Avoid Ripples on Gears

Simulation of Vibrations During Generating Grinding and Hobbing

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Abstract

Gearbox noise is often caused by ripples on the gear surfaces. In order to identify the causes of these ripples and to improve manufacturing processes, methods of manufacturing simulation for gear hobbing and generating grinding have been used successfully for quite some time. A new software module now allows turntable vibrations, tool vibrations and vibrations decoupled from the gear cutting process to be considered in the simulation. The software module is characterized in particular by the fact, that it is not initially necessary to distinguish between the types of vibration, but all three variants can be considered simultaneously. A practical example from production is used to show how this approach can be used to find the fingerprint of manufacturing in the measured spectrum of ripple. Finally, it will be demonstrated how simulation can be used to find more favorable process settings and thus to avoid surface ripples effectively and economically without having to eliminate the cause.

Ripples on Gear Surfaces

In automotive engineering, the noise level of the transmission has become an important quality criterion. This applies in particular to electromobility, since the absence of noise from the combustion engine is making transmission noise much more noticeable. Transmission noise is often caused by ripples on the gear surfaces. Today, these ripples can be detected very accurately and reliably on gear measuring devices [1], [2].

Figure 1 shows in the top center the results of a gear measurement as deviation curves in profile or helix direction. In the so-called common evaluation at the bottom, all curves are displayed phase-correctly over the angle of rotation and appended to each other. In this way, the curves are in relation to each other in the same way as they are effective during rolling [3]. The contact ratio of the teeth is reflected here in an overlapping of the curves. With the help of sine functions, a discrete order spectrum is now calculated. Comparisons with the results of End-of-Line (EoL) noise testing in the automotive industry regularly show very good agreement between the noise orders and the measured orders for noisy gears. This evaluation of a measurement of all teeth represents the reference evaluation today and can detect ripple amplitudes down to 20 nm [2].

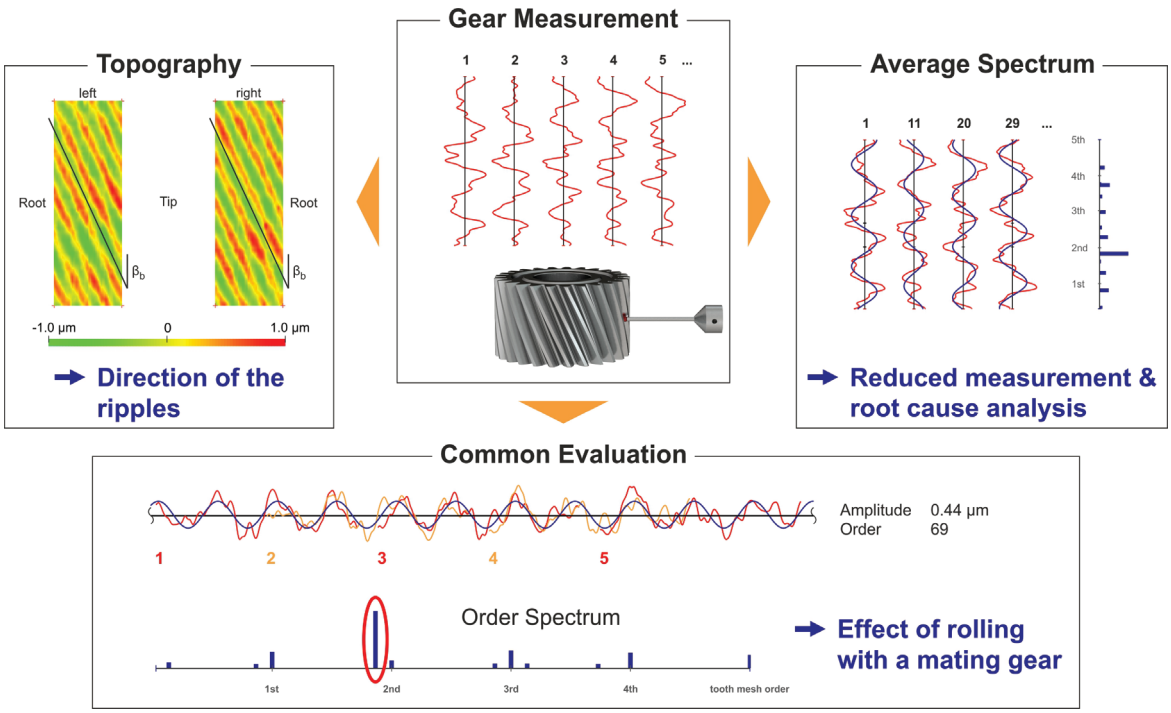


Figure 1: Ripple analysis tools

In addition, the topography of a single tooth flank is often recorded with many profile or helix measurements, shown in the left part of Figure 1. After eliminating the actual modifications, the ripples become clearly visible. Very critical is a ripple that runs parallel to the base helix angle β_b and thus parallel to the contact line with the mating gear. The contact line of the mating gear then runs through the peaks and valleys of this ripple during rolling, resulting in vibration excitation in the tooth contact [4]. Each of the calculated orders can have its own helix angle, which becomes visible through step-by-step elimination. At the same time, the evaluation of the topography can also provide information on the causes of the ripples, examples will follow. Since the measurement of all teeth is very time-consuming, a ripple evaluation can also be performed with only a few measurement curves. An average spectrum is then calculated from the individual spectra of the curves, but this does not consider the position of the curves relative to each other. If form deviations are present, the result is somewhat less accurate but more economical. This type of evaluation is also helpful for finding the cause.

Simulation of Vibrations

There is a great variety of possible causes for ripples and the effect of machine deviations on the gear surface is complex, especially with multi-start tools. Therefore, the cause analysis is often time-consuming and requires a lot of expert knowledge. Support can be provided by simulation software, which allows typical deviations in gear hobbing and generating grinding to be simulated very accurately [5].

Figure 2 shows the essential kinematics. On the tool and on the workpiece side, only cuts are considered. These individual cuts are brought into contact and an existing stock allowance is successively removed, as illustrated in the upper right of Figure 2. Tool and machine errors can be superimposed on an error-free machining process. Typical errors are eccentricity or wobble of the tool, deviations of the pitch or the displacement of individual threads on multi-start tools. A new software module now also allows the simulation of vibrations. All tool and machine deviations that can be simulated are summarized in the lower part of Figure 2.

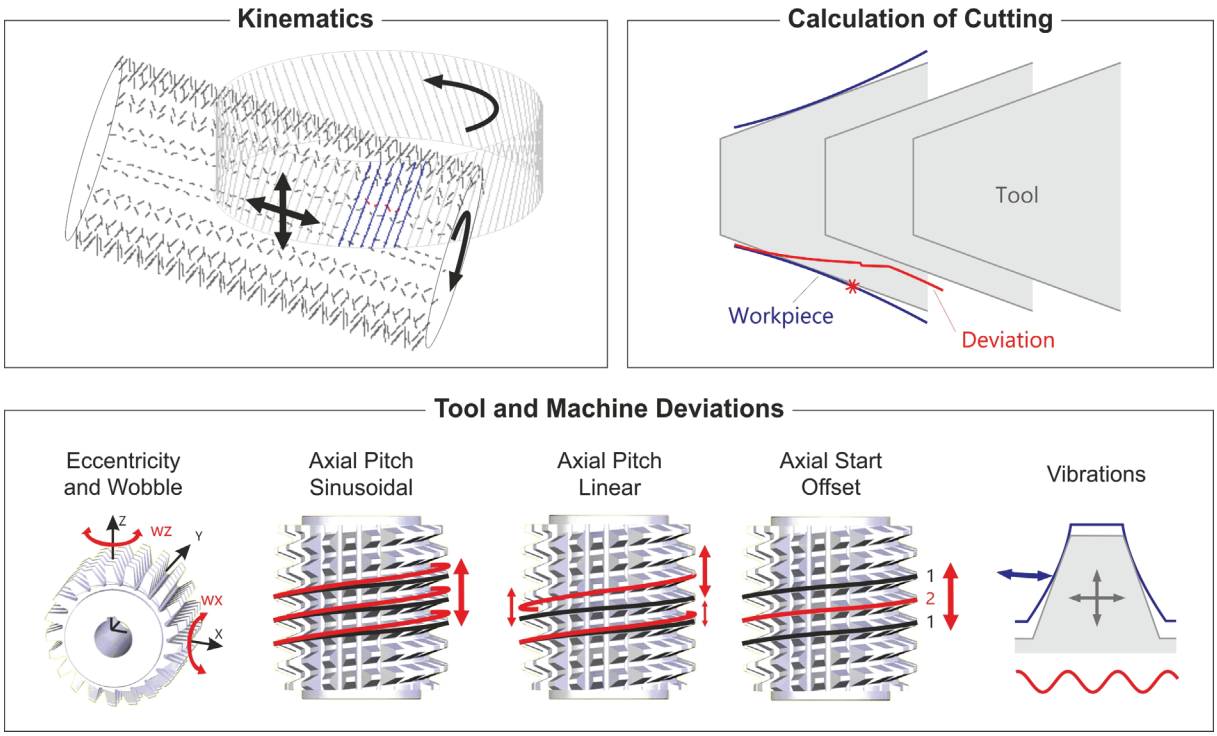


Figure 2: Simulation of deviations during hobbing and generating grinding

As the kinematics show, many axes of the machine tool are in motion at the same time. Since each axis can also have six degrees of freedom in the vibrations, there is an overwhelming number of potential vibration types. However, most of these vibrations produce similar patterns on the tooth surface, differing mainly in the magnitude of transmitted amplitude. For example, a radial displacement of the tool produces the same orders and helix angles as an axial displacement, only the ratio of vibration amplitude to ripple amplitude differs [6]. Ultimately, the actual deviations generated are also influenced by the dynamic properties of the machine [7]. For the investigation of real gear surfaces, however, it is mainly the patterns and less the amplitudes of the ripples which are of interest.

In the following, the geometric patterns and vibration orders are considered which result from a turntable-related and a tool-related vibration, as shown in Figure 3 top left. Turntable vibration and tool vibration are coupled via the transmission ratio between tool and workpiece. A vibration decoupled from this motion, e.g. from the factory floor or an auxiliary unit of the machine tool, oscillates independently at a frequency f. This vibration is transmitted to the tool or also to the workpiece in dependence of the tool speed. The software menu of the vibration simulation is shown at the bottom left of Figure 3. Here, the different vibration orders are automatically converted into each other. The transmission ratio between tool and workpiece has a specialty that has to be considered for helical gears. As shown in Figure 3 on the right, the workpiece must perform a superimposed differential rotation during the axial feed of the tool. Thus, the transmission ratio between workpiece and tool is not equal to the number of teeth divided by the number of starts.

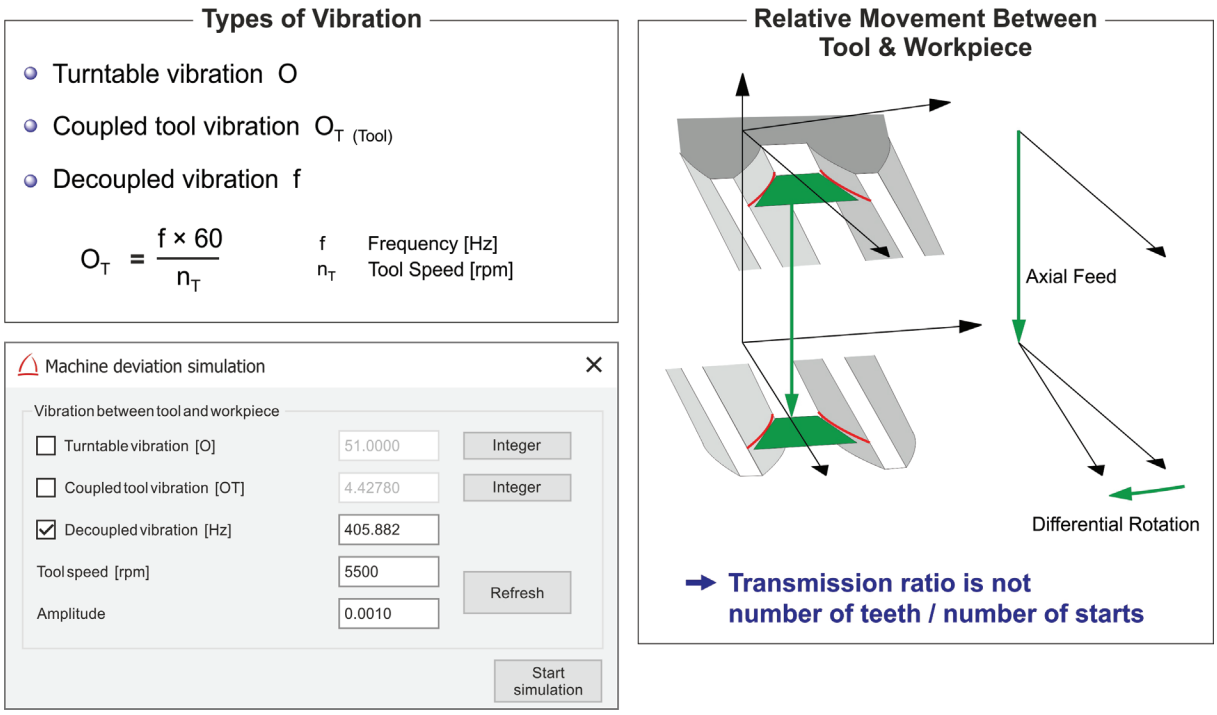


Figure 3: Types of vibration and geometric relations

Figure 4 illustrates the effect of different vibrations considered. In this example with 37 teeth of the workpiece, a single-start tool and an axial feed of 0.3 mm per revolution, the transmission ratio is 37/1.0006.

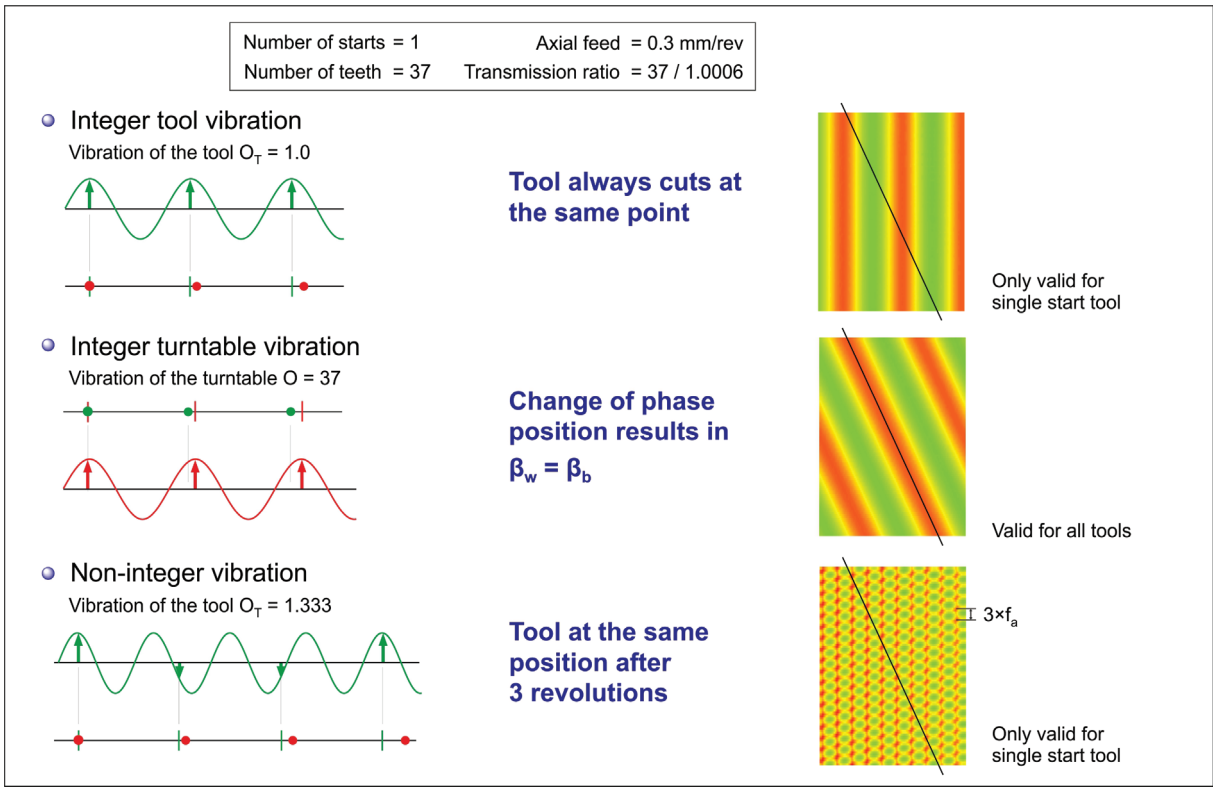


Figure 4: Effect of vibrations on generating grinding and hobbing

If an integer tool vibration $O_T = 1$ is assumed, as in the upper case in Figure 4, the tool is always at the same position of the vibration after one revolution and the tool cuts at the same point of the rolling path in the profile. In the topography, this oscillation produces a ripple with the same phase position over the tooth width for a single-start tool. However, after 37

revolutions of the tool, the turntable has not yet reached the same point again but is lagging slightly behind. If an integer turntable vibration is now simulated, the maximum of the vibration shifts a little with each revolution. This variable phase position in the rolling path generates ripples over the tooth width, which are orientated parallel to the base helix angle β_b. This applies to single- and multi-start tools. In general, non-integer vibration orders are also possible. They occur, for example, due to roller bearing damage. At the bottom of Figure 4, a tool oscillation $O_T = 1.333$ is shown. This means that the tool is only at the same position of the oscillation again after 3 revolutions. In the topography, depending on the axial feed and the tool data, a pattern results which has components in vertical direction and perpendicular to β_b.

The Fingerprint of Manufacturing

The following is an analysis of the measurement result of a gear that failed the EoL test with noise order 51. The finish machining was performed with a two-start hob with 17 gashes. Figure 5 shows the topography at the top and the measured ripple orders shown in blue in the spectrum. The simulation of a tool eccentricity, shown in red, shows good agreement in the spectrum with orders 23, 34 and 57. The vertical orientation of the order 23 on the tooth flank topography is also found in both the simulation and the measurement. Deviations from an eccentric or wobbling run of the tool are actually always to be expected due to the manual tool change.

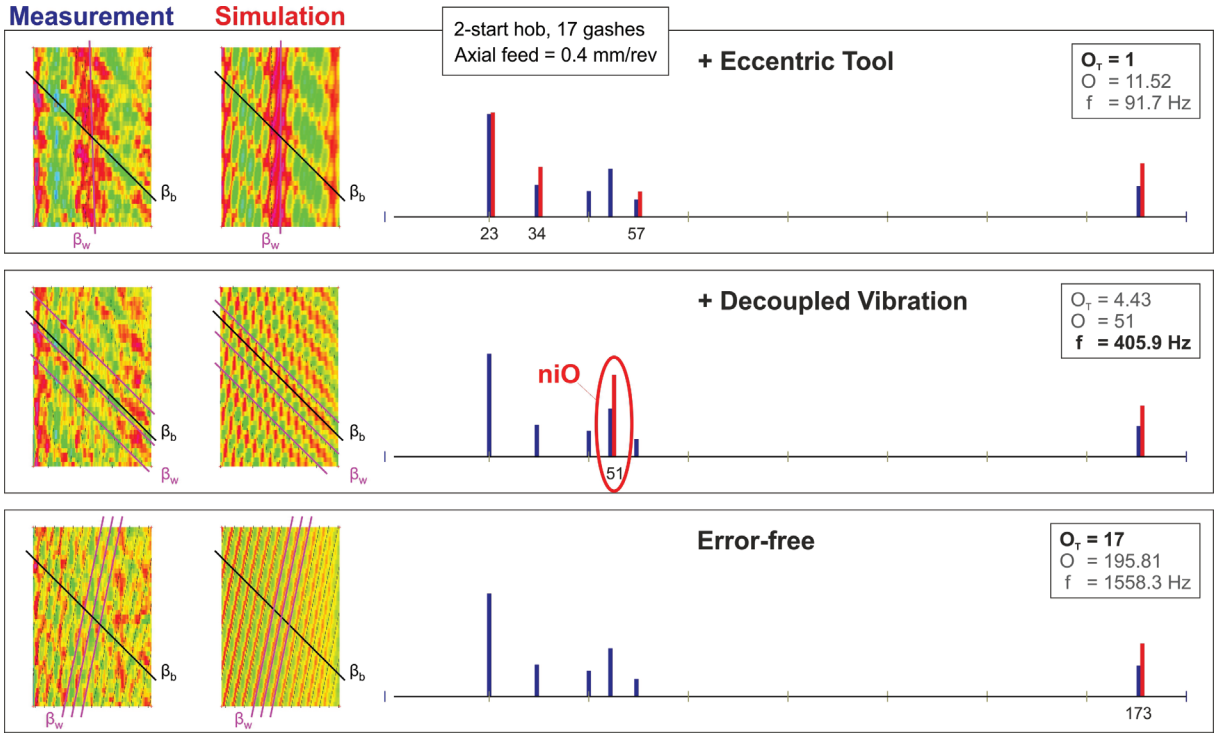


Figure 5: Fingerprint of the real machining process

The noise-causing order 51, figure 5 center, has a ripple helix angle of $\beta_w = \beta_b$. It is therefore simulated as a turntable vibration of order 51. However, considering the rotational speed, a decoupled vibration of frequency f = 405.9 Hz could also cause the same ripples. An error-free machining, which only considers the effect of the enveloping cuts by the 17 gashes of the gear hob, is shown in Figure 5 below. This can also be approximated by a tool vibration $O_T = 17$. In fact, a turntable vibration O = 195.81 or a decoupled vibration with frequency f = 1558.3 Hz could generate the same pattern. In this case, however, it is most likely that the ripple order 173 in the measurement is caused by the effect of the enveloping cuts. In practice, the effects can

often not be recognized so clearly, and one may have to try things out in the simulation. Thereby, it is most important that the exact real machining parameters such as axial feed and tool speed are known. Experience has shown that there is often a need for improvement in the documentation of these manufacturing parameters.

Avoidance of Ripples

Getting rid of noise-critical orders is not easy in practice. Often, expensive machine components are replaced or machining parameters are changed, resulting in uneconomical production. In the following, it will be shown how it can be achieved more easily under certain circumstances. Assuming the order 51 is caused by a decoupled vibration with the frequency f = 405.9 Hz, the tool speed is changed slightly. Figure 6 shows the topographies of this parameter variation.

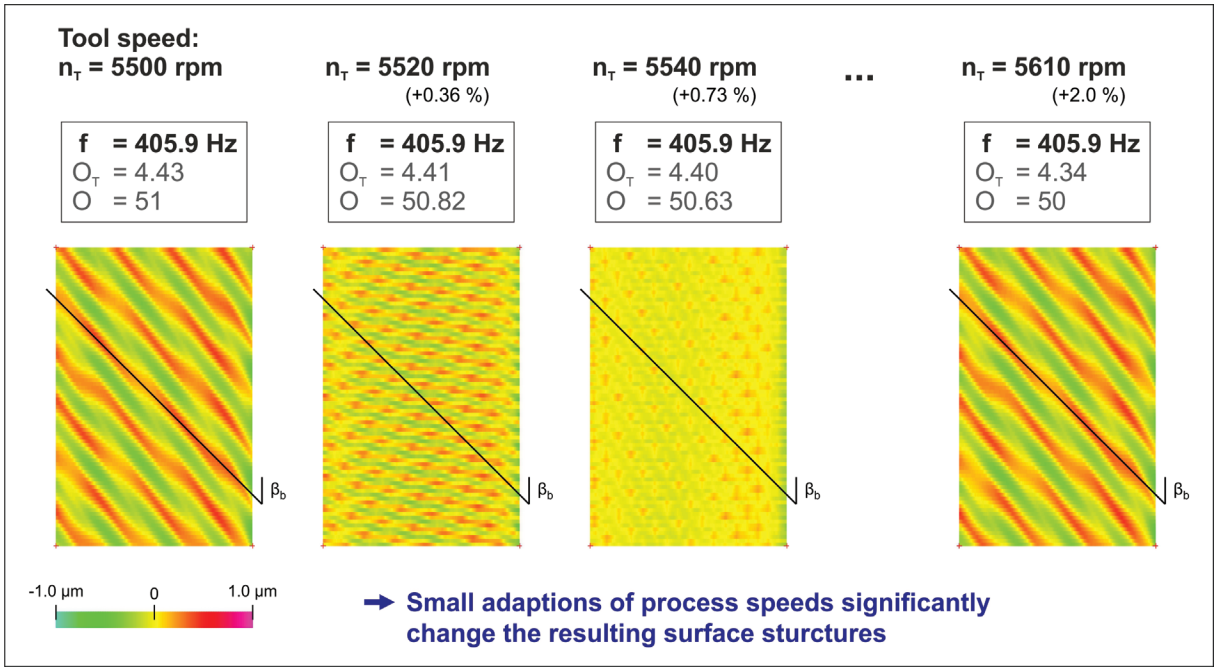


Figure 6: Variation of speed for decoupled vibration

If the speed is increased by 20 rpm (0.36 %), the topography already changes significantly. For a change of 40 rpm (0.73 %), the ripple on the tooth surface disappear. At a speed change of 110 rpm (2 %), a new ripple of order 50 is created. It is evident here that even small speed variations significantly change the resulting surface structures, amplitudes and orders. However, one also quickly ends up at the next maximum. A decoupled oscillation can in this way quickly be checked as a potential cause and probably lose its effect by small adjustments of the speed without having to eliminate the oscillation. A check of the expected surface structures in the simulation is advisable, since non-integer turntable vibrations can also generate noise-critical ripples.

Summary

Periodic structures on gear teeth can nowadays be measured very accurately and reproducibly. However, assigning the ripples to their causes is still complex and often ambiguous. It is therefore important to know the machining parameters that are actually effective. An extended simulation method can now also quickly and accurately calculate the effect of vibrations on the resulting surfaces. This makes it possible to assess the impact of

process variations in advance. Vibrations that are decoupled from the machining kinematics have a speed-dependent influence on the machining process. They can be detected by small changes in speed and possibly lose their effect. By this, at least one cause of ripples can be eliminated in an easy and economical way.

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