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Abrasion Monitoring and Automatic Chatter Detection in Cylindrical Plunge Grinding

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Abstract

Using conventional grinding wheels, wheel-sided chatter vibration is one of the limiting factors in terms of productivity and surface finish. Initial vibration related to the dynamic behavior of the machine tool copy on the grinding wheel and its amplitude amplifies by abrasion. To ensure high workpiece quality many expensive truing cycles are needed. In this context, we suggest a new set-up for the automatic chatter detection and elimination for external cylindrical grinding machines, reducing not only the high amount of true running cycles, but also improving the efficiency. In order to suppress the generation of the waviness on the grinding wheel the effect has to be identified during an early stage of its development. Therefore, a grinding machine is equipped with different types of sensors, i.e., eddy current, force, acoustic emission, acceleration sensors, and a tactile probe. Experimental results show, that exclusively measuring the displacement at the workpiece is sufficient for online computing wheel's waviness. Based on a model of the grinding process the other redundant sensors are used for validation. In addition, a robust online chatter detector based on the wavelet transformation is developed recognizing an instable grinding process. This model-based detection and estimation of waviness delivers solid results, it should be used for suppression of chatter in further work.

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1. Introduction

Finishing processes like grinding are used to produce highest surface quality and close tolerances. Vibrations obstruct accuracy as well as surface finish of the ground part. Using conventional grain like corundum, the wheel's geometric wear may lead to self-excited vibration and waves on the grinding wheel surface [6]. If the amplitude of waves and the resulting dynamic process forces get too large, the tool may break and damage the machine. Hence, the waves have to be removed by dressing operation. In plunge grinding, this chatter vibration often appears for a wide range of process parameters. In practical use, it is suppressed by lowering the feed rate to disturb the slow progress of development.

In order to monitor or suppress these vibrations they have to be identified in an early stage of their development. Different studies have been carried out for this purpose [7]. The coarse-grained information rate (CIR) is used for signals like measured process forces and effective values of acoustic emission (AE). This processing works fine for detection by single signals, but cannot provide detailed information about the kind of chatter. Other researches show the great potential of the signal processing by wavelet-transformation for AE signals [2, 8-9].

In this paper, the development of wheel-sided self-excited vibration and the resulting signal characteristic are discussed based on measurement data of a multi-sensor concept. The authors present two methods for monitoring chatter, i.e. amplitude- and wavelet-based detection, applied on different sensors. Further, an approach to monitor the grinding wheel's surface is suggested. For validation of this result, the wheel surface waviness is analyzed by dressing operation and in-process during grinding.

2. Regenerative effect on grinding wheel surface

The effect of grinding chatter is similar to self-excited vibrations in other cutting processes. The change in depth of cut after one rotation generates waves on the surface between tool and piece. Phase shift between tool and part leads to increasing waves and an unstable process. In

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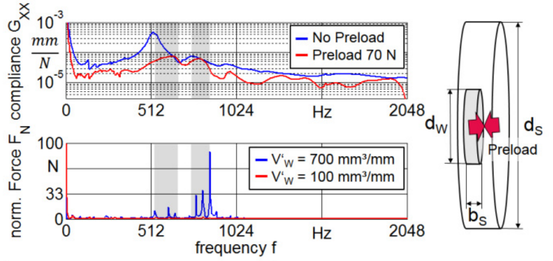
grinding, required radial wheel wear may lead to waviness on the surface of the grinding wheel. Due to the limited geometrical contact length, this wheel-sided regenerative effect appears in higher frequencies [10]. Therefore, it is a greater challenge compared to workpiece-sided regenerative effect in plunge grinding.

The formation of waves highly depends on the main parameters of the process and diameter of the tool as well as workpiece. Geometric interference may lead to nonlinear dynamics [11]. Also, the formation depends on the grinding forces and the dynamic compliance of the machine tool and the workpiece. In order to avoid or slow down the occurrence of chatter, manufacturers are interested in stiff design of grinding machines. Compliance of the workpiece is balanced by high damping of the machine tool. The machine in use gives a typical example; it provides hydrostatic guideways and a hydrostatic screw drive. Because of the high viscose damping, the dynamic behavior depends on the normal preload between grinding wheel and workpiece (cf. Figure 1).

Universal applicable modeling of chatter is difficult to predict – even at the same grinding machine.



grinding wheel diameter d_S = 400 mm
workpiece diameter d_W = 100-90 mm
eff. grinding wheel width b_S = 10 mm
cutting speed v_C = 50 m/s
speed ratio q = 60
spec. material removal rate Q_w' = 10 mm³/mm
grinding wheel 54A120 H15VPMF90
Fi/59246 © IFW

Figure 1: Compliance and process spectrum

By means of several distinctive eigenfrequencies and corresponding eigenmodes, a stable grinding process can be characterized by its wide range frequency spectrum and a workpiece performing chaotic vibrations. In case of chatter these turn to the direction of highest dynamic compliance. In addition in case of wheel-sided chatter, frequencies occur at multiples of the rotational speed. Because of the high damping of the machine, two or more frequencies are excited at one resonance (cf. Figure 1). Their interference leads to a beat frequency in time domain.

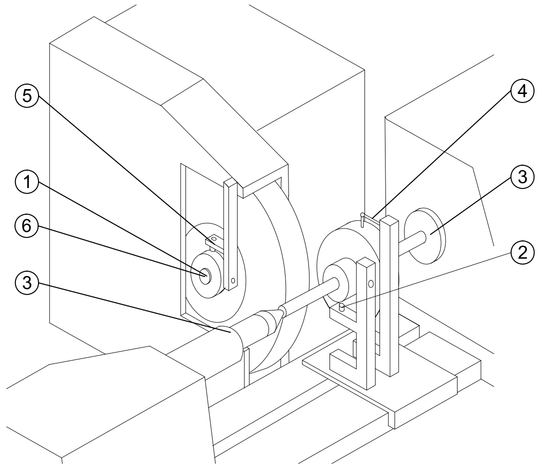
These two characteristics of the unstable grinding process are used for modeling and identification of the regenerative effect of the grinding wheel surface.

3. Chatter detection

There are many methods for direct measurement of the wheel’s surface, i.e. [3], [4]. Most of them require optical, tactile or air gap sensors. All methods challenge the measurement on the grinding wheel’s topography and cannot be used at high cutting speeds.

Another possibility to determine chatter is measuring the grinding forces directly. For experimental investigation, two piezoelectric dynamometers are implemented between workpiece fixture and machine frame. Hence, forces in three dimensions can be measured with high accuracy, whereas the applied mass distorts the measurements in higher frequencies.

Figure 2 shows the measurement setup, the sensor types and their location in use. Table 1 lists the additional sensors. Sensor data is recorded, converted and evaluated by the use of a digital signal processor.



① Acoustic emission
② Eddy current (workpiece)
③ 2x3 axis force
④ In-process diameter
⑤ Eddy current (grinding wheel)
⑥ Acceleration

Figure 2: Measurement setup

Table 1: Sensors

	Sensor	Unit	Signal Condition
1	Acoustic Emission	V	Band:50..150kHz Lowpass: 1 kHz
2	Eddy-Current Workpiece (2)	µm	Lowpass 10 kHz
3	Force (2x3-Axis)	N	Lowpass: 3 kHz
4	In-Process Diameter	mm	Lowpass: 1 kHz
5	Eddy-Current Grinding Wheel (2)	µm	Lowpass 10 kHz
6	Acceleration	m/s^2	Lowpass: 1 kHz
7	Spindle Current	A	Lowpass: 1 kHz

The presented results are examined on a CNC-type cylindrical plunge grinding machine. It is equipped with hydrostatic guideways and a belt-driven spindle with an automatic balancing system.

To create comparable measurement series a standardized grinding process was defined. The workpiece consists of bearing steel (100Cr6 / 1.3505 at 62 HRC) at width of 10 mm. In order to analyze the grinding wheel wear the workpiece was ground from 100 to 90 mm in different grinding cycles. The grinding wheel in use consists of white aluminum oxide at grain size F120 (FEPA) at bond hardness H and a slightly porous structure. All experiments are carried out with mineral oil as cutting fluid at 70 liter per minute. The process parameters were as follows: cutting speed of 50 m/s, speed ratio of 60, and specific material removal rate of $10\ mm^3/mm\ s$. They give a typical example for the wide range experimental parameter set. The test series was carried out until grinding chatter was acoustically detected.

3.1 *Amplitude-based chatter detection*

If chatter occurs, former undirected vibration turns into directed oscillations (cf. Figure 3). Analyzing the measured displacement, this leads to an elliptic trajectory in the XY-plane of the workpiece.

This is used for chatter detection [2]. Since the workpiece vibration is measured in two dimensions, the main direction of oscillation has to be determined to identify oscillation referred to the direction of the highest compliance.

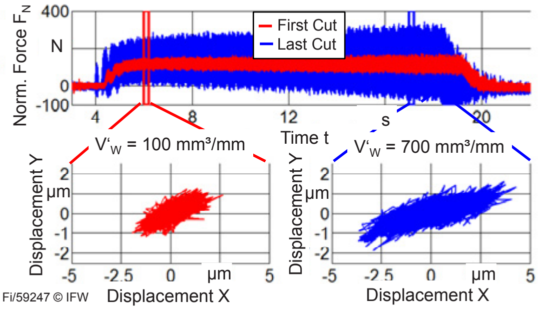


Figure 3: XY-Plot of the workpiece displacement

The ratio between the amplitude of both directions is used as an indicator for chatter. Figure 6 shows a grinding process with increasing amplitudes. The ratio increases from stable process conditions to significant chatter with a ratio of four in the main direction. The method requires the determination of a threshold to define a chattering process. It depends on the grinding machine or process parameter. For noise reduction, standard deviation of the measured signals is used and higher noise immunity is achieved.

3.2 *Wavelet-based chatter detection*

Besides the chatter frequencies there are other significant spectral components, i.e. workpiece rotation, cutting speed, which are not of interest for detection of an instable process. Wavelet transformation allows unfolding a signal's frequency spectrum in time domain. Unlike the Short-Term-Fourier-Transformation (STFT) it provides a variable time and frequency resolution. It depicts high frequencies at high time and low frequency resolution – and low frequencies vice versa. Calculating the FFT of the same signal will perform on every frequency equally. The basic idea of wavelet transformation is the convolution of a signal $x(t)$ with a group of wavelet tions $\psi_{s\tau}$, cf. (3.1). Each group is obtained by stretching a wavelet-base-function with various scaling factors s, see (3.2).

$$\mathcal{W}_{\psi}x(s,\tau) = \frac{1}{s}\int_{-\infty}^{\infty} \psi_{s\tau}\left(\frac{t-\tau}{s}\right)x(t)dt \qquad (3.1)$$

$$\psi_{s\tau} = \frac{1}{s}\psi\left(\frac{t-\tau}{s}\right) \quad : s \in \mathbb{R}^{+}, \tau \in \mathbb{R} \qquad (3.2)$$

There are many different wavelet-base-functions. The choice of the base-function has great influence on the transformation results.

Because of the similarity of Daubechi-wavelet and beat frequencies at unstable processes (cf. Figure 4) a db10-Daubechi-wavelet [5] was chosen. Parameter studies have shown the best results by use of this base-function.

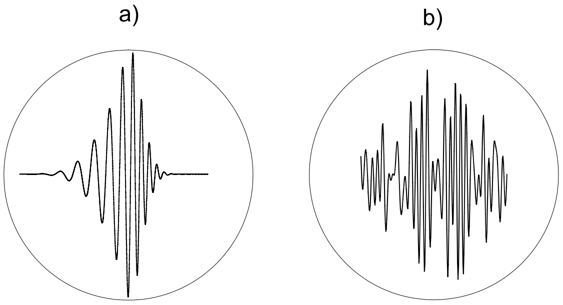


Figure 4: a) db10-wavelet and b) chatter-burst

Since Continuous Wavelet Transformation (CWT) holds redundancy and has high computational costs, the Discrete Wavelet Transformation (DWT) is used. The DWT can be understood as a chain of high and low pass filters which are simple to implement (cf. Figure 5).

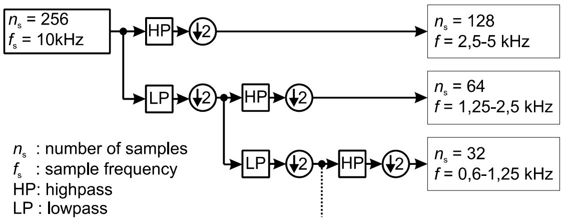


Figure 5: Discrete Wavelet Transformation

The result of a *n*th order DWT are *n* bands containing the different frequency sections. A stable grinding process has a wide ranged frequency spectrum whereas an unstable process exhibits significant peaks in a small frequency range. Figure 6 (bottom) shows the result of a 5th order DWT from the process mentioned in section 3.1, normalized with respect to the band with the highest amplitude at a certain time.

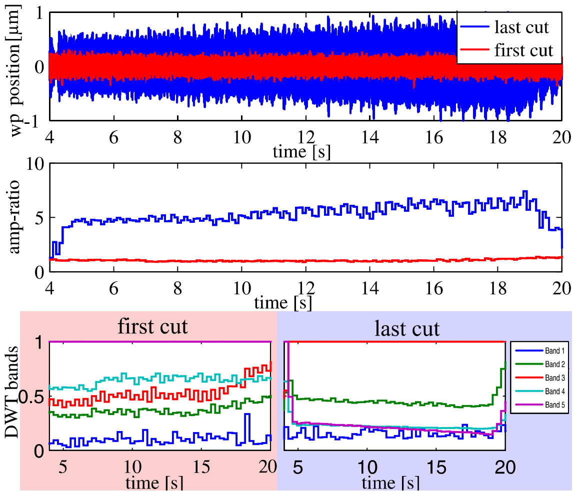


Figure 6: Workpiece vibration (top) with amplitude- (middle) and wavelet-based (bottom) chatter detection results

At the instable process, one or more multiples of the rotational frequencies increase with respect to the dynamic compliancy. This leads to one or two bands dominating the normalized DWT. Based on experimental results, a band which reaches more than 40% of the maximum bands amplitude at a time, is declared active. Chatter is identified, if there are less than three active bands. In the process analyzed in Figure 6 the wavelet-based approach detects chatter during the last cut, when only band 3 can be considered active. Contrary to the amplitude-based chatter detection this method provides results without any knowledge of the grinding machine or the process by using only one sensor. This wavelet-based chatter detection works similar for measured workpiece displacement, forces in normal and tangential direction, and acceleration signals on the workpiece clamping system.

The wheel-sided sensors (spindle current, acceleration and displacement) give poorer results. By means of noise, chatter cannot be detected until it appears acoustically. This is explained by the dynamic behavior; in plunge grinding the workpiece causes the highest compliance.

4. Estimation of the grinding wheel surface

In order to suppress or distort the regenerative effect, additional information in amplitudes, and frequency of the surface are needed. The presented approach estimates the grinding wheel surface by eddy current sensors. They are mounted near to the grinding wheel and work piece and provide the best signal quality regarding surface reconstruction. In a first step it is necessary to remove parts of the signal that are caused by other sources. With the information gained from the DWT it is possible to isolate the specific frequencies by applying inverse DWT or corresponding bandpass filtering. By means, runout and noise can be reduced without detailed analysis of the grinding machine and parameters. To calculate the estimated wheel surface the resulting signal is mapped on the wheels rotation speed. Further reduction of noise is achieved by the weighted, averaged estimated surface of the last grinding passes (cf. Figure 8).

Experimental results show that this method is also suitable for evaluating the force-sensor signal. However, the resulting quality is not as good as using eddy current sensors, due to the shorter signal path between them and the grinding wheel.

5. Determination of the grinding wheel surface by AE

To validate this estimation, the AE-signals are analyzed during dressing operation. The approach suggested in this paper follows the method presented in [1]. It analyses the contact between wheel and dresser around the grinding wheel axis by AE. With the aim of achieving a higher resolution of the resulting surface, the depth of cut was adjusted from 35 µm to 1 µm. Each dressing stroke can be mapped by the axial feed position and the grinding wheel surface (cf. Figure 7). In addition to this well-known method, different dressing strokes are stored and combined afterwards. Therefore, the AE-level at the last stroke is used to define a threshold. Comparing this threshold defines the contact for each stroke. These values are used to combine the signal for each dressing stroke of 1 µm. Mean values over the effective grinding wheel width are calculated for each angular position.

Figure 7 shows the results. In this experiment, the width of the grinding wheel is greater as the width of the workpiece. Therefore, the area with no contact can be shown. The single wave in this curve indicates the runout of the grinding wheel at a differing dressing speed. The track area exhibits distinctive waves in higher frequencies and amplitudes.

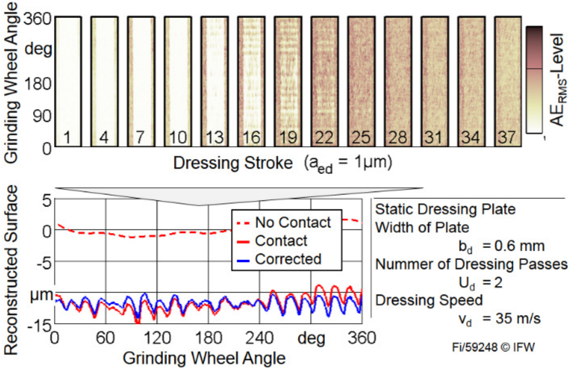


Figure 7: Grinding wheel surface

A comparison between the reconstructed and the estimated surface of the grinding wheel is given by Figure 8. Using Fast Fourier Transformation (FFT) the number of waves on the grinding wheel surface can be calculated for the estimated surface. The surface reconstructed by dressing is analyzed equally for different numbers of waves. In Figure 9 the frequencies and amplitudes of both methods are compared.

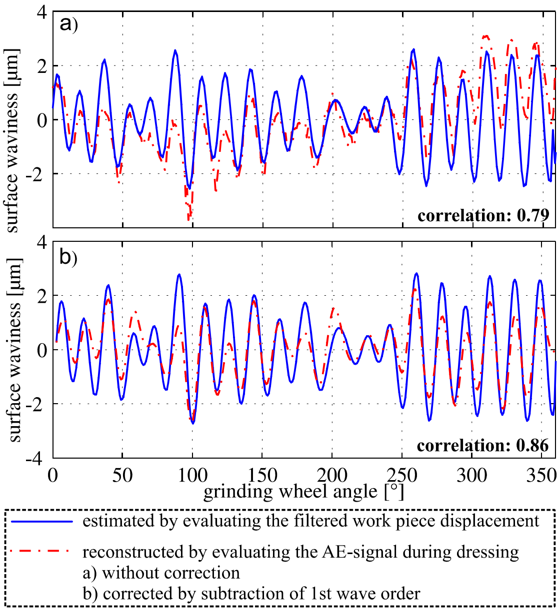


Figure 8: Grinding wheel surface

Because there is no way to distinguish between one single wave order and wheel runout in consequence of different speed of rotation during the mapping, there is an error visible, related to exactly one wheel revolution.

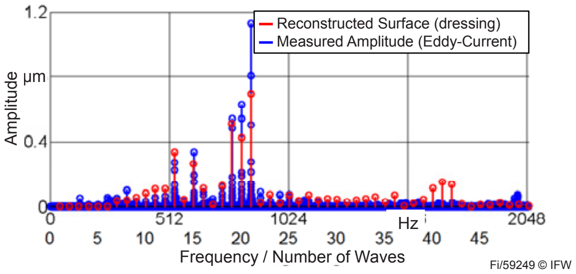


Figure 9: Waviness of grinding wheel surface

The results show a good qualitative fit with a correlation up to 0.86 between the two methods. The estimated surface can be used for reacting to the waviness of the wheel and stabilize an instable grinding process.

6. Conclusion and outlook

Using a multi-sensor concept, the authors identified the sensors with the highest potential for chatter detection. In plunge grinding of long work pieces, eddy-current-sensors measuring its displacement are preferred. Additionally to the particular experiment shown in this paper exemplarily, the method also works for a wide range of different process parameters in plunge grinding (cutting speed: 35 to 60 m/s; grinding ratio: 60 to 180; Material removal rate up to 16 $mm^3/mm\ s$). This method works fine for cylindrical plunge grinding; it can be easily adapted to surface or from grinding. In different processes like surface- or inner diameter grinding, different sensors or sensor placement has to be used.

The analysis of workpiece displacement shows good results regarding detection of chatter in an early stage of its development. A drawback of this method is the determination of a threshold, since it depends on the direction of the mode shape and the ground workpiece. Additionally, two expensive sensors are needed for this method. The presented wavelet-based chatter detection surpasses these disadvantages by evaluating only one eddy-current sensor and being mostly invariant to parameter changes. Further information is obtained by estimation of the grinding wheel surface. It can be estimated applying the presented filter to data of a single eddy current sensor measuring workpiece oscillations.

It has been pointed out, that dressing the grinding wheel using AE-sensor data is a suitable method not only for evaluating patterns but also for indirect measuring of the wheels surface waviness. In combination with the presented chatter detectors it is planned to develop a control system for the active suppression of chatter in grinding processes.

References

[1] de Oliveira, J.F. G.; Dornfeld, D.A.: Application of AE Contact Sensing in Reliable Grinding Monitoring, Annals of the CIRP, 50/1, pp. 217-220, 2001.

[2] Schütte, O.: Analyse und Modellierung nichtlinearer Schwingungen beim Außenrundeinstechschleifen, Dr.-Ing Dissertation, Universität Hannover, 2003.

[3] Cuntze, E.O.: Entstehung und Minderung von Ratterschwingungen beim Schleifen, Dr.-Ing. Dissertation, TH Braunschweig, 1966.

[4] Gosebruch, H.: Rundschleifen im geschlossenen Regelkreis, Dr.-Ing. Dissertation, Universität Hannover, 1990.

[5] Daubechies, I.: Ten Lectures on Wavelets, Society for Industrial and Applied Mathematics, 1992.

[6] Inasaki, I. et al.: Grinding Chatter - Origin and Suppression, CIRP Annals-Manufacturing Technology, 50/2, pp. 515-534, 2001.

[7] Gradisek, J. et al.: Automatic chatter detection in grinding, International Journal of Machine Tools & Manufacture, 43, pp. 1397-1403, 2003.

[8] Yang, Z. et. al.: Grinding wheel wear monitoring based on wavelet analysis and support vector machine, International Journal of Advanced Manufacturing Technology 62, pp. 107-121, 2012.

[9] Yao, Y. et. al.: Study on the Wavelet Transform Based Monitor Signal Processing Method for Grinding Wheel Dull. Key Engineering Materials 598, pp. 375-376, 2008.

[10] Schiefer, K. H.: Theoretische und Experimentelle Stabilitätsanalyse des Schleifprozesses. Dr.-Ing. Dissertation TH Aachen, 1980.

[11] Folkerts, W.: Dynamic Process Parameters of grinding and their influence on the process stability. Dr.-Ing. Dissertation RWTH Aachen, 1993.