ACTIVE CHATTER DAMPING IN PLUNGE GRINDING USING MAGNETIC ACTUATORS

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ABSTRACT  
In cylindrical plunge grinding with conventional grinding wheels, self-excited vibrations are one of the most limiting factors in terms of productivity and process stability. Initial vibration related to the dynamic behavior of the workpiece and machine copy on the grinding wheel, causing an increasing waviness due to uneven wear and therefore, an increasing vibration of the workpiece. These self-excited oscillations lead to many expensive true-running cycles in order to ensure high workpiece quality and process stability. In this context, we present an abrasion manipulation system for active vibration control using a self-built magnetic actuator to influence the tool wear and prevent the development of wheel-sided chatter. Estimation of the grinding wheel’s surface waviness has been achieved using a surface model, which parameters are estimated by a recursive-least-square-algorithm (rls), exclusively using data of workpiece movement. Using the estimated tool-surface-signal to predict forces onto the workpiece, it is possible to compensate them by the actuator and impend the development of waves on the wheel’s surface.

The concept has been applied to a standardized plunge grinding process demonstrating successful chatter suppression at a former instable process.

INTRODUCTION  
In production industry, finishing processes like grinding are used to achieve high surface quality. Vibrations may hamper the production of a flawless workpiece. The sources can be external or internal. Internal disturbance is often caused by self-excited oscillations, also called chatter. Using conventional abrasives like corundum, vibrations can appear due to wheel-sided regenerative effect. That is because the workpiece movement casts onto the wheel by varying the wear and excites itself with every tool revolution. Even at low amplitudes below one micron, surface waves excite dynamic process forces and may damage machine and workpiece as they increase. Thus, waves on the wheel have to be removed by time consuming dressing operations. In this paper, an active vibration control using a magnetic actuator is presented to stabilize chattering processes and gain more robust and productive automatic manufacturing processes.
Regenerative Effect on Grinding Wheels

In contrast to workpiece-sided chatter, where waves form directly on the workpiece, the wheel-sided chatter can be characterized by waves developing on the grinding wheel. Wheel-sided chatter is caused by oscillations of the workpiece leading to varying cutting depth. This leads to varying contact force, which in turn causes inconsistent tool-wear. Taking the wheel’s rotation speed into account, frequencies that match an integer multiple of the rotation speed will be excited. Due to the limited contact length, waves develop only at higher frequencies beyond 100 Hz, depending on the individual grinding machine. Thus, wheel-sided chatter is more difficult to handle.

Various researches discuss the reduction or prevention of wheel-sided chatter. Passive damping methods were analyzed by Tönshoff et al. [1] and Altintas et al. [2]. It is possible to prevent chatter vibrations with this method, but the damping system has to be adjusted for each individual workpiece. Altering the grinding wheel’s rotations speed is a suitable approach to reduce waves on the wheel’s surface (cf. Hoshi et al. [3] and Spur et al. [4]). The first active damping method was proposed in 1966 by Cuntze [5]. 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 [6] and Michels [7] utilized active piezo-centre points and were able to slow down the development of chatter vibrations.

Dynamic Behavior of Grinding Machines

The development of waves on the grinding wheel depends highly on the process parameters, e.g. rotation speed, contact length between wheel and workpiece, and removal rate as well as the grinding machine, workpiece, and tool diameter. The reason is the variable dynamic behavior of the machine which varies heavily with the contact force. Fig.1 shows the compliance of a modified SCHAUDT CR41CBN grinding machine, which was used for the experiments presented in this paper.

The highest compliance of the machine without preload is at approx. 500 Hz. This peak is highly damped with rising preload leaving the highest compliance in a frequency band between 500 Hz and 1000 Hz. Thus, chatter develops in this frequency band at discrete peaks representing the multiples of the wheel’s rotation speed. Hence, manufacturers are interested in stiff design and high damping. Hydrostatic guide ways and screw drives increase damping and slow down or avoid development of chatter. After all, chatter remains to be a problem that restricts process parameters at the cost of productivity.

GRINDING MACHINE AND MAGNETIC ACTUATOR

Amongst various sensors e.g. eddy-current, acoustic emission and force sensors (cf. Table 1), a magnetic actuator has been integrated into the grinding machine, to apply forces on the workpiece, cf. Fig 2.

FIG 2. MEASUREMENT SETUP AND MAGNETIC ACTUATOR

Grinding Machine and Measurement Setup

The grinding machine in use is a CNC type cylindrical plunge-grinding machine with belt driven spindle and automatic balancing system. To obtain results, which are comparable to each other, a standardized grinding process was defined. The workpiece is a 10 mm wide disks with 100 mm diameter consisting of bearing steel (C100Cr6 / 1.3505 at 62HRC). 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 70 ℓ/min. Running the process at a cutting velocity of $v_c = 50$ m/s a speed ratio $q = 60$, and a specific material removal rate $q'_m = 5$ mm$^3$/mm - s resulted in a slightly instable process with slow developing chatter.

To monitor the experiments, different sensors are used. Piezoelectric dynamometers are positioned between workpiece fixture and machine frame to measure forces at high accuracy.
However, the applied inertia distorts the measurements at high frequencies, so that the resulting bandwidth is below 100 Hz. In addition, an acoustic emission sensor is used and acceleration sensors are placed on head- and tailstock. Whereas the data of those sensors are used for validation, the eddy current sensors measure the workpiece movement. With an accuracy of less than 1 µm and a frequency range of up to 5 kHz without significant phase delay. Therefore they allow for a proper surface reconstruction for active vibration control (3.1). All data are recorded and processed using a dSPACE DS1103 PPC Controller Board process computer system at 10 kHz sample rate.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Unit</th>
<th>Signal Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Eddy-Current Workpiece</td>
<td>µm</td>
<td>Lowpass 10 kHz</td>
</tr>
<tr>
<td>2 Acoustic Emission</td>
<td>V</td>
<td>Lowpass: 1 kHz</td>
</tr>
<tr>
<td>3 Force (2x3-Axis)</td>
<td>N</td>
<td>Lowpass: 3 kHz</td>
</tr>
<tr>
<td>5 Eddy-Current Grinding Wheel</td>
<td>µm</td>
<td>Lowpass 10 kHz</td>
</tr>
<tr>
<td>6 Acceleration</td>
<td>m/s²</td>
<td>Lowpass: 1 kHz</td>
</tr>
<tr>
<td>7 Spindle Current</td>
<td>A</td>
<td>Lowpass: 1 kHz</td>
</tr>
</tbody>
</table>

**Magnetic Actuator**

In order to manipulate and control the grinding process, a four-degree-of-freedom magnetic actuator was built, consisting of two parts, each with four individual magnets, see Fig. 2. One magnet is able to induce a magnetic field of about 1.1 T at an air gap of 2 mm resulting in a force of up to 20 N.

![Magnetic Actuator Diagram](image)

**FIG 3. MAGNETIC ACTUATOR**

Fig. 3 shows one part of the actuator and its components. The circular design allows for adjusting the axial position since the maximum force of \( \sqrt{2} \cdot 2 \cdot 20 \text{ N} \approx 57 \text{ N} \) is reached at an angle of 45°, because of the resulting force of both magnet pairs. Hall sensors in the air gap provide measurement of the magnetic field and allow for precise calculation of the applied forces. The magnet’s iron cores are 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 servo amplifiers connected to a 160 V intermediate circuit. Using a pseudo-random-bit-sequence-signal (prbs), its dynamic 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 (cf. Fig. 4). The highest chatter frequencies in the presented setup are roughly at 1.1 kHz [8].

**FIG 4. FREQUENCY PLOT OF THE MAGNETIC ACTUATOR**

**ACTIVE VIBRATION CONTROL**

The active damping of chatter vibrations is performed as depicted in Fig. 5. The grinding process itself is modeled by the grinding wheel, whose wavy surface \( \tilde{w}_{ws} \) causes oscillations of the workpiece \( x_w \), which induce and excite the waves on the wheel’s surface, respectively. A modal analysis gave indication of the shape of the oscillation modes. The workpiece oscillates mainly in its first mode in normal direction referred to the grinding wheel. Thus, it is possible to manipulate these oscillations by applying a dynamic force in this oscillation direction.

Based on the measurement of the workpiece vibrations \( x_w \), a waviness-observer delivers the estimated surface of the wheel \( \tilde{w}_{ws} \). A proportional controller calculates the desired force. The gain is tuned in a way that the actuator applies its maximum force without clipping at the maximum waviness during a reference process without active damping. 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 \( G_A^{-1} \). The actuator is now able to apply a phase-correct force onto the workpiece. Because of the influence of this force on the surface-estimation, the transfer function \( G_{sys} \) 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.
Observation of the Wheel’s Waviness

Based on the fact, that chatter and waves on the grinding wheel’s surface only occur at multiples of its rotation speed \( \omega_{ss} \), it is possible to reconstruct and observe the wheel’s waviness by extracting those frequencies out of the measured workpiece displacement. Therefore, a surface model was created, consisting of the sum of sine and cosine waves with those frequencies at parametric amplitude and phase delay:

\[
\hat{w}_{ss} = \sum_{k=W_1}^{W_2} a_k \cdot \sin(k \cdot \omega_{ss} \cdot t) + b_k \cdot \cos(k \cdot \omega_{ss} \cdot t),
\]

\( n, k, W_1, W_2 \in \mathbb{N}, W_1 < W_2. \)

Using the recursive-least-square-algorithm (rls) for identification of the parameter \( a_k \) and \( b_k \), a low-noise surface-estimation \( \hat{w}_{ss} \) can be achieved. Adjusting the rls forgetting factor influences the balance between noise and dynamics of the signal. Since the wheels waviness develops slowly, noise can be canceled out almost completely. Fig. 6 shows the comparison between the surface estimation and the reconstructed surface by evaluating the acoustic emission signal as presented in Ahrens et al. [8].

The determination of the necessary frequencies can easily be done by performing a fast-fourier-transformation analysis. The model presented in this paper included frequencies of \( W_1 = 22 \) to \( W_2 = 40 \) times the wheel’s rotation speed \( \omega_{ss} = 2\pi \cdot 40 \) Hz.

Identification of the Workpiece’s Transfer Function

Applying forces using the magnetic actuator causes displacement of the workpiece. Since the estimated surface signal is obtained out of the workpiece movement, the estimation would be distorted without proper compensation, i.e. by subtracting the effect of the actuator force on the workpiece displacement \( x_w \) from the surface estimation \( \hat{w}_{ss} \). Therefore, the dynamic behavior of the system actuator – workpiece, represented by the reference system \( G_{sys} \) in Fig. 5, is needed. Identification at static conditions without rotation of the wheel is not reasonable because of the highly damped grinding machine (cf. Fig. 1). Also, attempts using prbs-, step- or impulse-stimulation signals during the grinding process failed due to high disturbances caused by initial errors of the grinding wheel’s surface by dressing and stochastic defects. Thus, in a series of experiments chatter was induced at set of discrete frequencies by stimulating the process at different multiples of the wheel’s rotation speed. Switching off the actuator after a few seconds allowed for comparison between surface estimation with and without stimulation. This procedure delivers the dynamic behavior depicted in Fig. 7. The resulting transfer function is similar to the results presented by various authors e.g. O. Schütte [9].
The identified dynamic behavior during the grinding process shows, that the highest compliance of the system is at approximately 900 Hz, a second resonance occurs at 1000 Hz. This coincides with the observed chatter frequencies. Since the phase-shift differs by more than 180°, it is of particular importance to know about the exact phase-delay allowing for its compensation.

**Phase-shift Compensation**

To apply the desired forces on the workpiece, the dynamic behavior of the magnetic actuator has to be taken into account. Since the inverse transfer function of the actuator is not causal in time, it is not possible to implement the required compensation of the phase-delay directly. However, development and change of the waves on the wheel’s surface is slow in comparison to the rotation speed. Thus, it is possible to use the calculated waviness of the previous wheel revolution for the active vibration control. Therefore, it is possible to compensate the delay, caused by the actuator.

**RESULTS**

In order to analyze the performance of the active vibration control and its ability to suppress chatter, two measurement series were carried out. The first series included ten grinding processes. Each of them removed 1 mm material (of the same workpiece referred to its radius) and included a dressing operation afterwards. The control was active, alternating at every second process to get comparable results which are depicted in Fig 8.

The rls-sum is calculated by the sum of wave’s amplitudes obtained by the waviness observer. This value has proved to be a good benchmark for the intensity of chatter. Since a value below 0.6 µm to 0.7 µm represents a chatter-free process using a dressed wheel, the result of this measurement series shows robust and reliable chatter compensation. The experiments without active control show the usual chaotic properties as almost identical starting conditions lead to different progression of chatter. The chatter intensity tends to fall, because the workpiece was getting smaller which leads to reduced contact length and more stability. The processes with active vibration control were stable with no evidence of chatter.

The second measurement series includes four long-term processes with duration of five minutes each (cf. Fig 9). Two of them were carried out with and without active vibration control, respectively. The uncontrolled processes show instable behavior and heavy chatter so that one process had to be aborted, preventing damage on the machine. In contrast, the controlled processes remained stable with no increase of vibration amplitude or chatter.

**FIG 8. RESULTS OF FIRST MEASUREMENT SERIES**

**CONCLUSION**

Performing an active chatter vibration control in plunge grinding is a suitable method to prevent development of waves on the grinding wheel’s surface, and hence, the occurrence of wheel-sided chatter vibration. For that purpose, forces of approx. 10 to 20 N applied by a magnetic actuator is sufficient. Furthermore, it was pointed out, that chatter vibration control is possible using only forces in direction orthogonal to the wheel’s surface. A crucial part is the identification of the dynamic behavior of the grinding wheel, which was achieved by forcing chatter vibrations at different frequencies with the magnetic actuator. Thus, the self-identification of the dynamic behavior will be part of future work as well as testing the influence of different actuator positions and oscillation modes. Additionally, the construction of a new magnetic actuator will enable higher forces and a more flexible utilization in practical use. Since the application of vertical forces is not needed for vibration control, this new actuator can be simplified for application of only one-dimensional forces.

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