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A model-based adaptive controller for chatter mitigation and productivity enhancement in CNC milling machines

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ABSTRACT

Seeking a higher level of automation, according to Intelligent Manufacturing paradigm, an optimal process control for milling process has been developed, aiming at optimizing a multi-objective target function defined in order to mitigate vibration level and surface quality, while preserving production times and decreasing tool wear rate. The control architecture relies on a real-time process model able to capture the most significant phenomena ongoing during the machining, such as cutting forces and tool vibration (both forced and self-excited). For a given tool path and workpiece material, an optimal sequence of feedrate and spindle speed is calculated both for the initial setup of the machining process and for the continuous, in-process adaptation of process parameters to changes the current machining behavior. For the first time in the literature, following a *Model-Predictive-Control* (*MPC*) approach, the controller is able to adapt its actions taking into account process and axes dynamics on the basis of Optimal Control theory. The developed controller has been implemented in a commercial CNC of a 3-axes milling machine manufactured by Alesamonti; the effectiveness of the approach is demonstrated on a real industrial application and the performance enhancement is evaluated and discussed.

1. Introduction

In the last 20 years the rapid evolution of products, changing of user needs, and global competition have forced companies to redesign manufacture chains thus taking into account not only the mere productivity, but also the quality, economy, and the flexibility of the production. These reasons motivated an increasing number of enterprises to research and evolve their production systems towards paradigm of *intelligence manufacturing* [1,2]. Increasing of automation in manufacturing systems has both technological and economical impact on a wide sectors of production chains. Optimal control can be exploited to optimize multi-objective target functions defined in order to reduce production times, costs, and increase the quality. The cooperation of multiple intelligent systems will moreover ease the definition and calibration of reliable models of the process [3], thus improving the goodness of the calculated optimal controls. In this scenario, the Computer Numerical Controlled (CNC) machine tools have become popular and have played a key role in workshops, leading to a vast area of research on machining process modeling and optimization [4].

Despite the continuous performance enhancements, since 1968 when the first machining center was marketed, the automation level has not been evolving as much as in other mechatronic fields like robotic vehicles, planes, anthropomorphic manipulators, and humanoids. Advanced robots have perception layers to sense, reconstruct, and learn their state, can plan on line the future actions to take in order to achieve a specified goal. When dealing with machine tools, these features could be aimed at ensuring the operation at optimal cutting conditions, which are constantly identified based on a theoretical knowledge of the process and on the current state of the machine.

Effectiveness and reliability of intelligent systems depend on the level of accuracy of the description of processes. A *good* model captures the most significant phenomena ongoing during the machining, such as force level, material removal rate, tool wear, tool deflection and vibration. The latter is the more critical issue for machine users, since it has effect on the surface quality achieved by the cut, on the stresses acting on the tool and machine components. Vibrations generated during machining can be classified into forced vibrations and self-excited (also called chatter). The former are due to the excitation of the natural frequencies of the tool-workpiece system by the discontinuous cutting forces. In this case the dynamics of the system is stable and tends to be damped. On the other side, self-excited vibrations are mainly due to regenerative effect, namely, a phase shift between vibration

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waves left on the inner and outer surfaces of the cut chip. As the cut proceeds, the dynamics of the system becomes unstable, thus increasing progressively the chip thickness and consequently the magnitude of the cutting forces. Such unstable condition reduces the quality of the cut, as well as geometrical accuracy of the generated surfaces, but also might be dangerous for the tool, spindle and machine structure.

The key to predict and control regenerative chatter is the so-called Stability Lobes Diagram (SLD), which shows the boundary between chatter-free machining operations and unstable processes in terms of axial depth of cut as a function of spindle speed: the diagram is characterized by a critical depth of cut, that is the limit under which cutting is stable for all spindle speeds, and by several stability pockets, namely, particular spindle speeds where the stable depth reach higher levels. One of the main contributions to SLD computation in milling was given by Altintas [5], who developed a break-through approach that takes into account a 2DoF dynamics and the average cutting force vector. The main assumption at the core of this model was a linear dependency of the cutting force with respect to the chip thickness and the predominance of the average component in the force spectrum.

Several works have been carried out in the past tackling in-process chatter control in milling operations. Adopting a feedback strategy on any signal correlated to vibrations onset (forces, acceleration, sound, etc.), chatter control can be performed even without computing SLD: the most popular technique belonging to this category is the so-called spindle speed tuning, consisting in regulating the spindle speed on the basis of the measured chatter frequency (see for instance [6] or [7]). This approach is rather profitable, whereas it does not require any characterization of machine dynamics. Another approach involves the exploitation of active [8] or passive [9–11] damping devices, aimed at dissipating the vibrational energy due to instability. One of the first implemented active chatter suppression systems was developed by Dohner et al. [12]. The authors actively generated the lobes stability diagram of the cutting system, thus identifying spindle speeds that ensured a stable process. In this system the spindle was sensed through strain gages at tool root, and it was dumped through a piezo-electric actuator. A further example of active piezo-electric actuators utilized to reduce the dynamic displacement between the tool and workpiece was given by Abele et al. [13]. Moradi et al. [14] proposed a H_∞ control algorithm to control a piezo-electric actuator, used as chatter damper, under tool wear and parameter uncertainties. In a more recent study, Moradi et al. [15] exploited a *Linear Quadratic Regulator* (LQR) to suppress self-regenerative vibrations. This technique allowed the authors to use a non linear model of the process in which forces and chip thickness were related by a cubic relationship. The controls were the counterbalance forces exerted by external actuators, and the target function was defined in order to limit the chatter while minimizing the efforts of the controls. The last effective strategy nowadays being studied to mitigate the chatter is called *spindle speed variation*. It consists in continuously changing the spindle speed with a sinusoidal pattern around the mean speed to disturb the regenerative mechanism. The main advantage of this technique is that it does not require expensive tool holders and it can be implemented on modern CNCs. The calibration of this methodology however can be difficult. Hajikolaei et al. [16] used a genetic algorithm to calibrate the amplitude of the speed modulations such that the input energy to the process was minimized. Albertelli et al. [17] propose a method to optimize sinusoidal spindle speed variation parameters in the simple case of one dominant vibration mode: it is based on the computation and optimization of the phase shift between inner and outer chip modulation assuming a quasi-steady state condition.

Also tool deflection is recognized to provoke detrimental effects both on workpiece geometrical accuracy and surface roughness, as demonstrated by Costes and Moreau in [18]. This fact leaded to the development of specific models able to predict tool deflection in order to compensate and/or limit it by changing cutting parameters (for instance [19]).

The tool wear is another crucial performance affecting machining efficiency and it should be estimated as accurately as possible and permanently kept under control [20]. As a matter of fact, the tool wear has a large influence on the economics of machining operation: in fact, it affects not only the tool life but also the quality of the final product in terms of residual stress and surface integrity. Even in this case, several models have been developed in order to predict tool wear, above all when dealing with hard materials [21], often aimed at optimizing process parameters to increase tool life. While milling process modeling is often used for the off-line optimization of the part program [22], no works can be found merging such a pre-processing phase with axes dynamics in order to exploit properly the *a priori knowledge* about cutting process and machine responsiveness. Moving from these considerations, this paper presents the first system for fast optimization of process parameters for milling operations markedly spindle rotational speed and tool feedrate based on *Optimal Control Theory*. A suitable target function is defined on the basis of a model of the machine tool dynamics and the cutting process: it is specifically designed to suppress/mitigate vibration occurrence, while taking into account tool wear, tool deflection and productivity (material removal rate). Then, an optimal sequence of controls for a given path and workpiece material can be calculated both for the initial setup of the machining process and for the continuous, in-process adaptation of process parameters to changes in process behavior. The model capabilities include the prediction of self-excited and forced vibration (which is the main objective), tool wear, tool deflection, spindle force and power, feed axes response by means of a simplified first order dynamics. The developed controller has been implemented in a commercial 3 axes boring machine manufactured by Alesamonti. Machine dynamics, necessary for feeding the process model, has been measured via tap testing in several tool positions over the allowable work volume and, then, interpolated in order to get the dynamic response in every position along the tool path. The process model exploits commercial CSG (Constructive Solid Geometry) libraries, that provide methods and structures for tool-workpiece intersection, allowing the computation of MRR, depth of cut and engagements arcs that are needed by cutting force model. Once the various performance parameters are weighted in a single objective function, an advanced optimization engine is exploited for determining the proper control action. The paper is structured as follows: in Section 2 the controller architecture is framed together with a detailed description of the components of the objective function. In Section 3, the dynamic characterization of the test machine is presented and the results validated by means of stable and unstable milling passes. In Section 4 the controller effectiveness is demonstrated on the test machine for a real industrial application: the performance enhancement due to the introduction of the proposed innovative controller is discussed. In Section 5 the conclusions are reported.

2. Adaptive controls for CNC machines

Adaptive controllers (ANC) are devices that regulate process parameters to achieve a certain performance. In the case of milling process, the controls on which ANC acts are the spindle speed and the feed rate. A recent review of ANC system was given by Stavropoulos et al. [23]. Ulsoy and Koren [24] identified three types of ANC: