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An Active Damping Method for Chatter Vibration in Plunge Grinding using Electromagnetic Actuators

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Abstract

Using conventional grinding wheels, self-excited vibrations are one of the most limiting factors in terms of productivity and process stability in cylindrical plunge grinding. Depending on the dynamic behavior of the workpiece and machine, workpiece vibration copy on the grinding wheel's surface, caused by uneven wear. This results in increasing waviness and, therefore, increasing workpiece vibration. In this context, an active vibration control, using a self-built magnetic actuator to influence the tool wear, is presented. The limits and possibilities of this influence are examined in this paper, i. e. the generation and reduction of waves on the grinding wheel. Furthermore, the prevention of chatter vibration and its robustness against parameter variation is analyzed and presented.

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1. Introduction

In manufacturing, finishing processes like grinding are used to achieve high surface quality or low tolerance. The material removal rate of grinding is relatively low compared to other processes like turning or milling, which results in high process duration and cost-intensive processes. Therefore, grinding is only carried out, if the demands on a workpiece require this costly process, which makes the economic efficiency of the grinding process an important factor. The production of a flawless workpiece may be hampered by vibrations of internal or external sources. Internal disturbance is often caused by self-excited oscillations, also called chatter. Especially conventional abrasives like corundum grinding wheels tend to develop vibrations due to wheel-sided regenerative effect. Contrary to the workpiece-sided regenerative effect, where vibrations occur due to an increasingly wavy workpiece surface, the wheel-sided regenerative effect is caused by waves forming on the grinding wheel's surface. Vibrations of the workpiece copy onto the wheel due to varying contact force and tool wear. The uneven tool excites the workpiece's oscillation even more, causing an increasing waviness on the grinding wheel with every revolution [1]. Even at low amplitudes below one micron, surface waves excite dynamic process forces

and may damage machine as well as workpiece as they increase. The waves on the wheel have to be removed by time consuming dressing operations, limiting the economic efficiency of the grinding process. In contrast to workpiece-sided chatter vibration, waves develop only at higher frequencies beyond 100 Hz, due to the limited contact length, depending on the individual grinding machine. Thus, wheel-sided chatter is more difficult to handle. The formation of waves on the grinding wheel strongly depends on the process parameters, i.e. contact length, process forces, rotation speed and geometry of wheel and workpiece, cooling fluid, cutting velocity, and especially the dynamic behavior of the workpiece. In this paper, the performance of the active vibration control using a magnetic actuator presented in [1] is analyzed. Furthermore, the possibilities of generation and reduction of waves on the grinding wheel by influencing the tool wear, the prevention of chatter vibration and its robustness against parameter variation is presented.

The reduction or prevention of wheel-sided chatter is discussed by various researchers. Tönshoff et al and Altintas et al analyze passive damping methods [2], [3]. It is shown that a reduction of chatter vibrations is possible, but the damping systems have to be adjusted for each individual workpiece. Altering the grinding wheel's rotation speed is a suitable approach to reduce waves on the wheel's surface but usually

requires an experienced operator (cf. Hoshi et al. [4] and Spur et al. [5]). the first active damping method was proposed by Cuntze et al. proposed in 1966 [6]. Form rolls applied forces on the workpiece to reduce chatter vibrations and waves on the wheel. Most of the more recent approaches of active damping used piezo-actuators. Gosebruch [7] and Michels [8] utilized active piezo-centre points and were able to slow down the development of chatter vibrations. However, these methods are not able to permanently suppress chatter vibration or to reduce existing waves on the wheel at varying process parameters.

The machine used for the experiments presented in this paper is a SCHAUDT CR41 CBN with hydrostatic guide ways and screw drives enhancing the damping and stiffness of the machine to prevent or slow down chatter vibration.

2. Measurement Setup

Figure 1 shows the measurement setup used for the experiments in this paper. While the active chatter compensations only relies on the workpiece position measurement provided by eddy current sensors, various other sensors are implemented for validation. Besides acoustic emission, the tool position, tailstock acceleration, workpiece forces, and spindle current are measured. The magnetic actuator depicted in Figure 2 applies the necessary forces onto the workpiece.

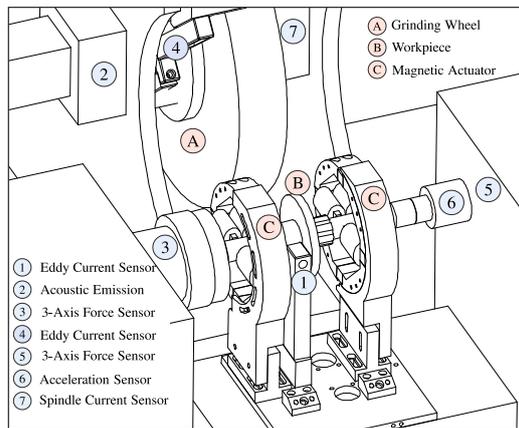


Figure 1: Measurement Setup

2.1. Grinding Machine

The SCHAUDT CR41CBN is a CNC type cylindrical plunge-grinding machine with automatic balancing system and belt driven spindle. To obtain comparable results, a standardized grinding process is defined. The workpiece consists of bearing steel (C100Cr6 / 1.3505 at 62HRC) in form of 10 mm wide disks with a diameter of 100 mm on a 200 mm shaft. The used grinding wheel is composed of white aluminum oxide at grain size F120 (FEPA) with bond hardness H and slightly porous structure. The deployed cooling fluid is mineral oil at 45 l/min. Running the process at a cutting velocity of $v_c = 35$ m/s a speed ratio $q = 80$, and a specific material removal rate $Q'_w = 5$ mm³/mm · s results in a slightly instable process with slow developing chatter.

2.2. Magnetic Actuator

The grinding process can be influenced by the magnetic actuator depicted in Figure 2. In contrast to the measurement setup proposed by Ahrens et al. [1], a modified version of the actuator is used as it can apply forces only in one direction, since the active compensation can be achieved with forces solely in radial direction of the grinding wheel. This lowers requirements on power electronics and reduces mounting times. The actuators have a diameter of 160 mm and are able to generate forces of ± 20 N each at adjustable angle. The magnet's iron cores are 30 mm wide and composed of laminated soft magnetic material to reduce losses due to eddy currents and ensure high dynamics of the actuator. The current in the magnet coils is controlled by Junus servo amplifiers connected to a 160 V intermediate circuit [9]. Using a pseudo-random-bit-sequence-signal (prbs), its dynamic behavior can be identified as a PT₁-system with corner frequency at 700 Hz and 0.2 ms delay. Thus, it is possible to reach up to 20 N at 1 kHz. The highest chatter frequencies in the presented setup are roughly at 1.1 kHz [10].

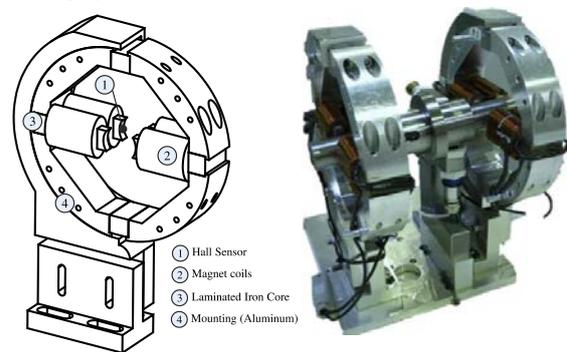


Figure 2: Electromagnetic Actuator CAD (left) and prototype (right)

3. Active Feedforward Chatter Reduction

As already proposed by Ahrens et al [1], this setup is able to prevent the development of chatter vibration during the defined standardized grinding process. However, the results show only the stabilization of an initially chatter free process when the active compensation is applied. In practical use it is a moot point whether the system is able not only to prevent waves but to reduce waves already existing on the wheel's surface. To analyze the actor's influence on the wheel's surface in this experiment a wave is deliberately generated and then afterwards reduced by inverting the generation signal.

In a first step a sine-shaped force and at approx. 950 Hz, which matches 32 times the wheel's rotation speed, synced with the wheel's angle is applied onto the workpiece. This frequency is chosen, because of the high dynamic compliance of the system at this point. Waves of other frequencies are excited by the process itself as well, but they remain small in comparison to the artificially excited wave. For an undistorted analysis of the chatter frequency, the actuator is switched off shortly before the end of process. The bottom left graph in Figure 3 gives a general view over this excitation process.

In a subsequent process, the generated wave shall be reduced. The actuator applies forces with the same frequency as before,

but with a phase delay of π . The existing wave on the wheel is countered by the actuator and eventually reduced. After 6 s, the actuator is switched off to get an undistorted estimation of the grinding wheel's surface. The graph in the bottom right of Figure 3 shows the compensation process.

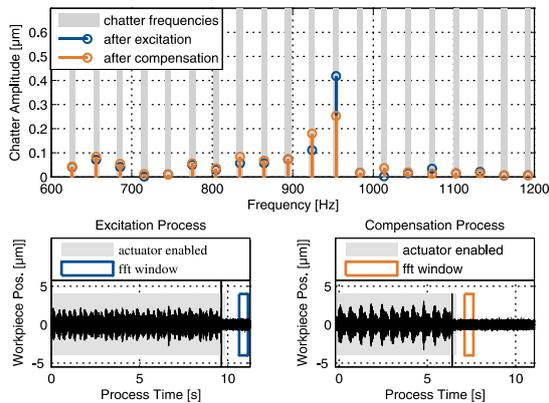


Figure 3: Feedforward Reduction of Waves on the Grinding Wheel

The upper section of Figure 3 shows the Fourier transform of the marked fft windows in both processes. It compares the chatter frequencies at the end of the excitation process to those after switching off the actuator during the compensation process. It can be seen, that the artificially excited wave is reduced by about 40% of its amplitude while other frequencies rise as expected. Since this is a feedforward control, eventually the reduced waves will arise with a phase shift after the original wave has disappeared. However, the experiment shows that the reduction of chatter vibration is possible.

4. Active Chatter Damping

The basic concept of the active chatter damping is the estimation of the waves forming on the grinding wheel and the generation of a force with the magnetic actuator countering the forces on the workpiece caused by the wavy surface.

4.1. Concept of Active Compensation

The control circuit is depicted in Figure 4. Based on the measurement of the workpiece vibrations x_w a surface-observer (see sec. 4.2) delivers the estimated surface of the grinding wheel \hat{w}_{ss} . A proportional controller calculates the desired force F_{target} . The gain is tuned in a way that the actuator applies its maximum force at the highest tolerable chatter intensity, which is the point in time, when the workpiece loses contact to the grinding wheel. Since there is a significant phase delay caused by the magnetic actuators transfer function G_A , the signal has to pass the inverse transfer function \hat{G}_A^{-1} . The actuator is now able to apply a phase-correct force onto the workpiece. Because of the influence of the actuator force on the surface-estimation, the transfer function \hat{G}_{sys} from the actuator force F_A to the workpiece movement x_w has to be identified and has to be taken into account in the waviness observer. The identification of this reference is a key aspect of the active compensation of chatter vibration and part of various researches. The transfer function identified for

this work is described by Ahrens et al. [1] and similar to the results of Schütte et al. [11].

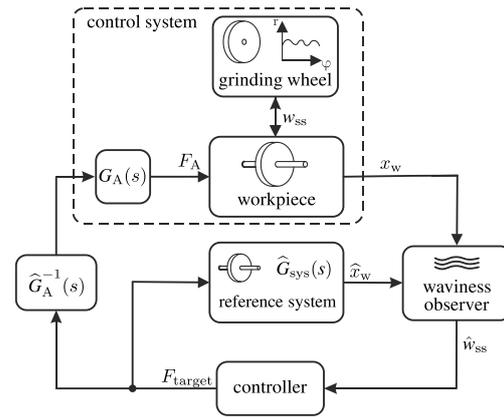


Figure 4: Control Circuit

4.2. Surface Observer

Since the waves on the grinding wheels surface form at multiples of its rotation speed $\dot{\varphi}_{ss}$, its surface can be reconstructed by extracting those frequencies out of the measured workpiece displacement [12]. A parametric surface model consisting of the sum of sine and cosine waves is used to estimate the workpiece displacement at those frequencies and therefore reconstruct the wheels surface:

$$\hat{w}_{ss} = \sum_{k=W_1}^{W_2} a_k \cdot \sin(k\dot{\varphi}_{ss}t) + b_k \cdot \cos(k\dot{\varphi}_{ss}t). \quad (1)$$

A recursive-least-square-algorithm (rls) enables identification of the parameter a_k and b_k , resulting in a low-noise surface-estimation \hat{w}_{ss} . The following equations enable parameter identification for a set of discrete frequencies at W_1 to W_2 times the rotation speed of the grinding wheel. The surface model is used to create the reference-signal x with the grinding wheels angle φ_{ss} as input, the parameter-vector w contains the desired parameters a_k and b_k :

$$x(n) = \begin{bmatrix} 1 \\ \sin(2\pi W_1 \cdot \varphi_{ss}(n)) \\ \cos(2\pi W_1 \cdot \varphi_{ss}(n)) \\ \vdots \\ \sin(2\pi W_2 \cdot \varphi_{ss}(n)) \\ \cos(2\pi W_2 \cdot \varphi_{ss}(n)) \end{bmatrix}, \quad \begin{matrix} n, W_1, W_2 \in \mathbb{N}, \\ W_1 < W_2, \end{matrix} \quad (2)$$

$$w(n) = \begin{bmatrix} a_{W_1}(n) \\ b_{W_1}(n) \\ \vdots \\ a_{W_2}(n) \\ b_{W_2}(n) \end{bmatrix}. \quad (3)$$

The rls-gain $g(n)$ and the difference between filter output and measured value $e(n)$ enable updating the parameter-vector of

the previous step $w(n-1)$ considering the new value of the workpiece displacement $x_w(n)$:

$$g(n) = \frac{g(n-1)}{\lambda + \mathbf{x}^T(n) \cdot \mathbf{g}(n-1) \cdot \mathbf{x}(n)}, \quad (4)$$

$$\mathbf{e}(n) = x_w(n) - \mathbf{x}^T(n) \cdot \mathbf{w}(n-1), \quad (5)$$

$$\mathbf{w}(n) = \mathbf{w}(n-1) + g(n) \cdot \mathbf{x}(n) \cdot \mathbf{e}(n). \quad (6)$$

Adjusting the rls-forgetting-factor λ influences the balance between noise and dynamics of the signal. The frequencies which should be part of the surface model can be determined performing a fast Fourier transform analysis. The model presented in this paper included frequencies of $W_1 = 21$ to $W_2 = 40$ times the wheels rotation speed $\omega_{ss} = 2\pi \cdot 40$ Hz.

5. Performance and Limits of Active Damping

The setup is able to prevent chatter vibration permanently for a specific set of process parameter [1]. To examine the robustness and the limits of the active damping, a set of processes with varying specific material removal rate are carried out. Figure 5 shows the stabilization of the defined standardized grinding process with $Q'_w = 5, 7, 8$ and $9 \text{ mm}^3/\text{mm} \cdot \text{s}$. A higher specific material removal rate Q'_w results in a shorter rise time of the wave's amplitudes as well as increasing process forces. These factors make the active compensation more difficult.

Each of the processes depicted Figure 5 reduces the diameter of the workpiece by 3 mm. After 2 mm the control is deactivated to demonstrate its effect on the process.

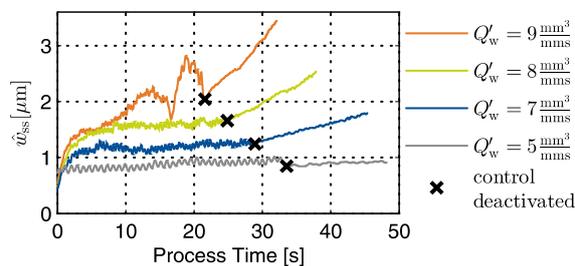


Figure 5: Chatter Compensation at different material removal rate

As the active compensation is based on a proportional controller, the control error, i. e. the waves on the grinding wheel which form despite control, increase with the disturbance, i. e. the removal rate. The active compensation is able to stabilize a grinding process with a specific material removal rate up to $Q'_w = 8 \text{ mm}^3/\text{mm} \cdot \text{s}$. Above this rate, the actuator may reach its maximum force. The clipping is not modeled by the reference system and leads to instability due to the unexpected workpiece movement. This effect occurs in the process with $Q'_w = 9 \text{ mm}^3/\text{mm} \cdot \text{s}$ after 5 s. At this point the actuator is not able to control the wheel's waviness. However, it still has a positive effect on the process, since the waves increase faster with deactivated control.

6. Conclusion

The active chatter compensation method proposed in this paper is able to stabilize a grinding process and prevent the occurrence of chatter vibration. The results of chapter 3 show, that the setup is able to actively reduce waves on the grinding wheel. However, the active damping method proposed in chapter 4 is not able to reduce waves. This is because the quality of the current identification of the reference system is not sufficient resulting in a small phase delay. The results indicate that the key aspects of this compensation are a proper identification of the workpiece's transfer function. Furthermore the maximum force, which can be applied by the actuator is an important factor. The active reduction of chatter vibration as well as the automatic identification of the reference system will be part of future work.

7. Acknowledgement

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