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Active chatter suppression with displacement-only measurement in turning process

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A B S T R A C T

Regenerative chatter is a major hindrance for achieving high quality and high production rate in machining processes. Various active controllers have been proposed to mitigate chatter. However, most of existing controllers were developed on the basis of multi-states feedback of the system and state observers were usually needed. Moreover, model parameters of the machining process (mass, damping and stiffness) were required in existing active controllers. In this study, an active sliding mode controller, which employs a dynamic output feedback sliding surface for the unmatched condition and an adaptive law for disturbance estimation, is designed, analyzed, and validated for chatter suppression in turning process. Only displacement measurement is required by this approach. Other sensors and state observers are not needed. Moreover, it facilitates a rapid implementation since the designed controller is established without using model parameters of the turning process. Theoretical analysis, numerical simulations and experiments on a computer numerical control (CNC) lathe are presented. It shows that the chatter can be substantially attenuated and the chatter-free region can be significantly expanded with the presented method.

1. Introduction

Machining belongs to the key steps in almost all modern industries. Machining productivity is often limited by the occurrence of chatter, which accordingly induces low dimensional accuracy, material removal rate (MRR) reduction, poor surface finish and serious tool wear [1,2]. Generally four mechanisms are responsible for chatter: (a) mode coupling, (b) variable friction, (c) thermo mechanics of chip formation, and (d) regeneration of surface waviness [3]. The last one, known as regenerative chatter, is found to be the main hindrance to most machining process. With the ever-growing demand for good-quality products with high efficient manufacturing, the need to develop chatter suppression techniques becomes critical and pressing for modern manufacturing industry [4].

There are mainly three methods for chatter suppression/control in literatures. The first method is to select proper machining parameters (width of cut and spindle speed) from the stability lobe diagram (SLD). When the machining parameters are selected outside the lobes, the chatter can be avoided [5]. However, accurate process parameters are needed to compute the lobe and the domain of stable operation cannot be enlarged by this method [6].

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The second method is to disturb the regenerative effect by continuous varying machining parameters. A typical example is the spindle speed variation (SSV), which can create a time-varying delay. As a result, the suppression of unfavorable phase lags between inner and outer chip modulation can reduce chatter vibrations [7]. By employing a nonlinear delay differential equation, Zhang et al. [7] developed a chatter model for stability analysis of SSV method. A formula was also presented to select SSV amplitude referring to the internal energy analysis. Although the stable operation domain is enlarged by this method, the spindle speed variation needs additional output from the spindle, which is usually limited by the spindle power [8].

The third method is to passively or actively alter the machine tools dynamics to expand the chatter boundary, usually by additional installed components or devices. Passive suppression techniques that adopt dynamic vibration absorber (DVA) and tuned mass damper (TMD) [9,10] have been widely used to dissipate the energy of chatter vibrations. For instance, Yang et al. [9] designed a TMD that had equal masses, and the values of damping and stiffness were optimized to improve chatter resistance using minimax numerical optimization algorithm. Passive absorbers and dampers exhibit some advantages such as low cost, easy implementation and never destabilizing the system. However, absorbers and dampers require special procedures and techniques in industry to ensure accurate tuning of their natural frequencies for acceptable performance. Hence, passive dampers and absorbers lack robustness to the changing machining conditions.

Active chatter suppression schemes (with suitable sensors/actuators installed on the spindle or tool holder) have demonstrated potentials to improve machine tool performances [11]. Closed-loop control systems can be established to properly regulate the self-excitation dynamics, and hence to enlarge the domain of stable operation region in the stability lobe diagram [2]. Ganguli et al. [12] presented an active damping controller with direct velocity feedback, and the effectiveness of this controller was demonstrated via a mechatronic simulator [13]. Experimental studies for chatter suppression on active damping of the machining process can be found in Harms et al. [14].

It is well known that machining processes suffer from nonlinear uncertainties, i.e. variations in the dynamic properties of the machine tools, variations in cutting conditions such as spindle speed, depth of cut and other disturbances. Robust feedback controllers, like sliding mode control (SMC), H_2/H_∞, disturbance observer (DOB) and linear quadratic regulator (LQR), are well suited for chatter suppression since they show good performance and robustness to nonlinear uncertainties and disturbances [15,16]. Shiraishi et al. [17] designed an optimal state-feedback controller for turning processes. The regenerate delay term was approximated with Pάde series and Luenberger state observer was employed to estimate the system states required by the optimal controller. Parus et al. [1] proposed an active chatter control system based on Linear Quadratic Gaussian (LQG) algorithm. The Kalman filter was also employed to estimate the system states required by LQG algorithm. Mei et al. [18] synthesized a linear-quadratic optimal controller considering the time delay induced by the regenerative effect. Chen et al. [19] designed an adaptive control scheme for milling process by approximating the variation matrix in Fourier series. Monnin et al. [20,21] proposed an active system for milling operation by mounting a piezoelectric stack at the front-end of the machine spindle. Then, two different H_2 optimal control strategies were designed to minimize the influence of cutting forces on tooltip deviations. van Dijk et al. [22] designed a control methodology for the high-speed milling process based on μ-synthesis, which alters the chatter stability boundary such that the chatter free domain could be increased.

It is noteworthy that the displacement information or measurement is required by most active controllers mentioned above [1], [15–22]. From the practical viewpoint, it is feasible to monitor the relative motion between the workpiece and the cutting tool [17,23,24], and properly designed controller can mitigate chatter while ensuring position and machining accuracy [23]. Displacement or acceleration measurement is needed in the active damping method with direct velocity feedback [12–14]. Nevertheless, additional system states of the machining process, like velocity, are assumed to be available or measurable in previous active controllers. However, it is burdensome to measure multi-states of the machining process. Estimating these states [1,12–22] by elaborate designed observers and filters will increase the burden on design and implementation of the control system. Moreover, the use of state observers will further reduce robustness or cause instability of the control system [25,26]. Since large disturbance and noise exist in machining processes, it is also difficult to observe system states correctly. Few studies have concerned about the active chatter suppression problem solely using displacement information. Furthermore, model parameters of the machining processes are required in most active controllers [1], [15–22]. As we know, identifying the model parameters of a machining process is difficult since these parameters alter with different cutting conditions, tools, machine tools, and workpieces. Although direct velocity feedback does not require a very accurate model of machining processes [12,13], the velocity has to be estimated by elaborate designed observers and filters. Moreover, the scope to enhance the stability of this method is limited to low stability domain of the SLD [6,15,16]. From the manufacturing application perspective, a robust controller, which can properly solve the two problems mentioned above, is still lacked.

Inspired by the above problems, an active sliding mode controller is presented for chatter suppression in turning process. The presented controller employs an adaptive law for disturbance estimation and a dynamic output feedback sliding surface for the unmatched condition. SMC has demonstrated itself an efficient nonlinear control featuring ease of implementation and robustness in the presence of disturbances [25]. Hence, SMC is well-suited for chatter suppression since large disturbance exists in machining processes. Unlike existing active chatter suppression controllers, the contributions of this work can be summarized as follows.

1) Its implementation requires displacement measurement only. Other sensors and state observers are not needed.