Analysis of ripple on noisy gears

This Paper was presented at the AGMA Fall Technical Meeting 2012 in Dearborn, USA

Author: Prof. Dr.-Ing. Günther Gravel
Institute for Production Engineering
Hamburg University of Applied Sciences (HAW)

1. Introduction

In modern passenger car transmissions, a low noise level is an extremely important quality feature. Noise generation is influenced by many variables, ranging from the structural design, to deviations in the components, to the mounting position of the finished transmission. If, during a noise test, a gear is identified as the cause, the problem can often be attributed to damage, irregularities in position or geometrical variations, or to geometrical ripples on the tooth flanks [1,2]. This paper presents a closer examination of ripple. The development of ripple is influenced by such factors as deviations in the tool, the stiffness of the work fixture, the parameters of the manufacturing process, and of course, excitations and natural frequencies of the tool machine [1].

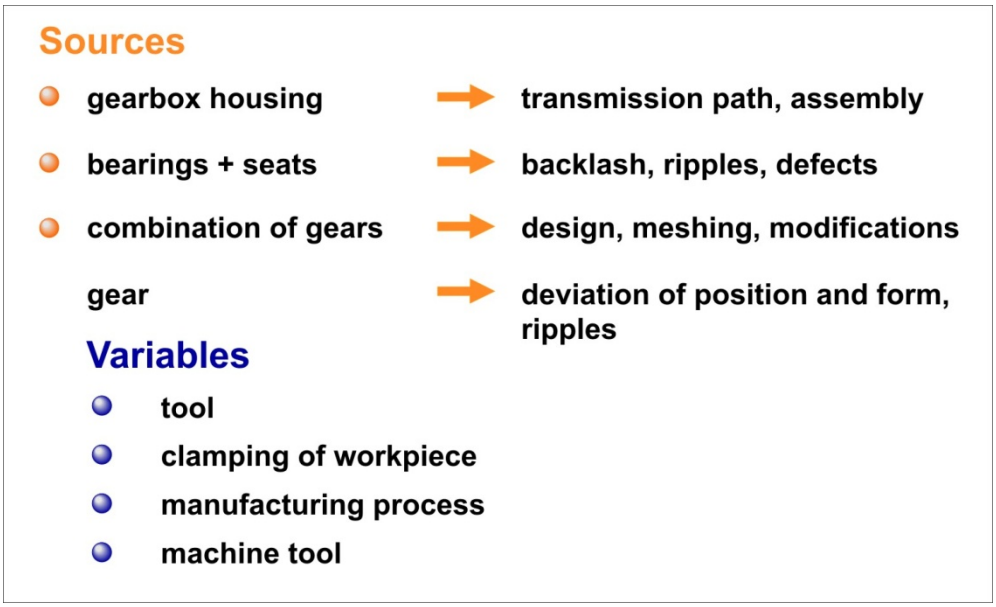


Figure 1: Sources of noise caused by a transmission

2. Gear measurement

Inspections of gear geometry are generally carried out during production on gear measuring devices that use a probe to trace the tooth flanks at individual points or on curves (figure 2, left). By conducting such individual error tests, it is possible to arrive at definite conclusions with respect to the quality of the gearing and corrections for the production process [3,4,5]. This holds true to the extent that the errors occur over large areas and systematically on a number of teeth, as is the case for a great deal of production errors.

If damage occurs on individual teeth, however, or if the behavior of the gear is to be inspected as installed in the transmission, a working inspection is used. Here, a complete inspection of the tooth flanks is carried out by rolling with a high-quality master gear (figure 2,

right). All errors of the gear act as a composite, in the form in which they have an effect when the gear is generated. A spectral analysis of the single flank generating signal reveals vibrations over the angle of rotation, which are caused by ripples on the tooth flanks and are also known as ghost frequencies [6]. Extended outfitting of the measuring device allows noise testing using structure-borne sound sensors and generation at higher rotational speeds and under load.

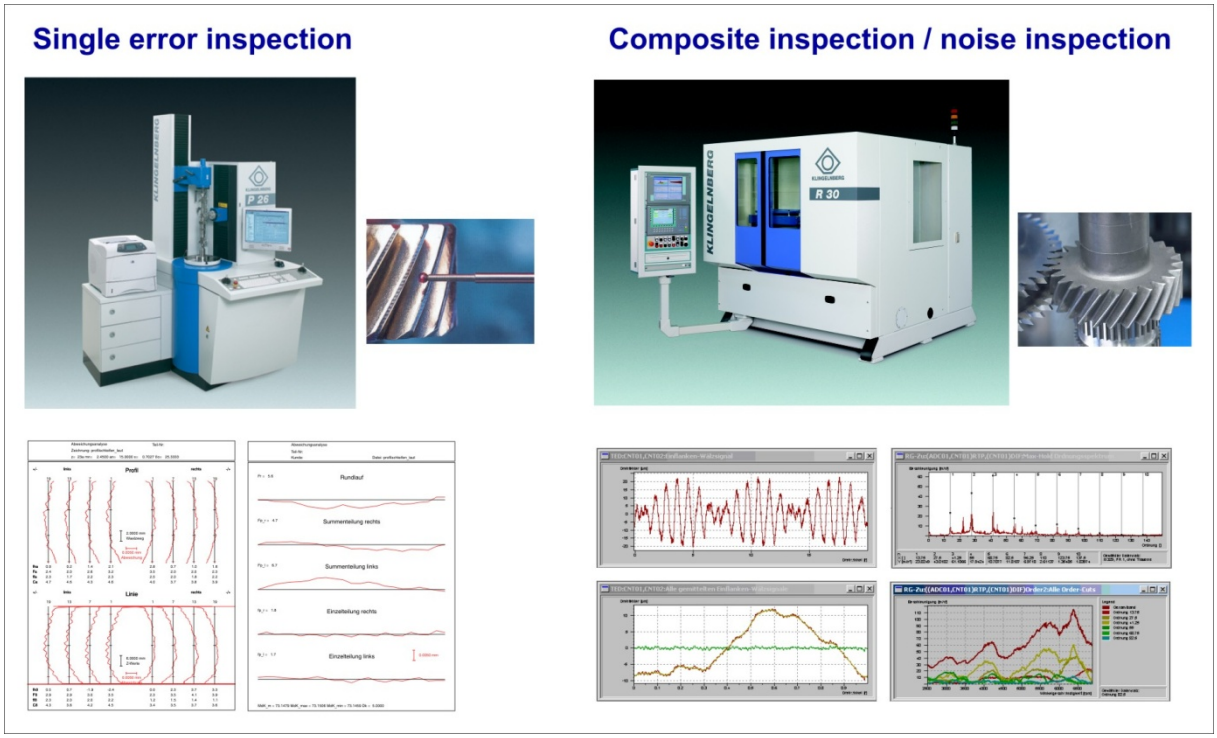


Figure 2: Inspection procedures when facing noise problems

When facing common noise problems, it is desirable to be able to easily identify ripples on the tooth flanks in the early stages, in order to intervene in the production process [7]. To this end, a software tool for ripple analysis has been developed, making it possible to describe ripples in a deviation curve based on the results of an individual error test.

3. Calculation of ripple

The most important step in the ripple calculation is the calculation of the amplitudes of compensating sine wave functions in a selected frequency range. The compensating sine wave with the largest amplitude is considered the first dominant frequency, and is plotted on the profile and displayed as a parameter. This dominant sine wave function is then eliminated from the deviation curve, and the remaining deviations are re-analyzed [8]. After 10 cycles, this ultimately produces a frequency spectrum of the 10 maximum amplitudes. In figure 3 above, the first dominant frequency in each case is plotted on the deviation curve. With this type of analysis, each flank is evaluated independently of the others; often, the calculated frequencies of individual teeth are not precisely identical due to form variations.

When analyzing a gear's running behavior, it is interesting to link the deviation curves so as to resemble the way in which they mesh during the rolling process [9]. For a specific angle of rotation, Figure 3 below shows the intersection of the gear with the plane of action. During the rolling with the mating gear, all points at the intersection curves of the flanks in this

position would ideally come into contact with the plane between the working tip and root circle. The measured curves of the profile and line measurement are also plotted. Owing to the overlap, it is possible to assign 2 profile measuring points and 2 tooth trace measuring points each to the current angle of rotation. It becomes evident here that the ratio of measuring points to actual contact points is always extremely unfavorable. A conclusion based on these few measuring points is therefore only possible if they are representative of the entire flank. If the gear does not even contact in the measured areas, for example, the calculated ripples will not be functionally effective, of course.

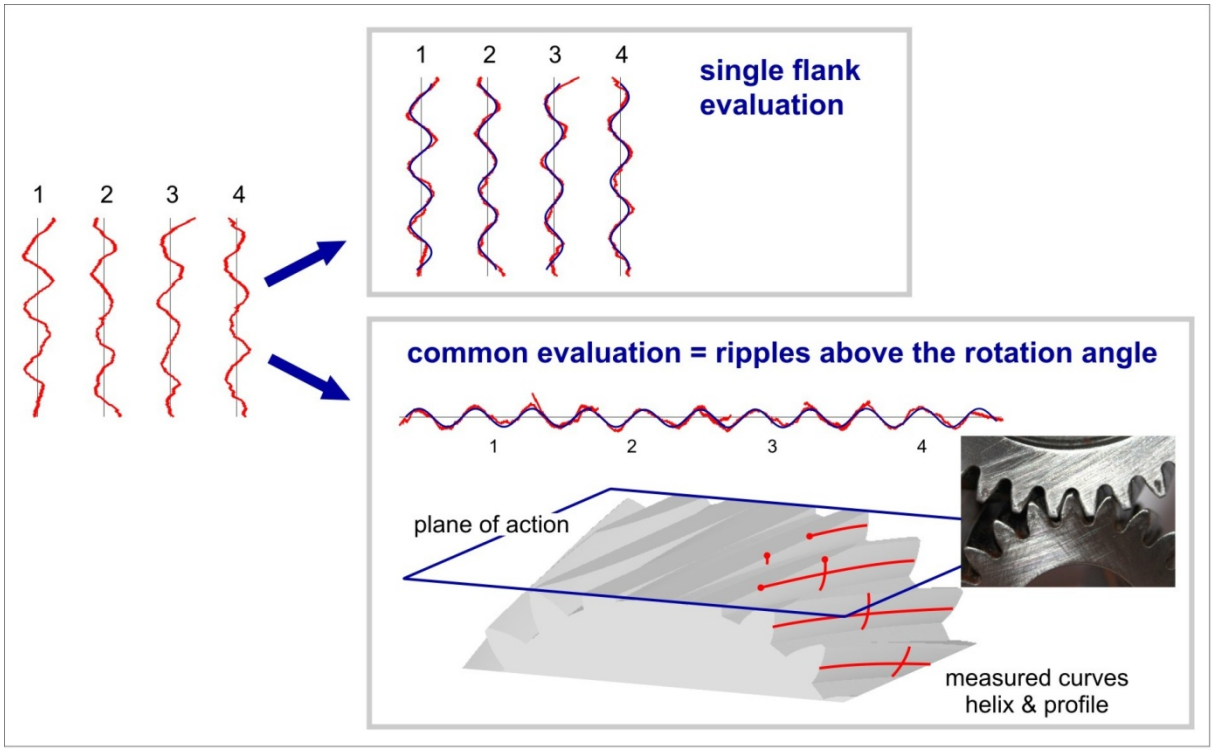


Figure 3: Methods of ripple evaluation

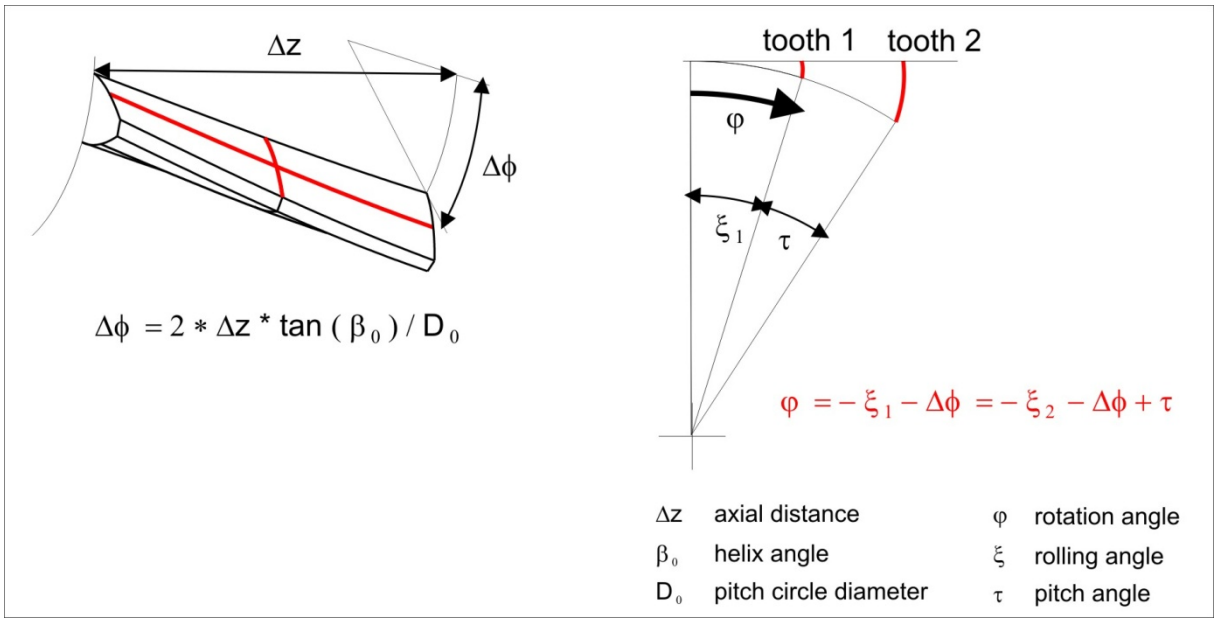


Figure 4: Calculation of the rotation angle

Every measuring point on the tooth flank has a rotation angle that characterizes its position during the generating process. As illustrated in figure 4 the rotation angle of a single point is calculated as the sum of its rolling angel, the rotation resulting from its axial positíon and its pitch angel. When all measuring points are lined up according to their angle of rotation, this produces a continuous, closed measured curve made up of all measured teeth over the circumference. For such a measured curve, a common ripple can be calculated. However, the evaluation algorithm must be capable of properly taking into account the overlaps and gaps that occur in the curve. This is the reason, why a compensating sine wave function is used here - a Fast Fourier Transformation (FFT) needs equidistant points and will not work properly with gaps and overlaps [8]. Because the curve is closed, only whole-number ripples can occur over the circumference.

In order to evaluate low frequencies per rotation in addition, pitch variations must be taken into account in the measured curves. If only 4 teeth are evaluated over the circumference, this means that the gaps in the continuous curve are very large, and the calculated ripples are therefore very uncertain. Measurement of all teeth, or a good number of them, is therefore highly recommended. For the profile evaluation, this type of evaluation corresponds for all intents and purposes to a single-flank working test [10] with an extremely narrow master gear that has no deviations, and for the tooth trace, it corresponds to a test with a master gear that only makes contact within the reference circle. While a single flank tester is covering the envelope deviation of the surface that is rolling with the master gear, here a selective test for selected areas is constituted.

4. Analysis of a honed gear

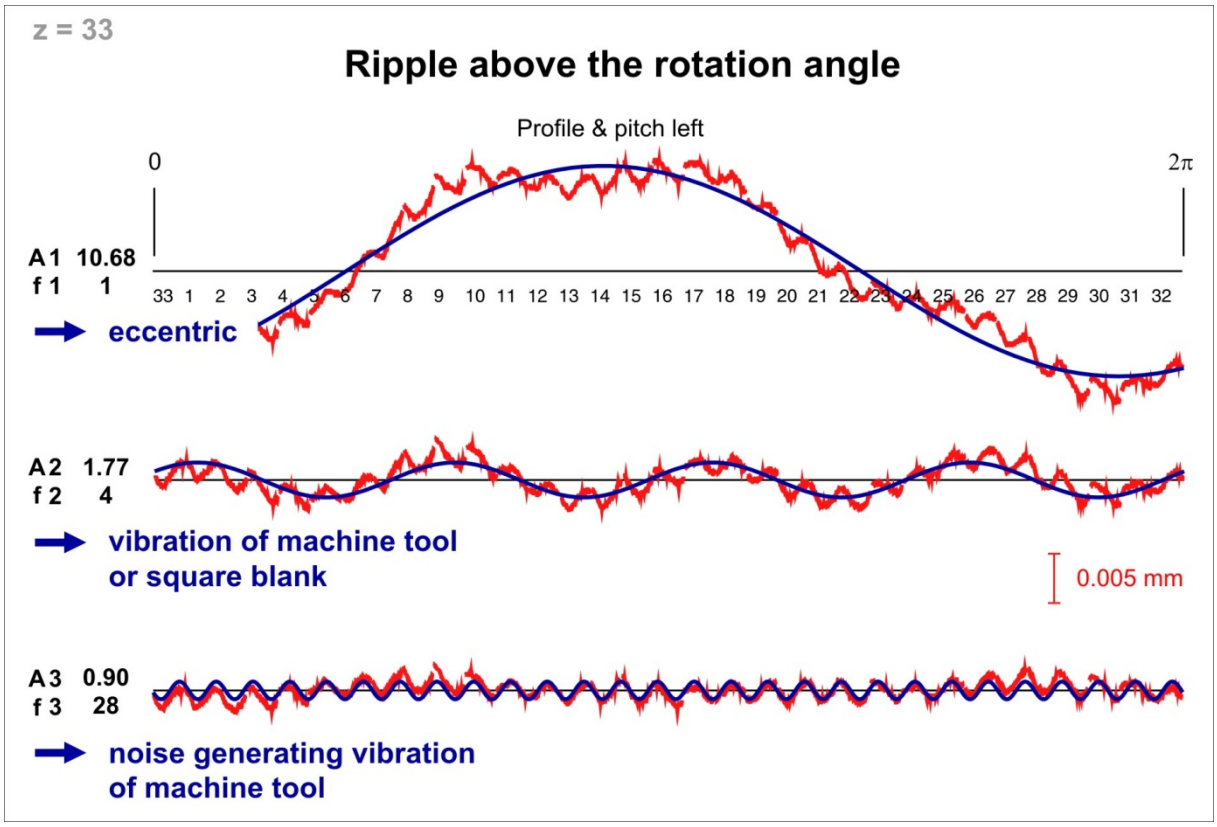


Figure 5: Deviation curves of common ripples of a honed gear

The evaluation results of common ripples of a noisy, honed gear are shown in figure 5. The profile deviations of the left flanks are plotted together as deviation curves for all measured teeth over the angle of rotation. The ripple with frequency 1 represents the runout deviation caused by the eccentric position of the gear axis. The next maximum occurs at 4 ripples per rotation. This ripple here is caused by a machine vibration. Generally speaking, however, it is also possible that the diagram could depict a square blank as the starting material or a 4-jaw chuck. This makes it clear that this evaluation method is also well-suited for describing such things as ovality or deformation caused by a chuck. Finally, a frequency 28 is shown. In a noise measurement, this frequency was clearly attributable to this gear, and resulted in a rejection of the transmission. The comparison measurement of a quiet gear does not show a frequency 28, but does likewise show a frequency 4.

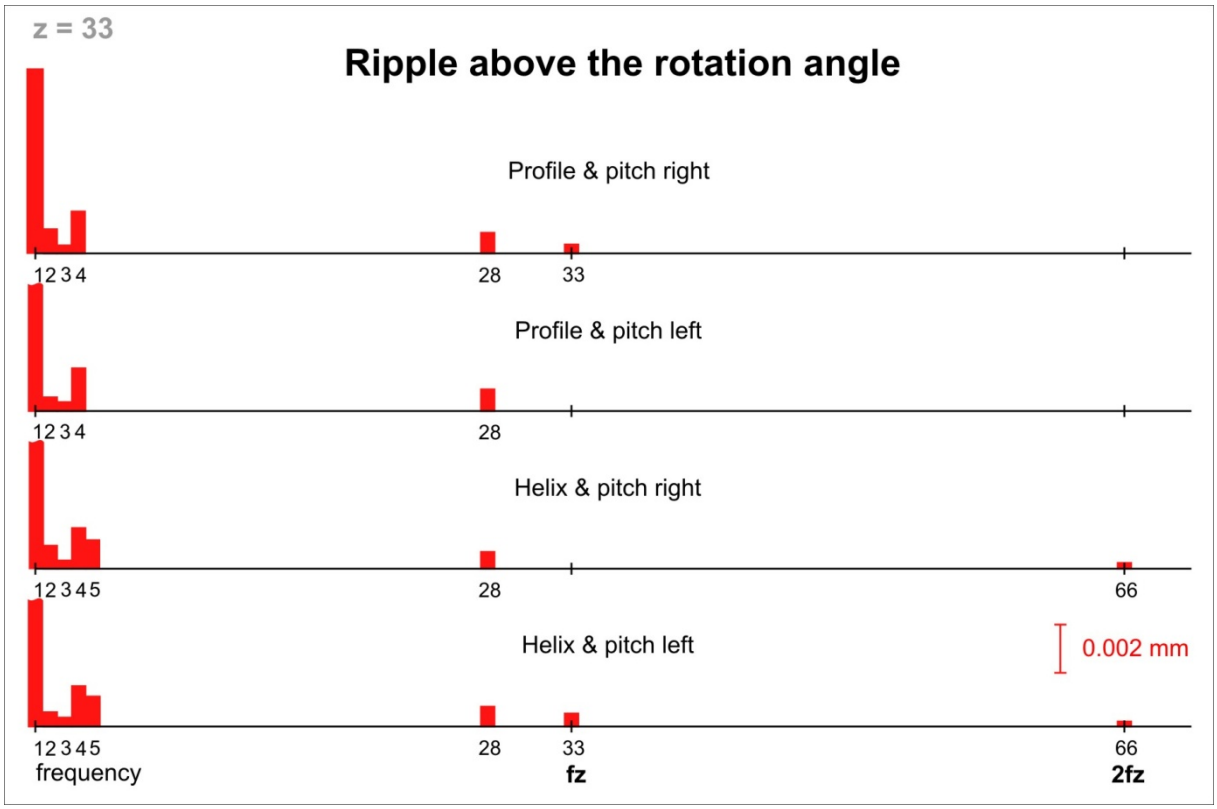


Figure 6: Spectra of common ripples of a honed gear

Figure 6 shows the spectra of the ripple evaluation for profile and tooth trace separately for the right and left sides. Frequency 28, that means 28 ripples per circumference, is clearly evident in all spectra.

5. Crowning and systematic slope deviations

The evaluation becomes problematic if the gear has crowned flanks or systematic slope deviations. Because these deviations are lined up one behind the other, a dominant ripple with the frequency of tooth count fz shows up in the evaluation. The evaluation of a measurement taken on a gear with a crowned tooth flank and slope deviations is shown in figure 7 above. Since crowning and slope deviations cannot be exactly reproduced by a compensation sine wave, this results in multiples of fz due to the residual errors. If the crowning is even larger, it can completely dominate the evaluation.

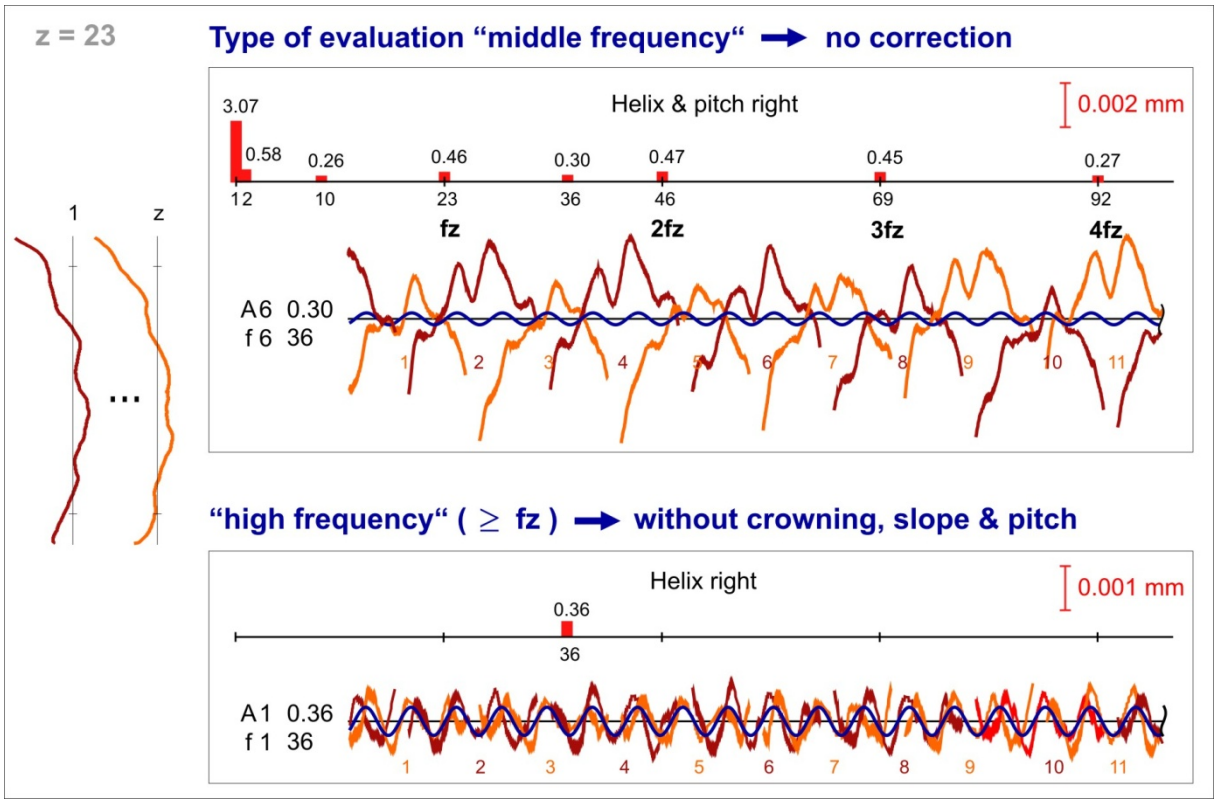


Figure 7: Analysis of gears with crowning

For this reason, an evaluation for high frequencies was introduced. When this evaluation setting is used, the individual crowning and the slope deviation are eliminated before the curves are merged. This evaluation does not take pitch variation into account, either. As can be seen in figure 7 below, there is now a signal that clearly contains only frequency 36. All mesh frequencies have disappeared, but so, too, have all low frequencies that are actually present in the signal.

The ripple analysis of a gear made by generation grinding is shown in figure 8. In the non-corrected evaluation, called a "middle frequency" evaluation, low-frequency ripples of frequency 1 to 8 appear, as well as the first and second mesh frequency. This evaluation should always be the first step in an analysis of ripple. In the next step, the "high frequency" evaluation, the low-frequency components disappear, as expected, but a significant portion of the mesh frequency remains, even though the crowning has been eliminated. Upon closer examination, it becomes evident that the gear in fact does exhibit a ripple with mesh frequency in the profile. Because there is more than one ripple in the evaluation range due to the high overlap, it is not eliminated by correcting the crowning.

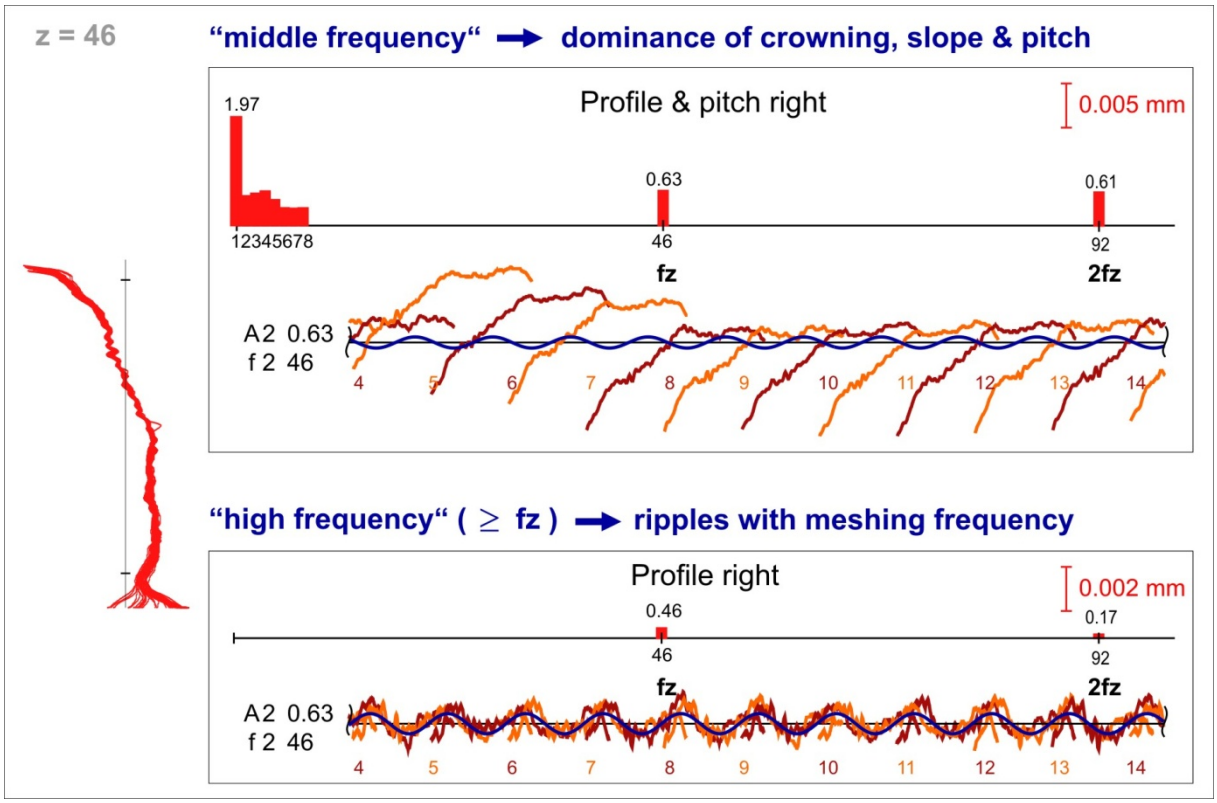


Figure 8: Analysis of a gear made by generation grinding

It is evident here that ripples with mesh frequency can also occur, which are due to form deviations or ripples on the flanks that overlap appropriately. The cause of these ripples may be attributed to an axial vibration of the grinding wheel or a vibration of the work fixture. These vibrations can be excited by tool deviations or by the machining process.

6. Ghost frequency and meshing frequency

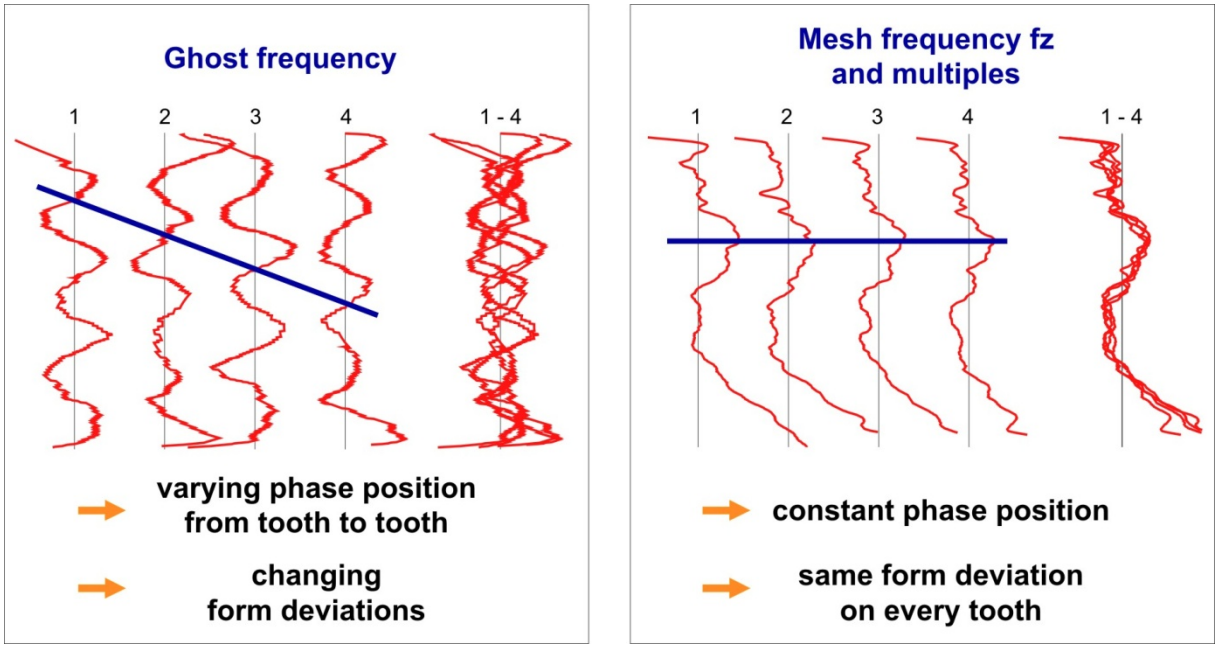


Figure 9: Types of ripples

Figure 9 illustrates a comparison of the deviation curves of 4 teeth measured in succession with ghost frequency and with mesh frequency. If a ghost frequency is present, the tooth flanks show a ripple with varying phase position, and the form changes from tooth to tooth. When evaluating a standard measurement on 4 distributed teeth, a varying form deviation is a good indication of a possible ghost frequency. For a reliable analysis, however, all teeth must be measured and evaluated. In contrast, a ripple with mesh frequency and multiples exhibits a constant phase position and very similar form deviations. Here, a ripple analysis of the standard measurement on 4 teeth is able to provide reliable results.

7. Examples of application

The following section presents the results of a ripple analysis on gears that have been manufactured using various production processes, some of which have resulted in noise problems. Figure 10 above shows the measurement of a broached internal gear for an evaluation with "high frequency." The broaching tool produces a ripple of frequency 95 ripples per rotation, which results in noise excitation in the transmission. The bottom part of the figure shows the ripple analysis of a gear made by generation grinding. In an evaluation with "high frequency," the previously described ripple with mesh frequency is seen, which is represented here as an S form on a single flank. As the second dominant frequency, a high-frequency ripple with 345 ripples occurs on the circumference. It is clearly recognizable on the flanks, but is not relevant for noise during operation.

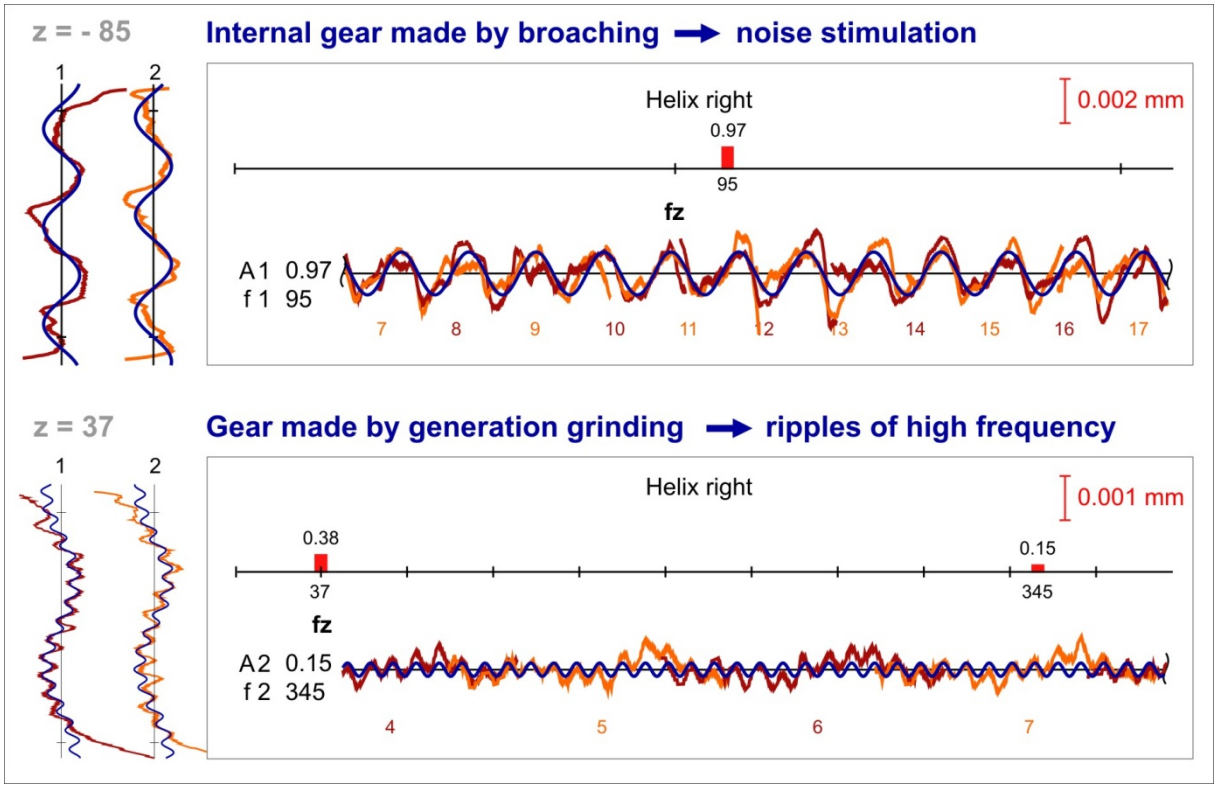


Figure 10: Analysis of gears made by broaching and by generation grinding

The question of the precision of a measuring device is also raised here. It is certainly true that vibrations of the measuring device can skew the results of the ripple analysis, particularly in the high-frequency range, and must therefore be avoided. Moreover, amplitudes of 0.15 micrometer, which may very well be relevant to noise at high frequencies,

or an S form with a 0.38-micrometer amplitude can only be reliably detected with extremely precise measuring devices. The measuring system needs to have a resolution of 0.1 micrometer and a very exact rotary table, like the gear measuring device mentioned in figure 2 left. In the case at hand, the high-frequency vibration is definitely not attributable to the measuring device because, as a ghost frequency, it demonstrates a phase position that varies from tooth to tooth. A vibration during measurement would not follow this context, but rather would show the same phase position on each tooth.

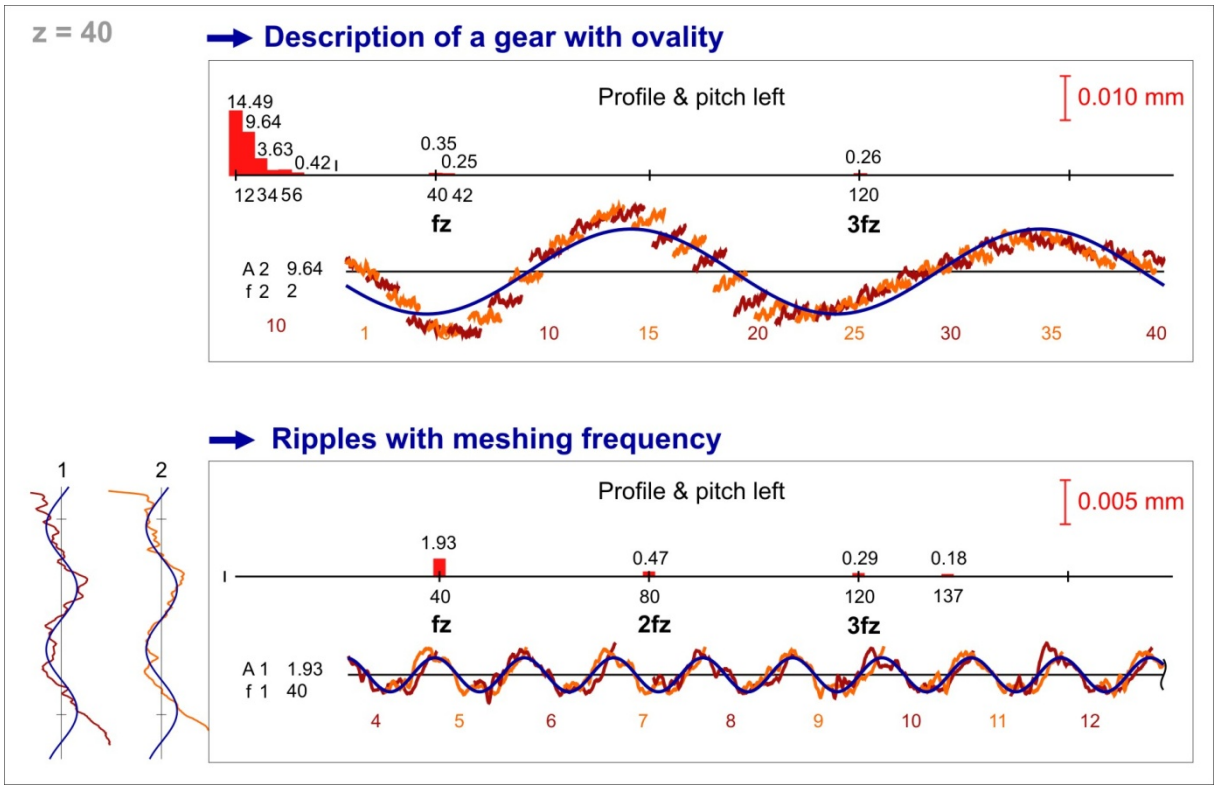


Figure 11: Analysis of gears made by shaving

Figure 11 shows the results of the ripple analysis on two gears made by shaving. The gear above exhibits a relatively broad, low-frequency spectrum, in which the ovality is noticeable. Even this ripple, which should be considered more as a form deviation over the circumference, can be described well with a ripple analysis. The bottom figure again shows a clear occurrence of a ripple with mesh frequency. Apparently, all generating production processes can exhibit this ripple form if specific conditions are present.

8. Summary

In conclusion, the new software tool for ripple analysis of gears makes it possible to detect and describe ripples in appropriate deviation curves. The use of compensating sine wave functions enables a robust, reproducible evaluation. By linking the deviation curves of individual flanks via the angle of rotation, ripples can be determined over the circumference of the gear, in a manner similar to the single flank working test. This type of evaluation corresponds both to the generation situation in the installed condition and to the production situation when generating manufacturing methods are used. Results on honed and ground gears show a good correlation between the parameters of a noise measurement and the ripple analysis [1]. It also demonstrates, however, that many gears show ripples, without

being conspicuous during operation. A ripple analysis without knowledge of the noise situation may therefore be inappropriate under certain circumstances. Finally, with the ripple analysis, it is possible for the first time to identify ripples with mesh frequency on the tooth flanks. This provides an opportunity to investigate previously unexplained noise issues with mesh frequency in a more nuanced manner.

Ripple analysis provides a tool that aids in the search for the causes of noise and can also be used for production monitoring in the case of known vibration problems.

9. References

[1] Rank, B.: Geräuschanalyse an PKW-Automatikgetrieben in der Praxis, VDI-Bericht 2148, 2011

[2] Brecher, C.; Gorgels, C.; Carl, C.; Brumm, M.: Benefit of Psychoacoustic Analyzing Methods for Gear Noise Investigation, Gear Technology 28, 5, 2011

[3] Mikoleizig, G.: Aktuelle Tendenzen bei der Einzelfehlerbestimmung an Verzahnungen: Maschinentechnologie, Anwendungsspektrum, Auswertesoftware, VDI-Bericht 1880, 2005

[4] Goch, G.: Gear Metrology, CIRP Annals - Manufacturing Technology, Volume 52, 2003

[5] Gravel, G.: Simulation und Korrektur von Verzahnungsabweichungen - Qualitätsregelkreis Zahnradproduktion, VDI-Bericht 2148, 2011

[6] Landvogt, A.: Einfluss der Hartfeinbearbeitung und der Flankentopographieauslegung auf das Lauf- und Geräuschverhalten von Hypoidverzahnungen mit bogenförmiger Flankenlinie, Dissertation RWTH Aachen, 2003

[7] Rank, B.: Verzahnungsmesstechnik aus Anwendersicht – ein Erfahrungsbericht, VDI-Bericht 1880, 2005

[8] Gravel, G.; Seewig, J.: Welligkeitsanalyse von Verzahnungsmessungen, VDI-Bericht 2053, 2008

[9] Faulstich, I.: Anwendungsorientierte Auswertung von Verzahnungsmessungen, VDI-Bericht 1673, 2002

[10] VDI/VDE Guideline 2608: Tangential composite and radial composite inspection of cylindrical gears, bevel gears, worms and worm wheels, 03.2001