RESEARCH ARTICLE

In-process evaluation of continuous generating gear grinding for maintaining workpiece quality and acoustic behavior of gear wheels

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Abstract
Hard finishing of gearings such as continuous generating gear grinding is highly essential for manufacturers due to increasing demands on gearboxes regarding quality and economical aspects, especially in the growing field of electric mobility. Here, high requirements on the acoustic behavior and low production cost come into conflict in the last stage of manufacturing gearings in a particular way. Against this background, in-process evaluation methods for manufacturing processes are developed in order to reduce scrap parts and to exploit the process limits by collecting and processing of sensor signal data and by adapting measures based on reasonable process models. This investigation shows how the condition of abrasive tools and workpiece quality are evaluated by means of process near acoustic emission sensor application and motor current of the grinding spindle in order to adapt shifting and feed movement in generating gear grinding process. A calculation method based on a simulation process model is introduced to characterize relevant vibration frequency bands and the resulting acoustically effective waviness on tooth flanks, depending on workpiece and process parameters. Appropriate adaption of the grinding process for increasing productivity while maintaining workpiece quality is based on the findings of an intelligent in-process evaluation.

KEYWORDS
gear grinding, gear wheel, process monitoring, topography

1 INTRODUCTION

In the past years, there have been essential developments in the process chain design of manufacturing gearings for vehicle transmissions. While 10 years ago, most car manufacturers applied hard precision machining only in exceptional cases, today more than 40% of the gearings are manufactured by hard precision machining using grinding or honing. Particularly in the growing field of electric mobility, the share of hard precision machining will considerably increase due to the rising requirements regarding accuracy caused by downsizing and regarding acoustic behavior.1

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Continuous gear grinding is currently the predominant process of hard precision machining. This machining process with geometrically undefined cutting edges, enables accuracies between 2 and 7 according to ISO 1328, while offering acceptable manufacturing times using universally employable grinding tools. \(^2\) In continuous generating gear grinding, conventional vitrified bonded grinding tools are utilized in more than 90\% of the cases. In contrast to machining with geometrically defined cutting edges (e.g., hobbing), applying geometrically undefined cutting edges has certain peculiarities that deal with different cutting abilities of stochastic distributed grains that need to be considered in process control. \(^3\) Besides the achievable geometric accuracy, acoustic behavior of the gear wheel in the gearbox is of great interest to customers. In series production, the acoustic noise emission is commonly monitored with an end-of-line test stand after complete assembly of the gearbox. However, it is necessary to detect scrap parts at an earlier state in the production process due to economic aspects. In order to achieve this, sensor data, which allow for an in-process measurement in a generating gear grinding machine combined with appropriate process evaluation and calculation methods are used in order to adapt the process and maintain quality of the gear wheels continuously.

2 | STATE OF THE ART AND RESEARCH OBJECTIVE

Continuous generating gear grinding is characterized by the strict coupling of certain axis movements of the machine. The rotational velocities of workpiece \(\omega_1\) (C-axis) and tool \(\omega_0\) (B-axis) are synchronized in accordance to their teeth ratio so that the teeth of the workpiece \((z_1)\) are immersed in a gear of the grinding worm \((z_0)\), see Figure 1(A). In order to maintain a steady removal rate across the width of the gear wheel, the grinding worm moves axially in \(Z\) direction (axial feedrate \(f_a\)), whereas the workpiece axis carries out an additional rotational compensation movement. Moreover, the worm with a lead angle \(\gamma_0\) can be moved along its rotation axis by a certain shifting velocity \(v_{sh}\), which is similarly compensated by the C-axis. The axis coupling is represented by the following equation:

\[
\omega_1 = \omega_0 \frac{z_0}{z_1} + \omega_0 \frac{z_0}{z_1} \cdot \frac{f_a \cdot \sin \beta}{m_n \cdot \pi \cdot z_1} + v_{sh} \frac{2 \cdot \cos \gamma_0}{m_n \cdot z_1}
\]

The radial infeed is realized along X-direction toward the workpiece. Between each machining stroke a discrete infeed and shifting travel are executed so that a new tool area is engaged at any time. The whole finishing process for one workpiece usually consists of two roughing strokes and one finishing stroke. If the entire width of the grinding wheel is used up by the shifting process, dressing must be performed to ensure geometric accuracy and cutting ability (see Figure 1(B)). Diamond profile rollers are used almost exclusively for this purpose. With this technology, a very high component accuracy with comparably high productivity rate can be achieved. However, the technological process design
in series production poses various challenges for manufacturers. Numerous publications are known from the literature, in which solutions for the description of the tool condition are contained, but an industrial application is only known for specific applications. Thus, the exact tool condition as the main influencing variable on the process is unknown. In addition, not all workpieces are pre-machined the exact same way. Deviations also occur in the allowance and the distribution of allowance on the tooth flanks. In this context, safety factors have to be considered since the process has to be designed in such a way that accepted parts can be reliably manufactured even under unfavorable conditions such as

- maximum allowance with asymmetrical flank distribution
- blunt grinding tool with low cutting ability
- few abrasive grains on the grinding tool's circumference at end of tool life

Additionally, deviations like damage to the grinding worm as well as static and dynamic machine displacements or respectively their impact on component quality are difficult to detect and evaluate with conventional manufacturing processes and random sampling of workpieces in production.

The acoustic behavior of a gearbox is highly influenced by the surface characteristics of the built-in gear wheels. The greatest impact on excitation behavior occurs due to the gear mesh which leads to harmonic frequencies in dependence of number of teeth and the revolutionary speed of the gear wheel. It has therefore been the aim to design the microgeometry of gear teeth in order to reduce gear mesh frequencies in defined working points. These modifications of the gear flank topography are introduced by topological manufacturing processes with aligned tool geometry and kinematic movement of the machine. Apart from that, acoustic noise of certain frequency components might occur in gearboxes, which are not related to the number of teeth.

Previous investigations could link the excited gear noise to waviness on tooth flanks which is caused by deviations of the manufacturing process. Reasons for the occurrence of waviness in continuous generating gear grinding are manifold and are exemplarily mentioned for an actual manufacturing environment in Reference 17. It has been shown that waviness on gear flank has a substantial influence on gear noise with even 0.1 μm amplitude as long as it runs periodically under a certain angle over circumference of the gear wheel. Works have focused on the systematic searching from measured topography of gear flanks to reasons in manufacturing. Consequently, it is necessary to exploit these findings for a monitoring of the finishing process.

In summary, the following two considerable challenges exist in the state-of-the-art:

- Unused potentials of feedrate and tool life due to safety factors in process design
- Sampling does not allow reliable detection of scrap parts due to wear and relative displacements of tool and workpiece

These issues may be solved by application of an adaptive grinding process which involves selection of sensor and sensor position, acquisition of data, as well as interpretation, evaluation of and reasonable reaction to the collected information. Here, control of axial feed or shifting velocity is performed and demonstrated with the help of an example based on the data determined during the process. The objective comprises not to exceed limit values determined in advance, utilizing a process model or grinding tests, thus reducing conventionally determined safety factors. A further approach here is to draw the analytical connection between origin of process deviation and surface topography. The generated angle of waviness due to certain vibration frequency is examined under consideration of geometric contact conditions of a cylindrical screw drive between tool and workpiece in generating gear grinding (according to References 10,18). Based on this, a criterion for detecting frequency ranges in manufacturing process is defined with the aim to detect scrap parts in production. Results are reflected and discussed on basis of chosen gear and technology parameters.

3 ADAPTIVE GRINDING FOR REDUCING SAFETY FACTORS BASED ON A FLEXIBLE SHIFT PATH

Modern generating gear grinding machines are equipped with multiple sensors that are not continuously used for process evaluation; see Figure 2.

Sensors for measuring the grinding spindle's motor current are of particular interest in addition to the AE sensor (Acoustic Emission), which is used for touch detection. Comparative studies with additional measurement technology have shown that these sensors, combined with suitable signal processing, allow for a sufficiently accurate evaluation...
of the grinding process. The evaluation using the signal processing is based on a process model of the generating gear grinding process, which describes the effects of selected input variables (e.g., grinding wheel condition) on the process (e.g., AE signal) and the work result (e.g., geometric errors on the workpiece). This model can be used to create process images that characterize the grinding process (AE signal or spindle current) for accepted parts and typical scrap parts. Moreover, such images can be created by grinding tests with specifically introduced processing errors (e.g., uneven distribution of allowances or macroscopic breakout on the grinding tool), followed by their comparison with the model. These characteristic values are then used as control limits for the adaptive process.

Dressing comprises a significant cost driver in generating gear grinding. While in conventional grinding processes (e.g., cam form grinding), the dressing cost amounts to approx. 1% of the unit costs for grinding; this value is up to 15% in gear grinding. By reducing the shift path, safety factors can be diminished, and it is possible to tap considerable time and cost potentials. In this context, an essential factor is the grinding wheel diameter, which is reduced from 280 mm to approx. 160 mm during the tool life. This also reduces the number of grinding grains on the circumference. The shift path is designed for the smallest diameter of 160 mm; that is, in the reference case, 40 workpieces can be ground. However, assuming that the number of workpieces is directly proportional to the number of available abrasive grains, more than 70 parts can be produced with a new wheel which increases productivity of around 40% on average (see Figure 3).
The following two possibilities exist for implementing a flexible shift path:

- Programming of different shift paths depending on the current grinding wheel diameter (this method is described in the literature, but no implementation is known)
- Adjustment of the shift path based on in-process measurement

The second variant has considerably more potential, as its evaluation considers not only the number of abrasive grains but also the entire cutting behavior. This second variant is based on an in-process evaluation of the cutting behavior based on the acquisition of the AE signal. The selection of the sensor position is of great importance. The sensor must be placed as close as possible to the contact point between the grinding tool and the workpiece, and there must not be a ball bearing between the sensor and the contact point. If a stationary tailstock center is used, a surface at the tip is a well-suited location for the sensor (see Figure 4(A)). Other sensors can also be integrated here. As a rule, however, a revolving tailstock is used. In this context, contactless data transmission is required, the technical basis of which is available. Alternatively, existing AE sensors can also be applied, for example, those used for touch detection. These existing AE sensors are usually mounted inside the grinding spindle.

Figure 4(B) illustrates significant differences between a new grinding wheel and a wheel at the end of its tool life, both in the AE level (black curve) and in the individual frequencies (colored lines). Apart from the increased grinding wheel speed (grinding was carried out at constant cutting speed), the reason for these vast differences lies in the different number of abrasive grains, which has a considerable effect on the cutting ability of the tool. The process image of the worn grinding wheel can be used as a limit value for control of the shift path. Thus, a verification takes place by the existing process model. Then the shifting velocity for larger diameters is reduced so that the reference level of the worn grinding wheel is reached. The resulting reduced shift path can significantly increase the tool life (the time for the shift path remains unchanged); see Figure 3. At the same time, it is possible to detect and to react to damage to the grinding wheel in the macro range. Here the shifting velocity must be increased until the damaged area is outside the contact zone, and thus the reference level is no longer exceeded. As a result, the shift distance is also inevitably increased, but it is possible to avoid workpieces that do not conform to specifications.

As part of a research project on the wear behavior of diamond rolls, several grinding worms were completely machined. Within this framework, the potential of a modified shifting amount could be demonstrated in grinding samples. In the selected tests, which are indicated in Figure 5(A) all dimensional and shape tolerances were met even with greatly reduced shifting amount, up to 45%. The measurement of the Barkhausen noise to detect grinding burn showed no abnormal test results. Within the scope of these tests, the correlation shown in Figure 4(B) could also be verified. By defining a limit curve for the AE level, which was derived from the smallest possible grinding wheel diameter, a control concept could be...
Another means of process evaluation is the motor current of the grinding spindle. The required sensors are available in modern machines. Figure 5(B) illustrates an example. The red curve describes the usual course (data acquisition technology similar to the one used in Figure 4). In the black curve, a deviation occurred in the roughing area; a considerably higher current is required there. This deviation may be caused by an increased allowance or a pitch deviation. Due to the increased power consumption, the workpiece was partially heated, which resulted in more material being removed in roughing. Thus, the allowance is decreased in the finishing stroke, which leads to power reduction and may imply loss of accuracy. In this case, process control may be performed via an increase in shifting velocity (more sharp abrasive grains are utilized), or by reducing the axial feed. However, the grinding time is increased in the latter approach.

### 3.1 Development of a criterion for assessing vibration excitation in generating gear grinding

Basis for the in-depth analysis of the generating gear grinding process and the operational behavior is a simulation model, which is illustrated in Figure 6. Input parameters are geometry data of tool and workpiece, technology specification, as well as considered process deviation, e.g., tool errors and vibrations. The kinematic manufacturing simulation then calculates the relative kinematic movement of tool and workpiece in discrete time steps and the removal of material from the workpiece geometry. The resulting tooth flank topography is used to calculate the excitation rate of the gear wheel. The transmission error (TE), which is a reference value for the resulting noise excitation of the gear in operation is obtained by an evaluation of the surface topography related to the angular position of the gear wheel over 360°. The developed software is described in previous works. More in-depth analysis considers structural flexibilities and boundary conditions of the gearbox and has been carried out with RomaxDESIGNER software. Periodic waviness of at least 0.1 μm leads to excitation in the gearbox in light load range. A load-free evaluation of gear flank topography over wheel circumference showed sufficient correspondence regarding the resulting TE and is used in this work. Periodic waviness over circumference of a gear wheel has a particular high influence on the TE when the waviness of crest and trough runs under the certain angle of ρ_b vertically to the path of contact between combing gears. Against this background, appearing vibration frequencies in generating gear grinding process can be classified into integer and non-integer vibration orders. Integer vibration order means that the frequency has an integer relation to the rotational speed of the workpiece. Previous investigations showed that applied vibrations in the generating gear grinding process result in a certain pronounced waviness on gear flank. Figure 7 shows of the simulation results an applied vibration in x-axis direction between 33.9th and
FIGURE 6  Simulation tool for generating gear grinding and excitation behavior of gear wheels

FIGURE 7  Simulation results of applied radial vibration (X-direction, see Figure 1) in generating gear grinding (A) influence of vibration order on gear flank topography (above) and resulting TE (below), (B) influence of varying feed rate \( f_a \) of 34.1st order analogously

34.1st order and respectively the 34.1st order with varying feed rate \( f_a \) from 0.5 mm until 2 mm per workpiece revolution. In below, the resulting order spectrum of analyzed topography (Figure 7(A)) and the result of a gear mesh simulation (Figure 7(B)) is depicted. Integer order vibrations, like the 34th order, lead to a waviness under angle of \( \beta_b \) which results in significantly high excitation rate of the resulting TE in the spectrum of the gear wheel. Non-integer vibration orders result in divergent angles of waviness and therefore, have decreased influence on the TE (see Figure 7(A)). Here, the axial feed rate \( f_a \) has a substantial influence on surface topography and TE (see Figure 7(B)). In order to determine whether an upcoming frequency excitation in manufacturing process affects the TE, contact conditions are examined and a criterion for assessment of in-process sensor signals concerning noise excitation behavior is carried out.

For analysis of the contact conditions, gear wheel and worm are considered as a cylindrical screw drive with non-parallel axes. Both geometries describe a helix surface in space

\[
\begin{align*}
\begin{pmatrix} x_E \\ y_E \\ z_E \end{pmatrix} &= \rho_b \begin{pmatrix} \sin(\xi + \tau + \eta) - \xi \cos(\xi + \tau + \eta) \\ \cos(\xi + \tau + \eta) + \xi \sin(\xi + \tau + \eta) \\ \tau \cot \beta_b \end{pmatrix} 
\end{align*}
\]  

(2)
with respective surface parameters of \( \tau \) and \( \xi \), see Figure 8(A). They are defined between tip \((d_t)\) and root diameter \((d_r)\) and over width of the gear wheel \(b\), see Equation (3). Base circle diameter, radius as well as base helix angle \((d_b, r_b, \beta_b)\) are derived from the involute gear geometry. \( \eta \) describes the angle to the starting point of the involute of the gear flank.

\[
\sqrt{\left(\frac{d_r}{d_t}\right)^2 - 1} \leq \xi \leq \sqrt{\left(\frac{d_u}{d_t}\right)^2 - 1} \text{ and } 0 \leq \tau \leq \left(\frac{b \cdot \tan \beta_b}{r_b}\right)
\]  

(3)

When determining the intersection line between plane of action and the face gear for gear wheel (Figure 8(B)) and worm respectively, the intersection point of both lines is the current contact point of the worm on the flank of the gear wheel (according to Figure 8(C), following References 10,18). The coordinates of this point can be transferred back to the surface parameters \( \tau \) and \( \xi \) by solving Equation (2) numerically. Hellmann10 states that the path of this point described on the plane of action confines the angle of \( \beta_b \) against the face side and is independent from geometry data of the worm. When adding the axial movement, each new point after a full workpiece rotation follows the angle of \( \beta_b \) against the flank line. This corresponds to the simulation results of integer vibration orders where crest and trough run under the same angle on the flank topography. The simulated contact points and their temporal and local arrangement are shown in Figure 9(A). In this context, it is possible to determine the angle of waviness of non-integer vibration order on tooth flank. Coming from the integer order \( O_{int} \) referred to workpiece rotation, the maximum angle \( \delta_{w2} \) and the minimum angle \( \delta_{w1} \) of waviness can be calculated with Equation (4) in dependence of considered width of gear wheel \( L_{rb} \) (following14), see Figure 9(B)). A waviness beyond those angle limits should have a minor influence on the TE of the gear because the contact line of combing gears (described with \( \beta_b \)) glides over at least one wave crest at any moment.

\[
\tan \delta_{w1} = \tan \beta_b - \frac{\lambda_{int}}{L_{rb}} \quad \text{and} \quad \tan \delta_{w2} = \tan \beta_b + \frac{\lambda_{int}}{L_{rb}}
\]  

(4)

The following relation describes the wavelength \( \lambda_{int} \) along the evaluation length of the gear wheel \( L_\xi \) of an integer order vibration:

\[
\lambda_{int} = \frac{2 \pi \cdot r_b}{O_{int}}
\]  

(5)

FIGURE 8 Geometry of gear flank and evaluation length \( L_\xi \) and \( L_\tau \) (A), intersection between line of action and face gear (B), current contact point of cylindrical screw drive (C)
Two vibrations with slightly different orders \( O_{x1} \) or \( O_{x2} \) and \( O_{int} \) describe the same oscillation state after \( N_1 \), respectively \( N_2 \) periods, see also Figure 9(C):

\[
N_1 = \frac{1}{O_{x1} - O_{int}} \quad \text{and} \quad N_2 = \frac{1}{O_{int} - O_{x2}} \quad (6)
\]

When connecting this relation to the geometric conditions in Figure 9(B) and Equation (4) the following expression can be established:

\[
N_1 \cdot f_a = L_{rb} + L_{rb} \cdot \tan \delta_{w1} \cdot \tan \beta_b
\]

\[
N_2 \cdot f_a = L_{rb} + L_{rb} \cdot \tan \delta_{w2} \cdot \tan \beta_b
\quad (7)
\]

This formula considers a constant axial feedrate in the process. The influence of a shifting movement in one machining stroke is neglected here. It is possible to determine the range of vibration excitation in the generating gear grinding process, where orders \( O_{x1} \) and \( O_{x2} \) lead to an angle of the waviness of \( \delta_{w1} \) and \( \delta_{w2} \) on gear flank topography. This is done by inserting Equation (6) into (7) and rearranging it to:

\[
O_{x1} = O_{int} + \frac{f_a}{L_{rb} + L_{rb} \cdot \tan \delta_{w1} \cdot \tan \beta_b}
\]

\[
O_{x2} = O_{int} - \frac{f_a}{L_{rb} + L_{rb} \cdot \tan \delta_{w2} \cdot \tan \beta_b}
\quad (8)
\]
Likewise, it is possible to determine the angle of a waviness on tooth flank with a given excitation order \( O_x \) by transposing (8) into:

\[
\tan \delta_{w1} = -\frac{L_{rb} + \frac{f_a}{O_{\text{int}} - O_{x1}}}{L_{rb} \cdot \tan \beta_h} \quad \text{for} \quad O_{x1} > O_{\text{int}}
\]

\[
\tan \delta_{w2} = \frac{f_a - L_{rb} \cdot O_{\text{int}} + L_{rb} \cdot O_{x2}}{L_{rb} \cdot \tan \beta_h \cdot (O_{\text{int}} - O_{x2})} \quad \text{for} \quad O_{x2} < O_{\text{int}}
\]

In the case of a spur gear where \( \beta_b = 0 \) (compare to Figure 9(B)) the calculation of the angle of waviness \( \delta_{w1/2} \) is simply described by

\[
\tan \delta_{w1/2} = \pm \frac{O_{\text{int}}}{L_{rb}}
\]

In order to verify the calculation approach, a manufacturing simulation was carried out for a helical and a spur gear wheel, tool and process data depicted in Table 1. A constant radial vibration with an amplitude of \( 1 \mu m \) perpendicular between gear wheel and workpiece axis was applied in the simulation (see Figure 1). Coming from the integer order \( O_{\text{int}} = 34 \), upper \( O_{x1} \) and lower \( O_{x2} \) non-integer orders were determined with Equation (8). Considered evaluation width \( L_{rb} \) was chosen to be the width \( b \) of the gear wheel (see Table 1). Figure 10 shows simulation results of the calculated tooth flank topography the calculated angle of waviness and the resulting TE spectrum derived from topography deviation for excitation \( O_{x2} \) (Figure 10(A)), \( O_{\text{int}} \) (Figure 10(B)), and \( O_{x1} \) (Figure 10(C)). The angle of the pronounced waviness on the topography corresponds to the calculated angle (violet lines). The order spectrum (see in below) confirms the differences of the excitation rate of the waviness on gear wheel topography running across the line of action \( \beta_h \) in contrast to a waviness further away from this angle. In the case of the helical gear wheel, an excitation amplitude for \( O_{x2} \) is still visible (see Figure 10(A) below). The reason is that the waviness is not evenly dispersed over the whole width of the gear wheel and shows minor deviations. Nevertheless, it is proven, that the generated topography of a certain constant vibration excitation in the process can be determined analytically with Equations (9) and (10). The limits of whether this vibration leads to an acoustic conspicuity can be drawn accordingly (Equation (8)), as the excitation spectrum shows plausible results.

The presented relation between excitation order and tooth flank topography derived from the contact conditions in generating gear grinding allow for an assessment of in-process measurement data regarding quality assurance in manufacturing. In dependence of the gear wheel and process data, limits of frequency bands are calculated. Figure 11 shows characteristic excitation frequencies from 0 to 1 kHz in a generating gear grinding process with harmonics of axle speed (tool \( n_0 \) and workpiece \( n_1 \)) and gear mesh. For the given helical gear wheel and process (see Table 1) upper frequency \( f_{x1} \), lower frequency \( f_{x2} \) and the integer frequency \( f_{\text{int}} \) in the middle are calculated marked between first and second gear mesh frequency. The close-up views to the left and the right show two exemplary frequency bands. The frequency range of upper and lower frequency in those cases lies between 0.792 Hz and 0.765 Hz. When taking one tenth of this range as the required frequency resolution for the fast Fourier transform analysis, the sampling time of the in-process measurement yields 13.1 s. With this approach, monitoring of vibrations in generating gear grinding process und beyond that, automated speed adjustment of rotational machine axes in order to avoid reject in the production is possible.

### Table 1

Input for manufacturing simulation with gear wheel, tool, and process data

| Gear wheel data       | Symbol/unit | Value | Tool and process data       | Symbol/unit | Value |
|-----------------------|-------------|-------|-----------------------------|-------------|-------|
| Number of teeth       | \( z_1 \) / – | 26 / 16 | Number of threads           | \( z_0 \) / – | 5     |
| Normal module         | \( m_n \) / mm | 2 / 4.5 | Pitch diameter              | \( d_0 \) / mm | 260   |
| Helix angle           | \( \beta \) / deg | 34 / 0 | Rotational speed            | \( n_0 \) / min\(^{-1} \) | 5000  |
| Normal pressure angle | \( \alpha_n \) / deg | 16 / 20 | Axial feed rate             | \( f_a \) / (mm/rev) | 0.5   |
| Width                 | \( b \) / mm | 15 / 10 |                             |             |       |
FIGURE 10  Result of simulated gear flank topography (above) with radial vibration excitation, respectively $O_{\omega_2}$ (A), $O_{\omega_1}$ (B), $O_{x_1}$ (C) and derived order spectrum of the helical and spur gear wheels from Table 1 (below). Calculated wave fronts with Equation (9) (light violet line) and representation of $\beta_b$ (dashed red line).

FIGURE 11  Example for monitoring frequency bands in generating gear grinding process, frequency band (left hand side) of integer order 27, frequency band (right hand side) of integer order 51.

4 | SUMMARY AND OUTLOOK

Fine machining of gearings is predominantly performed using geometrically undefined cutting edges as in the case of continuous generating gear grinding. Since the exact tool conditions are unknown, safety factors have to be considered in order to eminently ensure the quality of manufactured gear wheels toward defects, such as grinding burn. Furthermore, displacement of tool and workpiece, e.g., vibrations have significant influence on topography and acoustic behavior but they will hardly be detected in manufacturing processes yet. The presented in-process evaluation methods include sensor
selection, data acquisition, signal processing and interpretation based on referenced process images from conducted experiments and analytical process models. AE- and motor spindle current signals have been proven to be appropriate for evaluating distinct process conditions in order to adapt shifting movement and feed rate of the process. In that way, it is possible to increase productivity up to 40% for the given example while retaining consistent workpiece quality. Moreover, a calculation method has been developed, which connects vibrational displacement in the machining process with the resulting structure in topography and excitation behavior of a manufactured gear wheel. The analytical calculation method shows well accordance between predicted and simulated angle of waviness on gear flank topography and similarly corresponds with the expected excitation spectrum derived from this topography. Furthermore, the calculation of process-dependent frequency bands in generating gear grinding allows detecting acoustically effective waviness in the process. Further investigations will focus on the extension of the evaluation methods as well as implementation on sample processes in order to refine the adaption procedure in production environment. An extension of monitoring algorithms with various signals toward a soft sensor solution is a promising strategy for industrial manufacturing processes.

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REFERENCES

1. Brecher C, Schroers M, Löpenhaus C. Experimental analysis of the dynamic noise behavior of a two-stage cylindrical gearbox. *Prod Eng*. 2017;11(6):695-702.
2. Linke H, Börner J, Heß R. Manufacturing of cylindrical gearings. In: Linke H, Börner J, Hess R, eds. Cylindrical Gears: Calculation, Materials, Manufacturing. Cincinnati, OH: Hanser Publications; 2016:605-707.
3. Wegener K, Hoffmeister H-W, Karpuschewski B, Kuster F, Hahmann WC, Rabiey M. Conditioning and monitoring of grinding wheels. *CIRP Ann*. 2011;60(2):757-777.
4. Brecher C, Klocke F, Löpenhaus C, Hübner F. Analysis of abrasive grit cutting for generating gear grinding. *Procedia CIRP*. 2017;62:299-304.
5. Kundrák J, Markopoulos AP, Karkalos NE. Numerical simulation of grinding with realistic representation of grinding wheel and workpiece movements: a finite volumes study. *Procedia CIRP*. 2017;58:275-280.
6. Brecher C, Brumm M, Hübner F. Approach for the calculation of cutting forces in generating gear grinding. *Procedia CIRP*. 2015;33:287-292.
7. Dietz C, Wegener K, Thyssen W. Coupled manufacturing of simulation and process optimization of continuous generating grinding involute gears by numerical methods. Paper presented at: International Conference on Gears; 2015; Düsseldorf: VDI Verlag.
8. Baldeck BJ, Chapin PE. Method of maintaining a constant grinding process. US patent US20070275638A1. May 24, 2006.
9. Jiang J, Fang Z. Design and analysis of modified cylindrical gears with a higher-order transmission error. *Mech Mach Theory*. 2015;88:141-152.
10. Hellmann M. Berücksichtigung von Fertigungsabweichungen bei der Auslegung von Zahnflankenmodifikationen für Stirnradverzahnungen [dissertation]. IIF—Institut für Industriekommunikation und Fachmedien GmbH; 2015.
11. Fong Z-H, Chen G-H. Gear flank modification using a variable Lead grinding worm method on a computer numerical control gear grinding machine. J Mech Des. 2016;138(8):343.
12. Amini N. Gear Surface Machining for Noise Suppression. Göteborg, Sweden: Chalmers Univ. of Technology; 1999.
13. Gravel G. Simulation of deviations in Hobbing and generation grinding. Paper presneted at: International Conference on Gears; 2013; Düsseldorf: VDI Verlag.
14. Kahnhenley T. Methodik zur Ursachensuche geräuschanregender Oberflächenwelligkeiten an Zahnrädern: FVA-Projekt, Nr. 733 II, progress report 03/01/2019. Forschungsvereinigung Antriebstechnik e.V. 2019;1-20.
15. Böttger J, Kimme S, Drossel W-G. Analysis of periodic components on tooth flanks by simulation of continuous generating gear grinding. Paper presented at: International Gear Conference; 2018;342–351.
16. Böttger J, Kimme S, Drossel W-G. Characterization of vibration in continuous generating grinding and resulting influence on tooth flank topography and gear excitation. Procedia CIRP. in press. 2021.
17. Rank B. Welligkeiten auf Zahnflanken: Ursachen und akustische Auswirkungen. Verzahnungsmesstechnik. Düsseldorf, Germany: VDI Verlag; 2014:93-104.
18. Litvin FL, Fuentes A. Gear Geometry and Applied Theory. Cambridge, UK: Cambridge University Press; 2004.
19. Hochmuth C, Gentzen J, Krage R. Steigerung der Produktivität und Sicherung der Bauteilqualität beim Schleifen. 5. VDI-Fachtagung Stahl- und Gusszerspanung: Werkstoffe - Verfahren - Kühlschmierkonzepte - Werkzeuge - additive Fertigung. Düsseldorf, Germany: VDI Verlag; 2017.
20. Hochmuth C, Gentzen J. Industrie 4.0—Entwicklung adaptiver Bearbeitungsprozesse. Chemnitz: Fraunhofer Institute for Machine Tools and Forming Technology. Fachseminar Feinbearbeitung 2017: Schleifen, Honen und Finishen - Entwicklungstrends im Zeitalter der Digitalisierung. 2017;71-86. http://publica.fraunhofer.de/dokumente/N-473584.html.

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