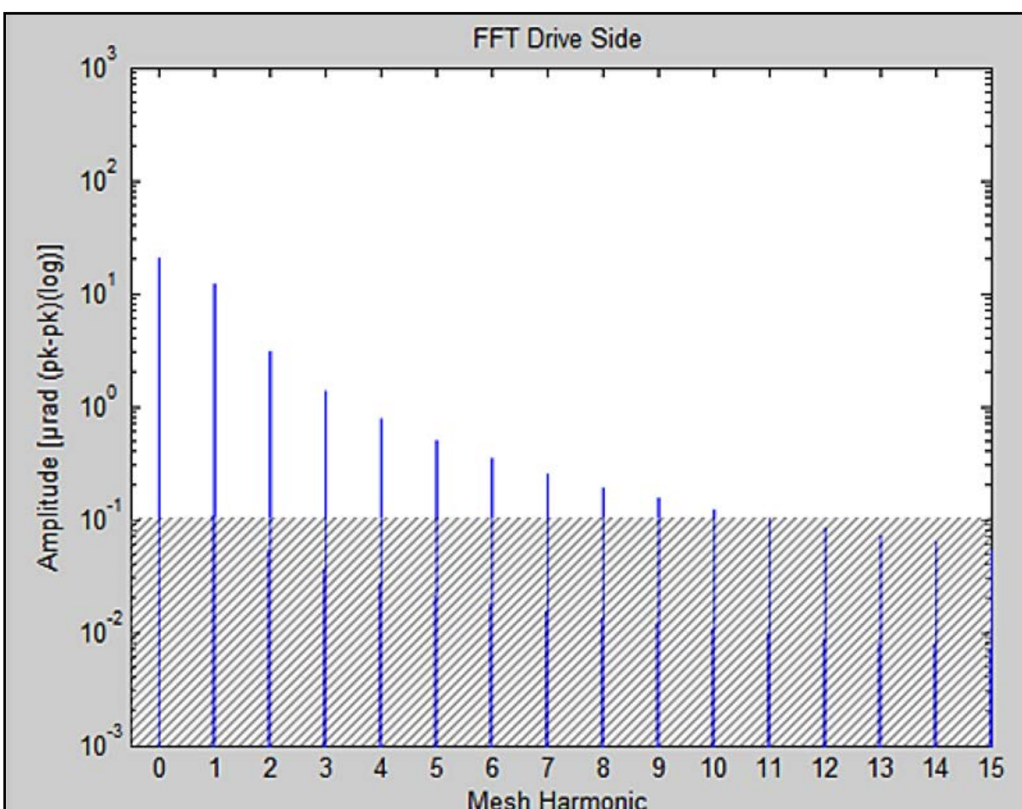

Figure 4 FFT of transmission error caused by designed motion error without any surface structure (waviness).

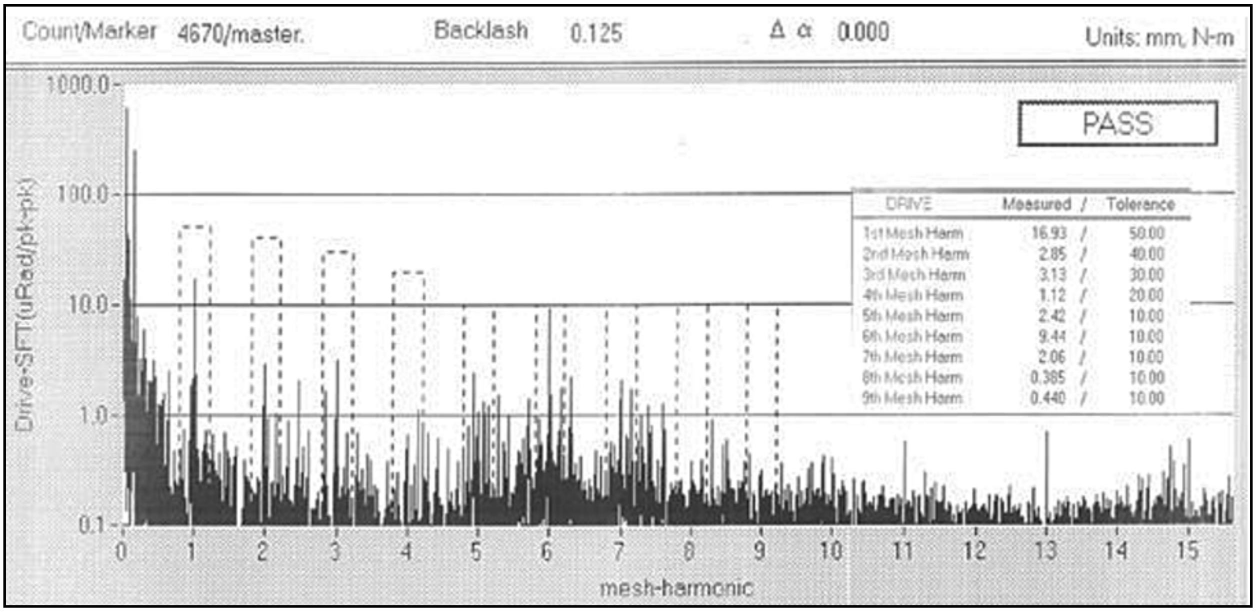

Figure 5 FFT of SFT of a real gear set (baseline) with high 6th mesh harmonic.

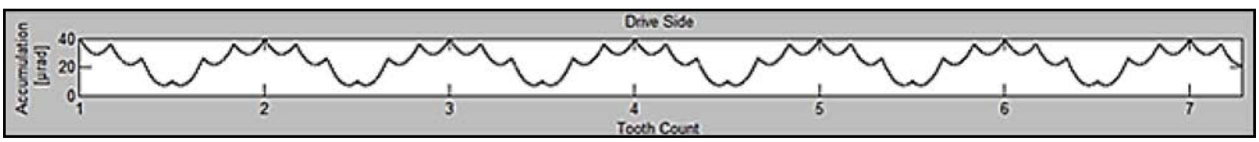

Figure 6 Simulation of transmission (motion) error — including anticipated surface structure (waviness) — leading to a high 6th mesh harmonic excitation.

Other ways to change the excitation behavior are to change several parameters of the standard grinding process. One example is to grind with lower roll rates. If the machine vibrations during grinding are independent of the roll rate and keep their frequency, then the resulting surface structures will become finer. This will lead to a shift of the excitations from lower to higher mesh harmonics.

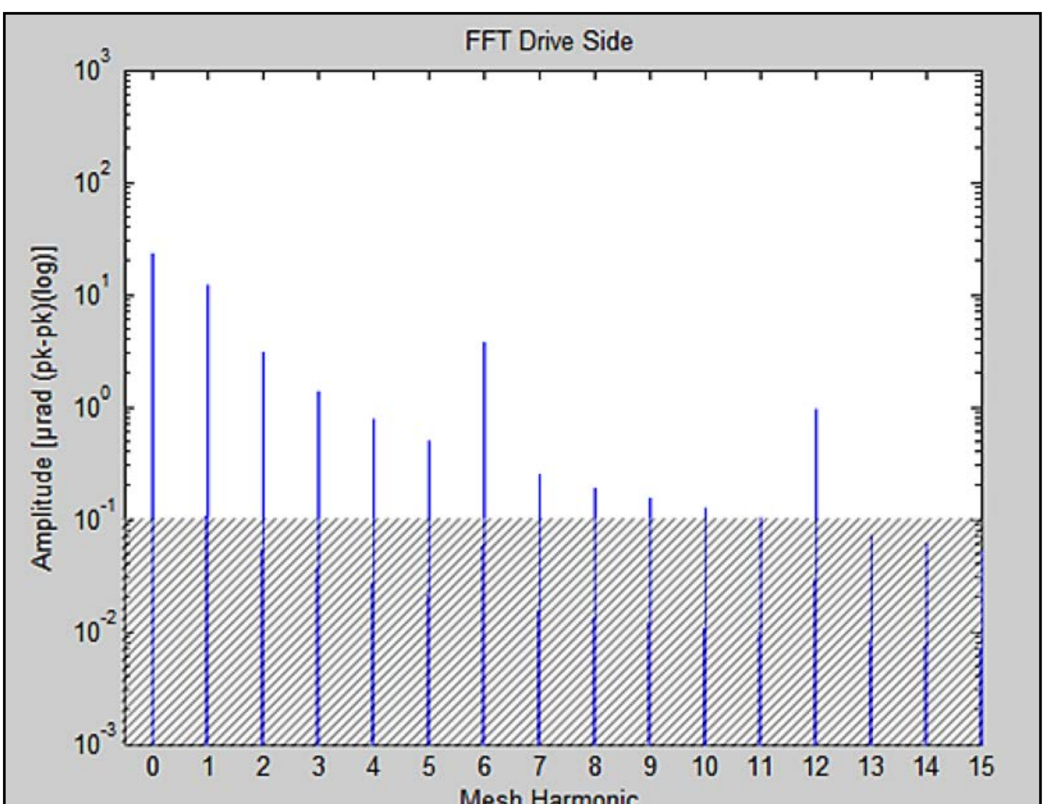

Figure 7 FFT of transmission error, including waviness leading to increased amplitudes of 6th and 12th order mesh harmonics.

Excitation problems can always occur on both members of the gear set. If one member is already ground in a certain quantity, then counteractions can only be applied to the other member. A purposely introduced waviness to offset the problems of the opposite member (EP 20130006061) seems impractical — in bevel gear grinding in particular — if this requires dressing waviness in the grinding wheel profile. The roll motion in generated pinions and gears and the plunging motion in non-generated gears will not allow certain grinding wheel profile waves to be transferred to the flank surfaces. The process, affected by relative sliding between grinding wheel profile and flank surfaces, would wipe out sinusoidal or similar wave forms with maxima, minima, and inflection points. Therefore the inventive process does not use modifications to the grinding wheel profile, but strictly uses machine motions (MicroPulse) and process parameters (roll-positions) to introduce and alter surface structures, and is therefore limited to the generated member.

The theoretical idea is to change and improve the excitation behavior by changing the position of the surface structure (waviness) on each flank (structure shift), which is fundamentally different from the ideas of unequal tooth spacing that are referenced as state of the art. A change of the spacing in a defined or random way will lower the gear quality according to the internationally defined standards. Spacing variations cause also negative side effects like low frequency rumbling, which is not the case in the inventive process.

In case of a structure shift, only the surface structure is addressed in a defined way. Depending on the case, the surface structure in the entire generated flank area is positioned differently, e.g. — from slot to slot. In all cases this is done via roll-position-shifts and/or roll-increment-changes and/or via utilizing the MicroPulse motions.

Case 1. To change and improve the excitation behavior, the following steps are applied according to Case 1), which utilizes

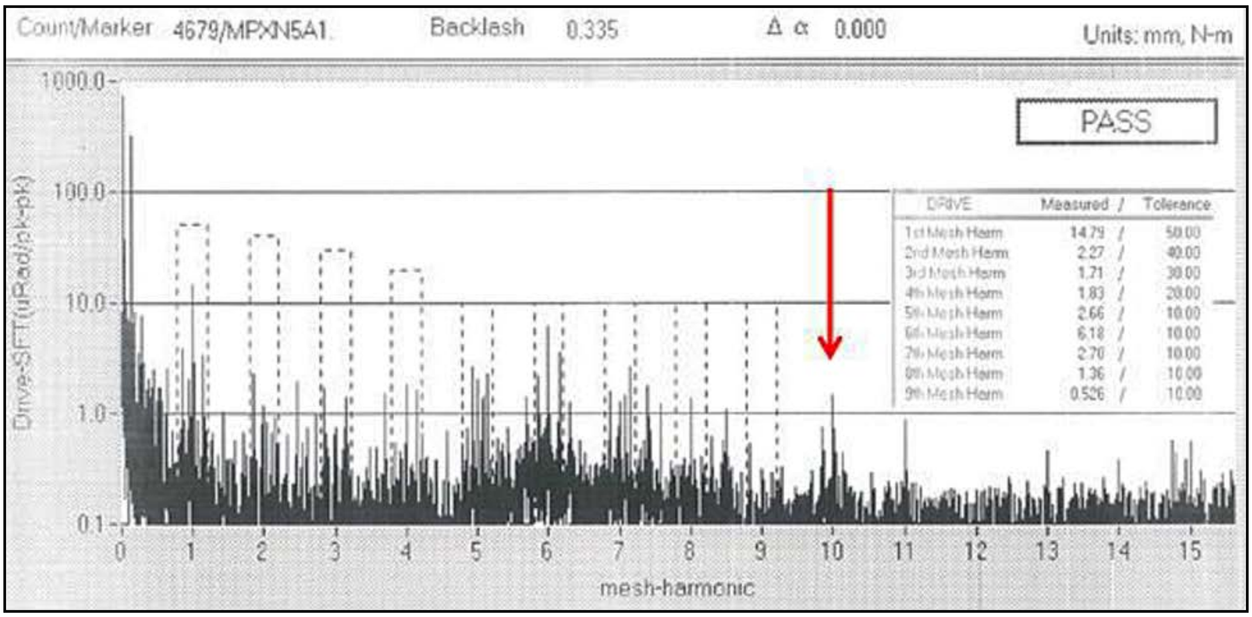

Figure 8 FFT of transmission error with MicroPulse leading to increased amplitude of 10th and 11th order mesh harmonics.

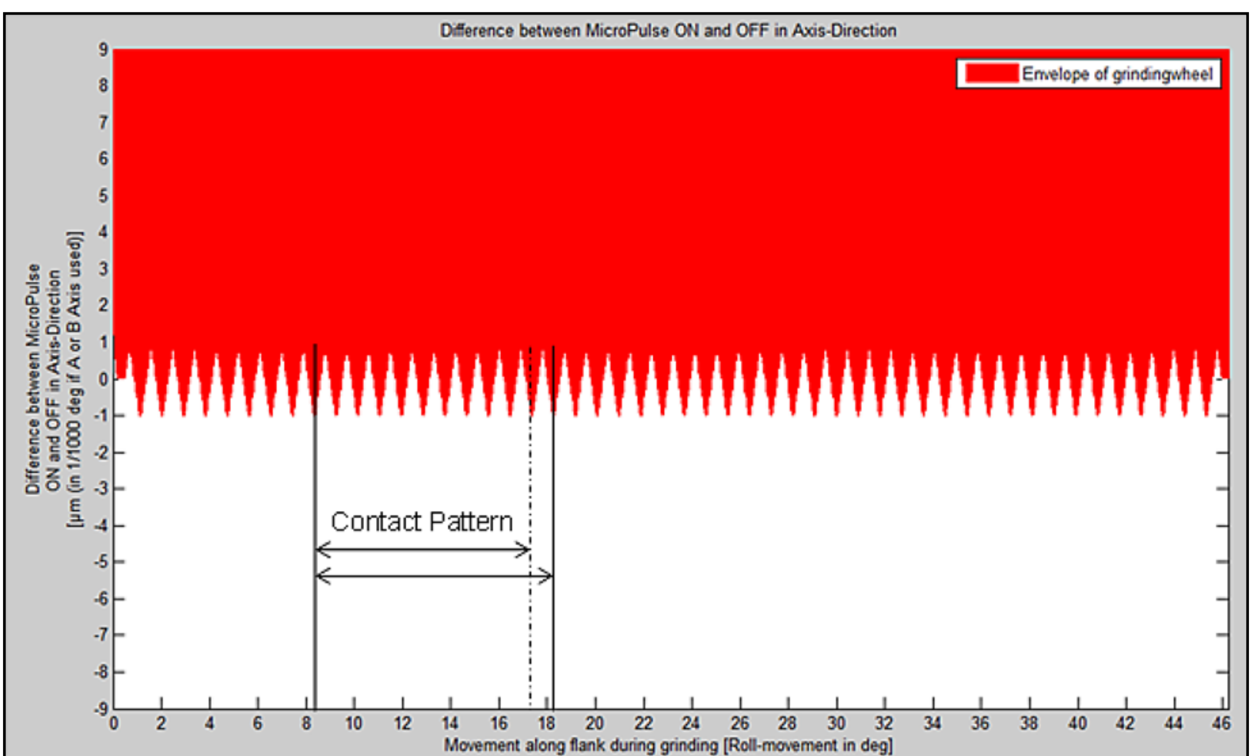

Figure 9 Theoretical effect of MicroPulse on surface structure, leading to an excitation of 10th and 11th order mesh harmonic (here ***N***=5).

MicroPulse motions and a predetermined change of the roll positions per slot.

The objected harmonic is identified via an SFT or similar test (Fig. 5), possibly using a master gear for the uninfluenced member. In this example the sixth mesh harmonic is the objected harmonic.

The iteration process is started to identify the correct MicroPulse parameters and to correlate them to the objected mesh harmonic. In a first grind of the generated member, the MicroPulse division-factor (parameter) N is chosen via educated guess. The amplitude A is chosen within the range of one 1 μm to alter the X axis motions. This axis moves the grinding wheel almost perpendicular into the flank surface.

The SFT of the newly ground part rolling with the master gear delivers a distinctly higher excitation of a certain harmonic (Fig. 8).

Based on the artificially excited harmonic (Fig. 8), a correlation can be established between the division-factor N of the MicroPulse and the introduced surface structure, leading to a distinct higher harmonic (Fig. 9).

In this case the chosen division-factor of $N=5$ leads to a higher 10th and 11th mesh harmonic.

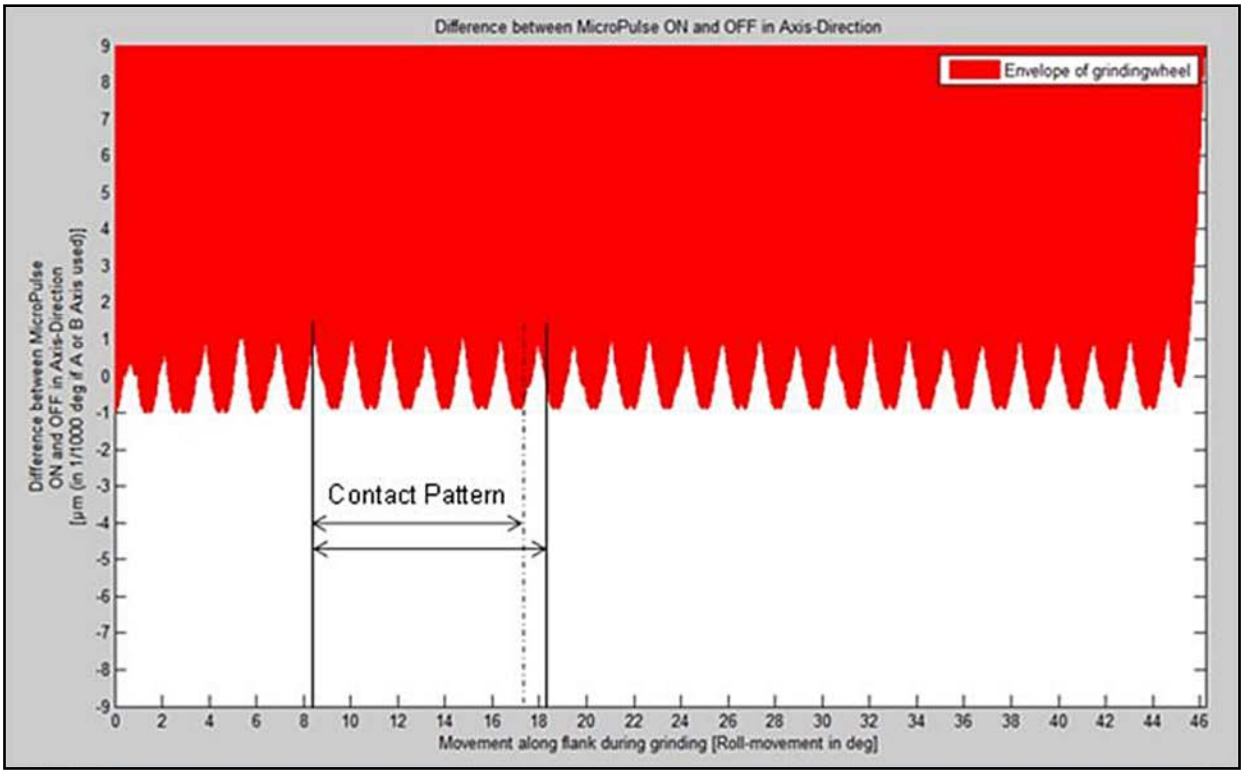

Figure 10 **Theoretical effect of MicroPulse on surface structure with iterated and correct parameter *N*; predicted to lead to an excitation of the 6th mesh harmonic (here *N*=8).**

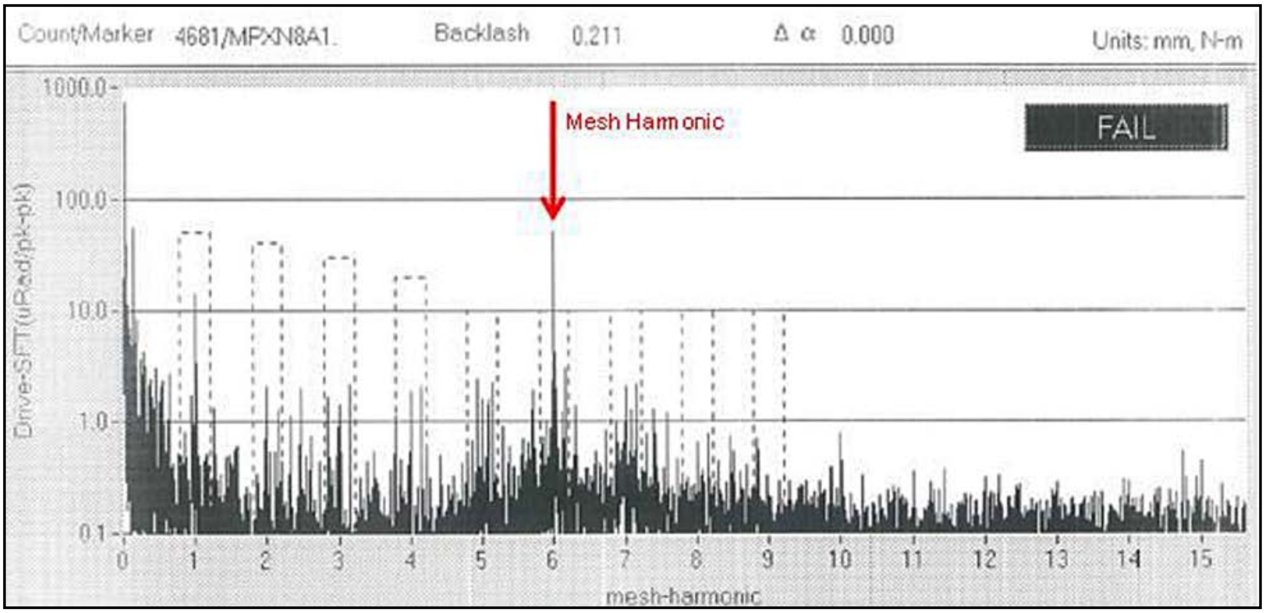

Figure 11 **Measured FFT of real SFT with higher 6th mesh harmonic due to MicroPulse.**

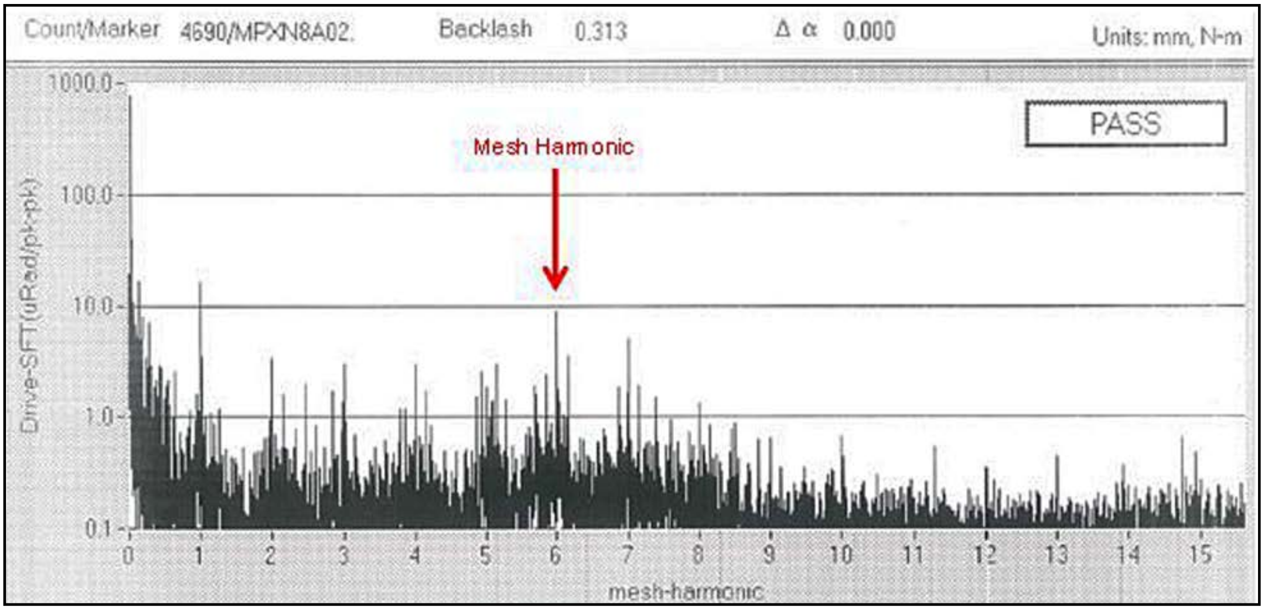

Figure 12 Measured FFT of real SFT with higher 6th mesh harmonic (8.8 µrad) due to MicroPulse with *N*=8 and *A*=0.2 µm.

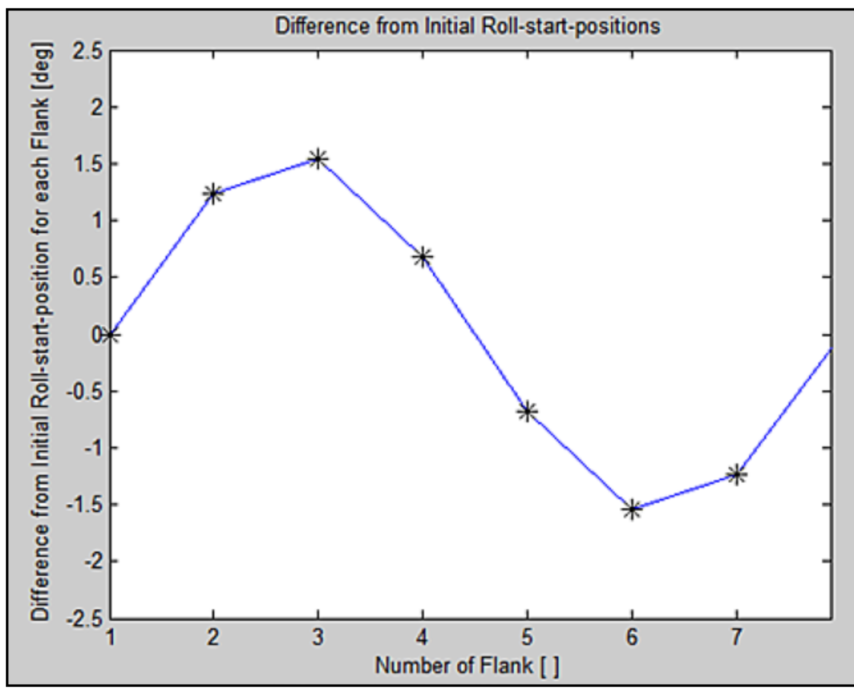

Figure 13 New start roll-positions for every slot with $N_R = N-1$ (here *N*=8).

With this correlated MicroPulse parameter *N* the new correct parameter *N** is calculated via simulation of the MicroPulse process (Fig. 10), which leads to an excitation of the objected mesh harmonic (Fig. 11). If required, after having the part ground with the new parameters, additional iterations must be conducted to address the objected mesh harmonic. This leads to the correct final parameter *N*.

The amplitude *A* of MicroPulse is lowered to an amount where the influence is still measurable and influencing the objected harmonic. The amounts will be in the lower tenth of a micron range (Fig. 12).

The shift of the pattern from flank to flank is calculated via the following procedure:

The amount of roll angle per line (RAPL) of the original axis-position-table is calculated:

$$RAPL = \frac{(Toe-roll-position)-(Heel-roll-position)}{Number\ of\ lines\ in\ axis-position-table} \tag{1}$$

The parameters triggering the shifted surface structure counteract the effects of the original surface structure, and are calculated from the MicroPulse parameters. To calculate the correlating shift in the roll-position for every slot (ΔRP_j) to change the surface structure from slot to slot, the previously determined division-factor *N* of MicroPulse is utilized. The shift-amplitude-factor N_R is calculated for a shift that is organized via a sine function:

$$\Delta RP_{j=i+1} = A_s * \sin\left[\left(\frac{2*\pi}{z_1}\right)*i\right] \tag{2}$$

with,

$$A_s = N_R * RAPL \tag{3}$$

with,

$$N_R = N - 1 \tag{4}$$

This formula will lead to a shift utilizing the maximal amount of amplitude. This means that when organizing the shift via one sine-wave, patterns that are maximally shifted will theoretically line up with the original non-shifted surface structure.

Alternatively

$$N_R = N - (1 + 0.1 * N) \tag{5}$$

This will lower the maximal amount of utilized shift-amplitude so that, theoretically, no alignments with the original structure will occur.

The shift-amplitude-factor in this case correlates to MicroPulse parameter *N* but can also be a factor calculated and chosen in a different way.

The shift-amplitude A_s is calculated via this formula:

$$A_s = N_R * RAPL \quad (6)$$

To calculate the amount and distribution of shift of the roll-position for each slot (ΔRP_j), a single sine-wave is utilized.

$$\Delta RP_{j=i+1} = A_s * \sin\left[\left(\frac{2*\pi}{z_1}\right)*i\right] \quad (7)$$

with i going from 0 to (z_1-1) and with z_1 being the number of teeth of the part.

The newly calculated ΔRP_j are added to the toe-(dwell) and heel-(dwell)-roll-positions for every slot, whereas the slot number $j=1$ has the untouched baseline roll-positions, thus leading to changed roll-positions (Figs. 13 and 14).

Also, other shift-patterns are possible; for example, a linear shift with a manually chosen amount of shift for every slot; the center of roll is not changed.

This leads to a pattern-shift $\Delta\varphi_i$ for every flank. Figure 15 shows the pattern shift for

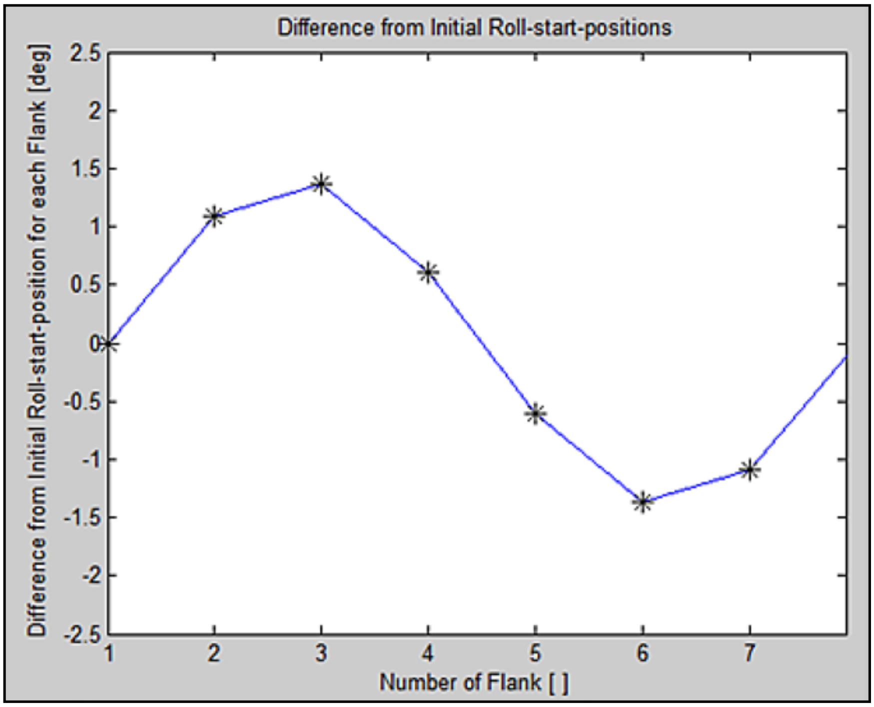

Figure 14 New start roll-positions for every slot with $N_R = N-(1+0.1*N)$ (here $N=8$).

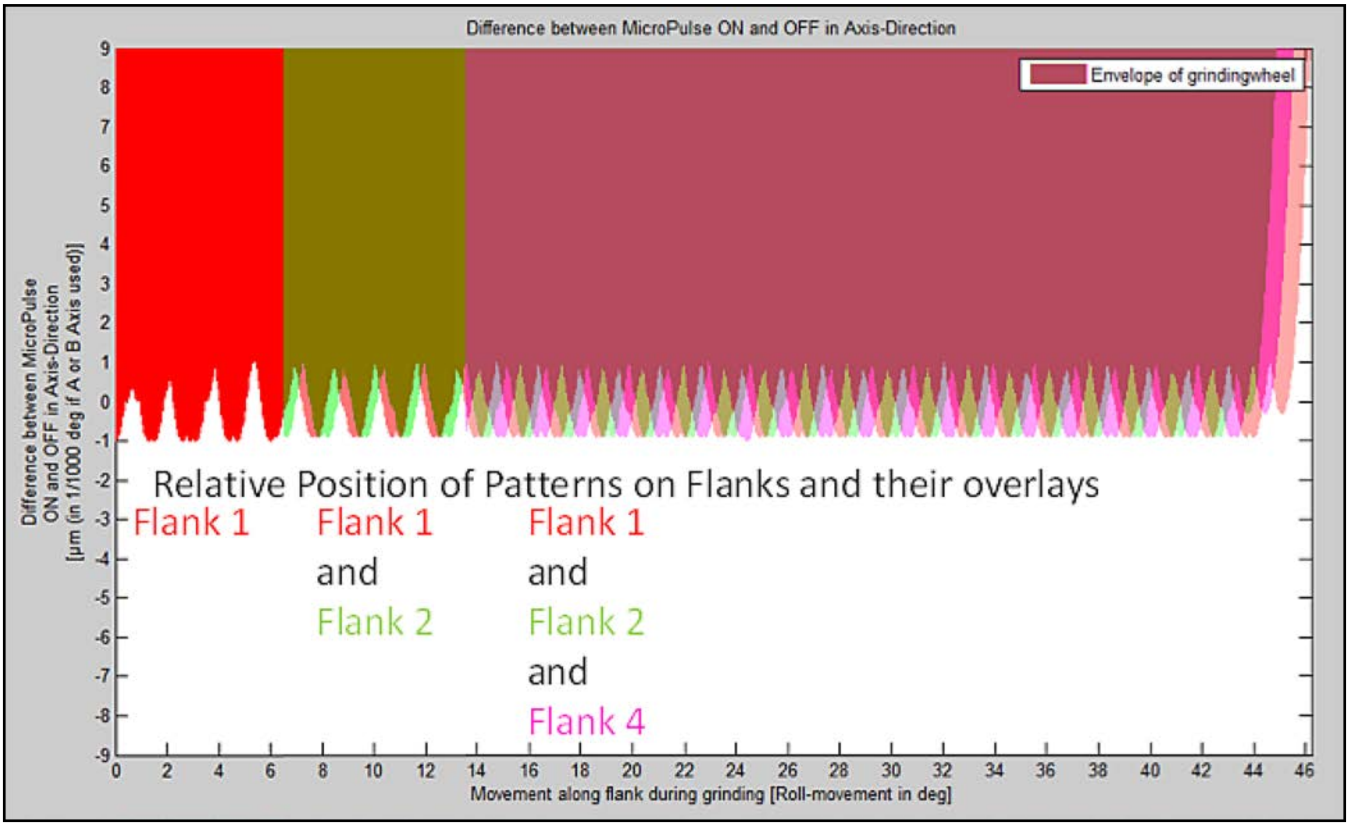

Figure 15 Relative position of patterns on flanks in regard to the new roll-positions for every slot (here $N=8$, $A=1$ µm).

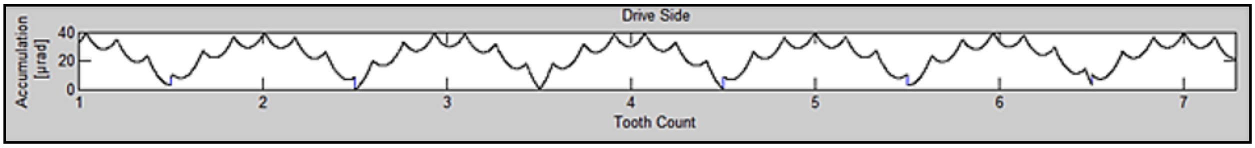

Figure 16 **Simulation of transmission (motion) error, including anticipated surface structure.**

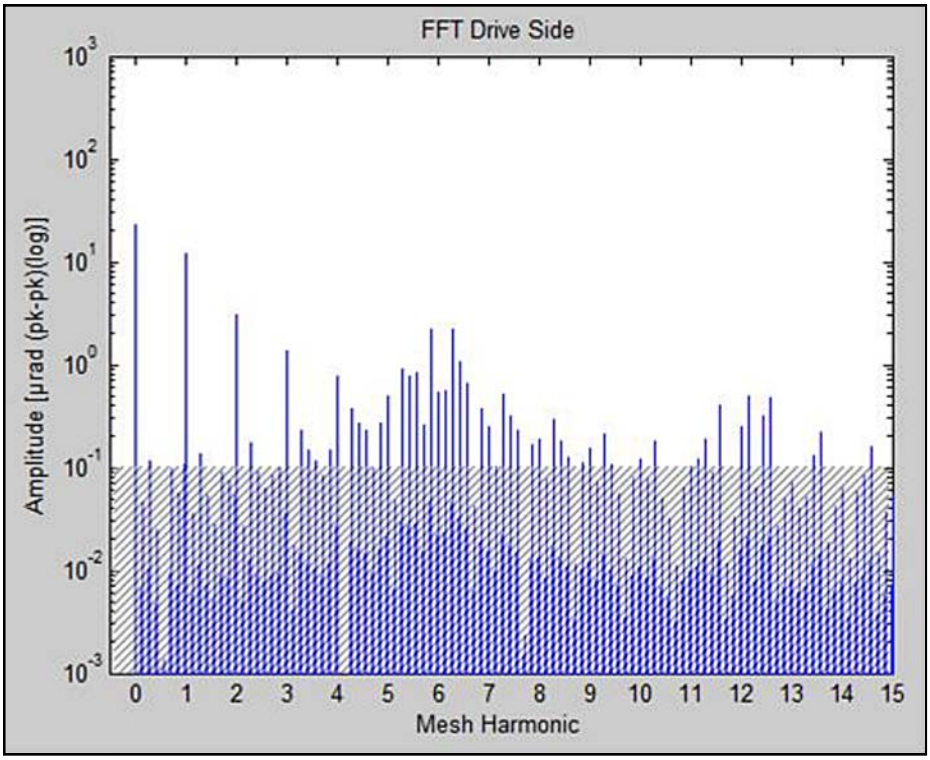

Figure 17 **FFT of transmission error, including introduced surface structure with shift of structure from flank to flank, leading to lowered peak harmonics and to introduction of sidebands around 6th- and 12th-order mesh harmonics.**

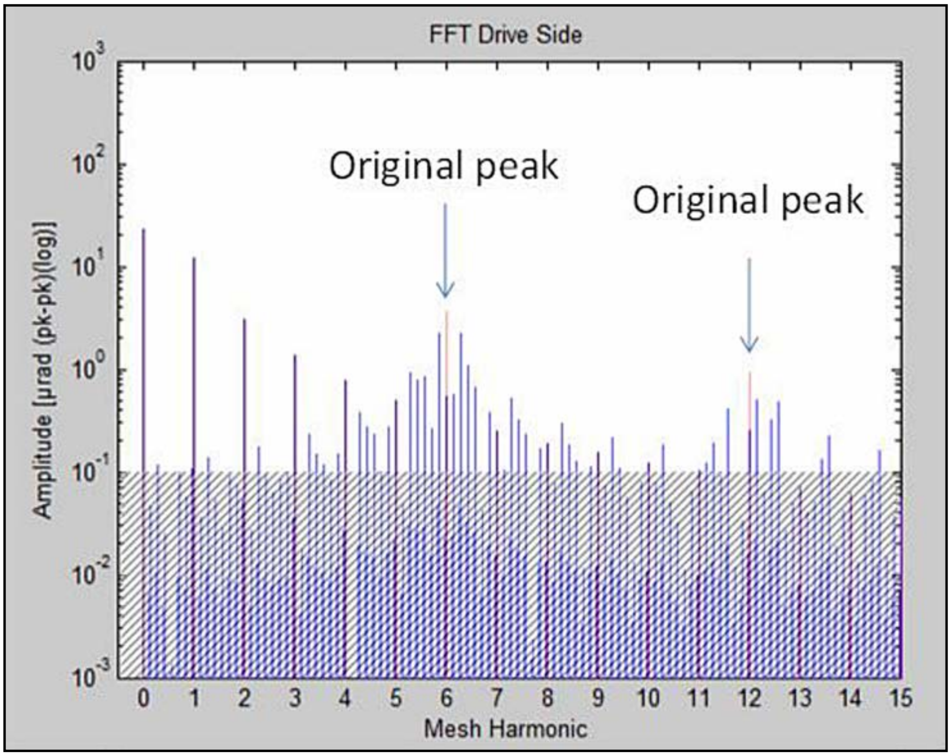

Figure 18 **Comparison of FFT of transmission error, including introduced surface structure with (blue) and without (red, Fig. 7) shift of structure from flank to flank, leading to lowered peak harmonics and introduction of sidebands around 6th- and 12th-order mesh harmonics.**

three flanks using $N_R = N-1$. For better visibility, the amplitude is chosen with $A = 1$ µm.

Applying the pattern shift to the simulation of the transmission error results in the surface structure shown (Fig. 16); every flank shows a differing position of the surface structure, leading to the simulated FFT of SFT (Fig. 17).

The comparison of the simulation with introduced surface structure and no shift (Fig. 7) — with the shifted surface structure (Fig. 17) — is shown (Fig. 18). The red graph shows the original non-shifted FFT of the simulated SFT (Fig. 7), whereas the blue graph shows the FFT of the SFT of the shifted surface structure.

By applying factors for the surface structure shift that were gleaned — via simulation to real-world grinding process — we learn that this approach leads to a following of actual-measured FFT of SFT (Fig. 19), and can be compared to the results of the original FFT of the baseline SFT (Fig. 5). The 6th mesh harmonic amounts to 1.4 µrad; maximal amount of the sidebands is 4.5 µrad.

Case 2. In this case, only a roll-position-shift is utilized without any additional micro-motions via MicroPulse. Facets at high roll rates can correlate to the lines in the axis-position-table and to the excited mesh harmonics. To improve and change the excitation behavior in these situations, the already-existing surface structure is shifted on the flank surface.

The shift-amplitude A_{SR} in roll-position for every slot is calculated via this formula:

$$\Delta RP_{j=i+1} = A_{SR} * \sin\left[\left(\frac{2*\pi}{z_1}\right)*i\right] \quad (8)$$

with,

$A_{SR} = RAPL$ and i going from 0 to (z_1-1) and with z_1 being the number of teeth of the part.

Figure 20 shows the FFT of SFT using unmodified roll-positions, and Figure 21 shows the FFT of SFT using modified roll-positions.

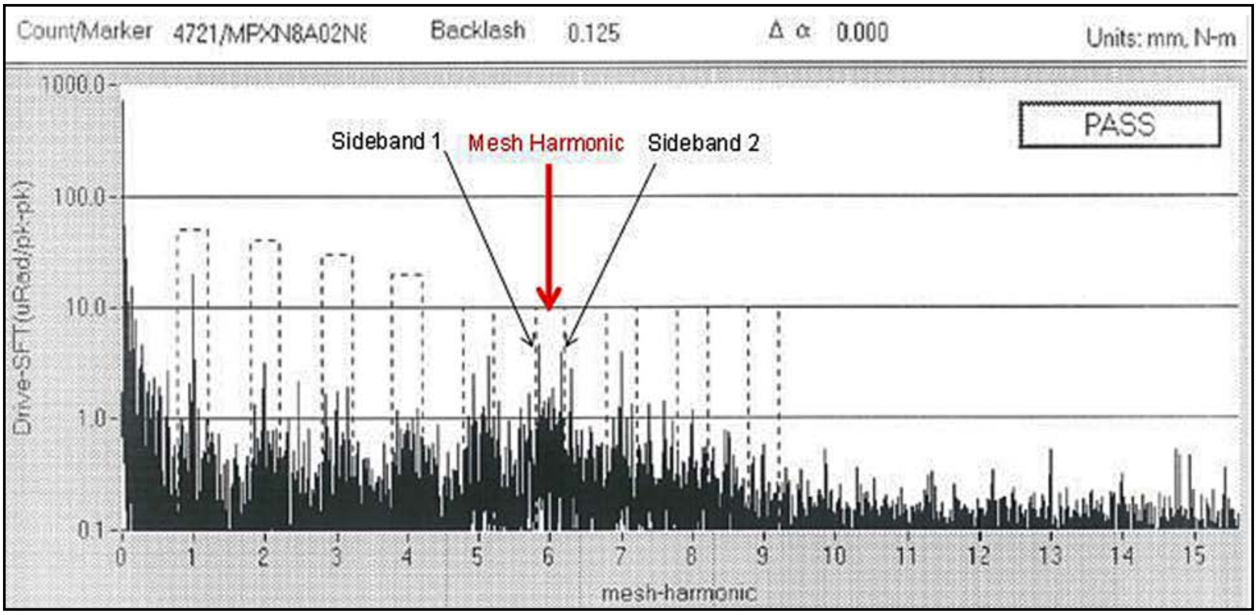

Figure 19 Measured FFT of real SFT with introduced and shifted surface structure via MicroPulse ($N=8$, $A=0.2\,\mu m$).

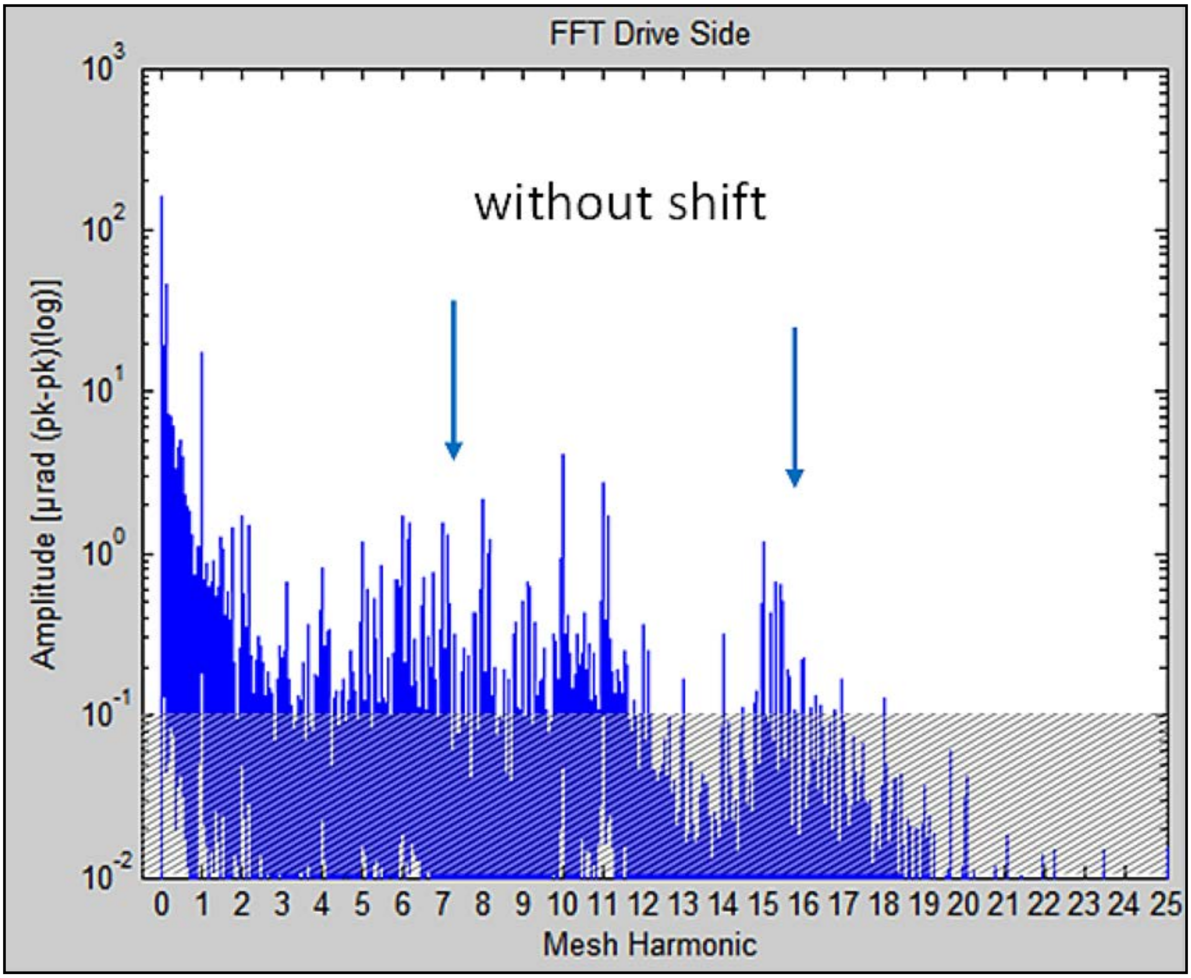

Figure 20 Measured FFT of real SFT with ground at a roll-rate of 20°/s without any roll position-shift.

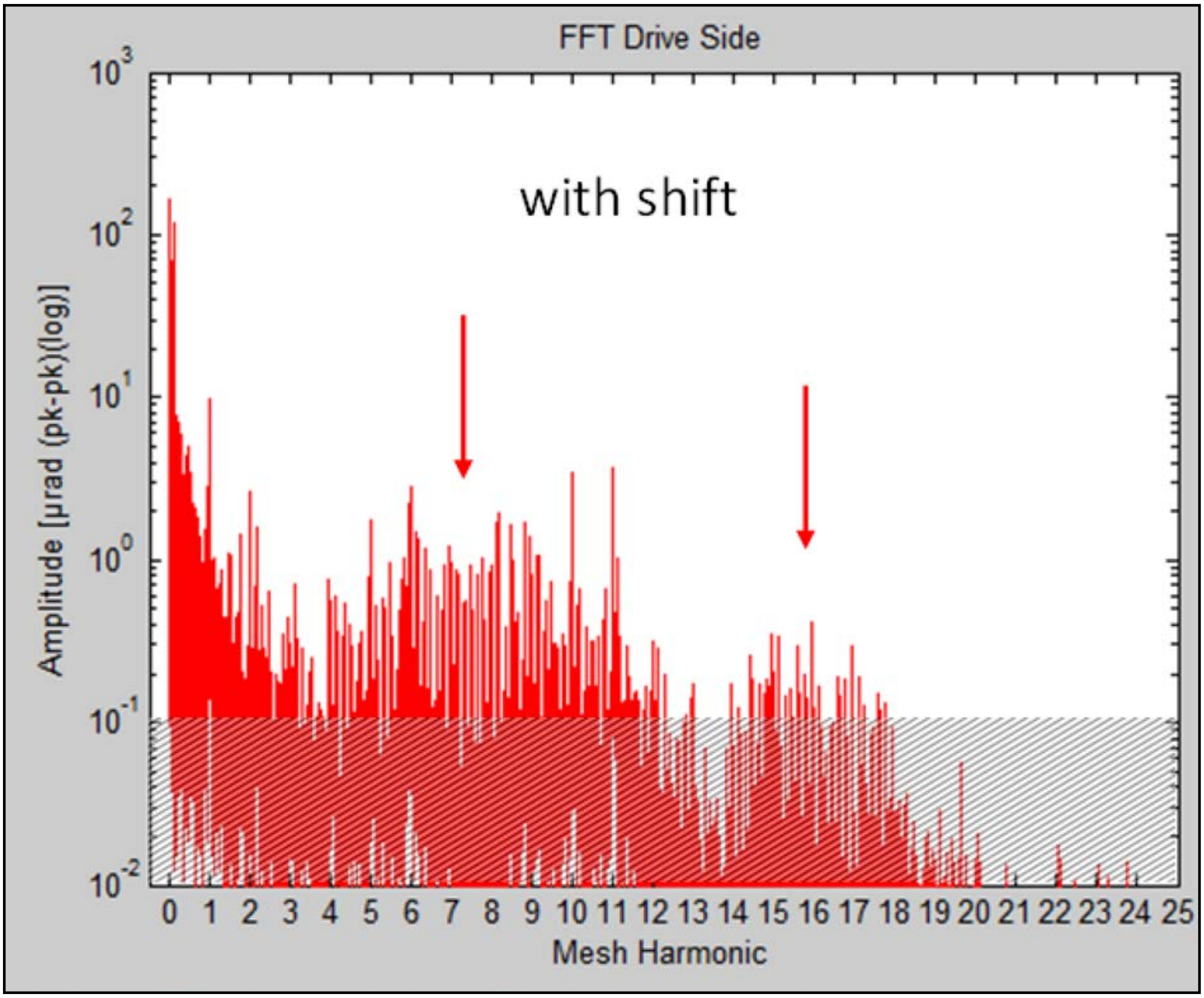

Figure 21 Measured FFT of real SFT with ground at a roll-rate of 20°/s with roll-position-shift.

Visible are the high peak harmonics in the area of 7th to 8th mesh harmonic, as well as in the area of the 14th to 16th mesh harmonic.

Visible is the lowering of peak harmonics in the area of 7th to 8th mesh harmonic as well as in the area of the 14th to 16th mesh harmonic.

The 10th and 11th mesh harmonic were identified as machine-introduced harmonics.

Case 3. In this case only the MicroPulse motions are utilized to introduce and alter the position of the facets on each flank. Patterns can only be realized if the resolution of the axis position table is sufficient.

Case 4. In this case, the distances of the roll angle increments in the axis position table along a slot (from start-roll position to end-roll position) are changed with or without a different function (for example, sine-function) for every slot. This process can also include additional MicroPulse axis movements.

Case 5. Changing the position for every facet/waviness for every flank with the same amount of shift (every flank has the same pattern, only shifted versus the original pattern) utilizing roll position shift and/or MicroPulse. This change is targeted to counteract dynamic effects during the grinding process.

Discussion and Future Work

Today, basic calculation tools for the "surface structure shift" are used to optimize gear sets, starting with an educated guess, calculation of the addressed mesh harmonic, and a guided optimization, as shown in this paper.

An alternative to the iteration process could be to calculate the exact division-factor *N* via the theoretical analysis of the contact pattern — assuming that theoretical and practical contact have a high correlation for the objected gear set. This means that if the objected gear set is far away from the original design, a "fresh" development or a reverse engineering via CMM to obtain the actual TCA is required. The first and last roll positions for the beginning and end of the contacting area at low load are obtained via analytical tooth contact analysis, e.g. — *Unical.*

The existing surface structure within this roll angle has a certain pattern, based on the SFT result, which is then replicated with the correct choice of the division factor *N* of the MicroPulse process. This should be done via simulation tools leading, e.g., to a MicroPulse pattern with six peaks within the contacting area.

In addition, future developments regarding the surface structure should focus not only on generated, but also on the non-generated members.

The tool of the "surface structure shift" is relatively new and needs further investigation and practical studies. This should include testing not only of gear sets on the test rig, but also end-of-line tests as well as vehicle testing.

Conclusion

- The results show that there is an effect of the "surface structure shift" as a tool to address a targeted reduction of excitation of higher harmonics in ground bevel gear sets.
- The theoretical background of "surface structure shift" and MicroPulse are explained at the beginning of this paper. After this, several cases are shown, on how to influence the surface structure with these tools. The two most relevant cases are explained in detail. Case 1 utilizes additional machine motions (MicroPulse) to influence the surface structure on the generated ground bevel gear flank surface, in combination with the "surface structure shift," predictably altering the surface structure from flank to flank. This leads, as shown via practical example, to the capability of lowering higher mesh harmonic excitations while introducing sidebands.
- Case 2 only uses the surface structure shift, without additional machine motions, and is preferably used under high-speed machine motions, leading to an improved higher mesh harmonic behavior.
- In general, the processes presented here aim at predictably introducing more sidebands while lowering higher mesh harmonic peak amplitudes.

References

1. Stadtfeld, H. J. and U. Gaiser. Method of Finishing Bevel Gears to Produce a Diffuse Surface Structure, U.S. Patent US 7462092 B2, 2007.
2. Stadtfeld, H. J. "MicroPulse – Structure Grinding," 2007, The Gleason Works Publishing, Rochester, New York.
3. Stadtfeld, H. J. "The Science of Gear Engineering and Modern Manufacturing Methods for Angular Transmissions," 2014, The Gleason Works Publishing, Rochester, New York.
4. Caruso, W. J. and B.M. Wundt. Turbo-Machine Blade Spacing with Modulated Pitch, U.S. Patent US 3006603 A, 1961.
5. Marathe, B. Torque Converter with Asymmetric Blade Spacing, U.S. Patent Application US 20110289909 A1, 2011.
6. Campbell, W. 1924, Steam-Turbine Rotor and Method of Avoiding Wave Phenomena Therein, US Patent US 1502903 A.
7. Strunk, S. 2015, "Gezielte Erzeugung von Oberflächenstrukturen und Nutzung von Modulationsprinzipien zur Optimierung des Verhaltens geschliffener Kegelradgetriebe," 2015, M.S. thesis, FG KFT, TU Ilmenau, Germany.

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