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# Model-based adaptive process control for surface finish improvement in traverse grinding

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ABSTRACT

The paper presents a process controller aimed at improving the surface quality generated by traverse grinding, avoiding the surface defects caused by vibrations onset. The innovation provided by the proposed controller consists in suppressing vibration occurrence by means of a model-based and self-learning approach: a monitoring layer classifies occurring problems and a control logic exploits these indications to select the proper mitigation actions. Since wheel-regenerative chatter represents one of the most important problems during traverse grinding in terms of achievable productivity and finishing quality, the main control variable is the wheel velocity. This variable is tuned exploiting an adaptive Speed tuning Map computed by the controller using a heuristic approach and learning methodology. The control can manage also the other sources of vibration by means of proper identification and mitigation strategies. Experimental tests are carried out on a roll grinder to validate the control system. Good performances are achieved after some training tests to allow controller learning.

## 1. Introduction

The current manufacturing environment places a growing demand on autonomous control of manufacturing processes, especially in unattended machines. In grinding, operator surveillance is required to cope with the strong process variability introduced by the tool characteristics. One of these is the wear evolution that decreases the final quality of the machined products through different mechanisms, as the vibration that results in the production of marked workpieces. The produced defects, often called "chatter marks", represent the most important surface defect of cylindrical products, such as hot rolling rolls: a periodical surface waviness with pitches ranging up to tens of millimeters and with amplitudes ranging up to tens of microns. Whenever the system vibrates, wheel and roll undergo a relative oscillation, mainly in the radial direction, modulating the actual infeed. Then, periodic surface defects are generated in the form of waviness on the workpiece and in some cases on the grinding wheel surface. The problem is very complex because different phenomena can lead to vibration onset and consequent waviness generation: wheel unbalance or roundness error, process instability due to modal coupling or surface regeneration (i.e. workpiece regenerative chatter and wheel regenerative chatter).

The presence of this defect on the machined rolls has to be avoided since it has detrimental effects either on the surface appearance of the cylinders (i.e. quality acceptance) and on their functionality in the rolling operations. In their paper, Panjkovic et al. [1] claimed that the presence of chatter marks in work rolls of rolling mills are also linked to vibration (both forced and self-induced) rising in the rolling plant.

In general, optimization strategies for grinding operations have been designed by many authors in literature. In their comprehensive review, Rowe et al. [2], show that most of them rely on Artificial Intelligence (AI). Among these techniques, two big families are identified consisting in desktop systems to assist tool and parameter selection and self-optimizing systems integrated within the machine controller. As stated by Chen and Tian [3], however, only few optimization algorithms in literature include an explicit term related to chatter instability in the optimization process, while dimensional accuracy is often the paramount objective. In fact, Choi and Lee [4] have developed an active control system for thermal error compensation in cylindrical grinding of long slender rolls. They have achieved a 30% improvement of workpiece cylindricity by means of actuated workpiece rests that cope with the quasi-static thermal machine distortion and the related variation of mechanical compliance. However, the very low bandwidth of the control system does not permit to address problems related with the dynamical compliance of the mechanical system.

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## Nomenclature

| | |
|---|---|
| $h_0$ | Commanded infeed [mm] |
| $d_r(t)$ | Relative displacement between wheel and workpiece centers [mm] |
| $h(t)$ | Actual engaged infeed at time t [mm] |
| $w(t)$ | Radial wheel wear at time t [mm] |
| $G_r$ | Radial Grinding Ratio |
| $G$ | Volumetric Grinding Ratio |
| $Q_{s,w}$ | Wheel and Workpiece material removal rate [mm$^3$/s] |
| $b$ | Cutting width [mm] |
| $v_{s,w}$ | Wheel and Workpiece tangential speed [m/s] |
| $s$ | Laplace operator |
| $\omega$ | Fourier operator |
| $k_c$ | Wheel rigidity [N/m] |
| $\tau$, $T_p$ | Time constants |
| $H(\omega)$ | wheel-workpiece relative FRF |
| $OSM_t$SSM $_t$ $FSM_t$ | Stability maps scores: Original, Smoothed, Filtered by operator preferences. |
| L,R | Open and Closed loop Transfer Function |
| I | Identity Matrix |
| $P_{pos}$,$P_{vel}$ | Cutting Process proportional and derivative coefficients matrices |
| $D_{s,w}$ | Wheel and Workpiece diameter [mm] |
| $\omega_{s,w}$ | Wheel and Workpiece rotational speed [rad/s] |
| $\theta_{S,\,W}$ | Wheel and Workpiece angular position [rad] |
| X | Radial/Normal direction |
| Y | Tangential direction |
| $k_t$ | Grinding specific energy [N/mm$^2$] |
| $\mu$ | Friction Ratio |
| $\ddot{X}_k$ | Accelerometer readings [m/s$^2$] |
| $w_k$ | Weights for sensors averaging |
| N | Number of harmonics |
| $a_S$,$a_W$ | Wheel and Workpiece complex waviness amplitude |
| T | Sensor Transmissibility function |
| $\Im$ | Fourier transform |
| n | Number of grinding passes in a cycle |
| $\alpha$ | Map update Weighting factor |
| $US_t$ | Updated wheel speed? score vector |
| $\gamma$ | Data aging Weighting factor |
| $\Delta e$ | Epoch time span |
| $OS_t$ | Operator Map Score |
| $\beta$ | Operator Weighting factor |
| $L_T$ | Cylinder length |
| $\Delta h_{S,\,W}$ | Radius deviations due to waviness |
| $H_{NCL}$ | Radial closed-loop structural response |

Möhring et al. [5] have developed an active error compensation system, involving hydraulic and piezoelectric actuators, for the compensation of distortions and unequal allowance distributions in crankshafts grinding. Thanks to the developed model-based approach and the active 2-DOF tailstock, the system provides an accuracy improvement and a reduction of spark out time.

Hekman and Liang [6] presented a method for optimizing the part parallelism in surface grinding by adopting a real-time depth of cut manipulation based on the machine predicted deflection and on the use of a dynamometer installed on the machine. This work however addresses only geometrical errors of the part and does not consider the surface accuracy optimization of the ground components.

On the other side, Inasaki [7] designed a methodology to monitor and control grinding processes, by using AI and including chatter in plunge grinding and by exploiting Acoustic Emission (AE) and power sensors. The monitoring approach showed good results however, it is not included in a real-time adaptive control of the grinding machine to produce an effective cutting process optimization.

Yuan et al. [8] tested in simulation the application of a fuzzy-logic controller (FLC) in roll grinding system, coping with the double regeneration problem. The control system showed good vibration reduction compared to a conventional control method. However, the feasibility and robustness of their approach on real applications has not been discussed.

Classical solutions based on active vibration suppression have also been studied for improving the accuracy on the parts: in this case, the main challenge consists in developing a measuring system able to perceive (or estimate) the micrometric displacements between wheel and workpiece, together with the proper actuating system that must be capable of influencing the system behavior.

Oh and Kim [9] developed an optical PID vibration control relying on an electromagnetic inertial actuator installed on a small grinder. Good system performance was shown on the laboratory test-rig, but no verifications in relevant industrial environments, with all the associated variables that could limit the actual system efficacy, were presented. Similarly, Albizuri at al. [10] adopted piezoelectric actuators, characterized by a high frequency bandwidth, in a small centerless grinding machine. The solution is effective but, due to the system dimensions, its applicability in other situations as the case of a large traverse grinding machine (such as the roll grinders) is limited. Nakano et al. [11] showed that passive vibration dampers can be properly adopted to cope with chatter issues, but they lack of automatic adaptivity. In this regard, it must be noted that large variability in close loop grinding machine dynamics may arise for several reasons. For instance, the cumulated wear of the grinding wheel affects cutting process coefficients and can cause a large change of the wheel mass affecting the modes of vibration of the spindle. Wear of machine components, such as spindle bearings or workpiece support pads, can also introduce variation on the machine dynamics. Similarly, variation of workpiece geometry and related weight could affect machine dynamics in terms of vibration mode shapes and frequencies. For these reasons, automatic adaptivity is considered as an important property for implementing effective process control at industrial scenarios level.

On the other side, regenerative chatter is a well-known phenomenon in many machining processes and is well investigated by Altintas and Weck [12] and other authors in the grinding literature. Several works have been dedicated to the analysis of process parameters effect on chatter onset. Inasaki et al. [13] presented a comprehensive survey, proposing models and chatter avoidance techniques. In that review, different mitigation and chatter control strategies are discussed, comprising modification of process parameters, as well-known in industrial practice. Indeed, a proper selection of grinding parameters may have a direct effect on the regeneration phenomenon improving cutting performance. This optimization, usually carried out by grinding experts during the first setup of a grinding cycle (in "out-of-process" phase), is mainly based on empirical knowledge and it depends on the different working situations and machine characteristics. A pioneering attempt to exploit theoretical knowledge to carry out an “out-of-process” optimization has been undertaken by Thompson [14],[15]: it is based on wheel and workpiece regenerative chatter theory. Unfortunately, any change of the system dynamic behavior during machine operations (e.g. due to machine components wear) or