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Chatter suppression in fast tool servo-assisted turning by spindle speed variation

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ABSTRACT

This paper focuses on the investigation, based on theoretical analysis and through machining experiments, of using variable spindle speed machining to suppress chatter in a fast tool servo-assisted noncircular turning process. Noncircular turning is accomplished by controlling the position of the radial cutting tool in the direction normal to the surface of a workpiece with noncircular cross-sections. The process stability is thus more involved than in a general cutting process. This is mainly due to strong dynamic feedback between the machining process and the fast tool servo drive. An enhanced closed loop dynamic model of the noncircular turning process is developed, in which the fast tool servo employs an active disturbance rejection control scheme. By using the spindle's angular position as the independent variable, the dynamics of the variable spindle speed noncircular turning process are described by a differential equation with linear periodic time-varying coefficients and a fixed delay in the angle domain. The Floquet theory is applied to determine the stability limit. Analytically predicted stability boundaries are compared with those of constant spindle speed machining generated by the Nyquist method. By investigating the effects of spindle speed variation amplitude and frequency on the stability limits, it is shown that a modest increase in noncircular turning stability is given by continuous spindle speed variations due to the limited performance of the fast tool servo controller. Experimental results are also presented, which validate the ability and explanation of increasing noncircular turning stability using spindle speed variations.

1. Introduction

Chatter, the self-excited high amplitude vibration between the workpiece and the cutting tool, is caused by the interaction of the cutting process and the structure of the machine tool. It significantly limits machining productivity, affects the surface finish quality, causes loss of dimensional accuracy of the workpiece, and accelerates the premature wear, chipping, and failure of the cutting tool [1]. The conventional approach to suppressing chatter has been to construct the machine tool with high structural stiffness. However, in noncircular turning process, the cutting tool is driven by a fast tool servo and reciprocates in the direction normal to the surface of the workpiece. The cutting tool motion must synchronize with the spindle rotation to generate a workpiece with noncircular cross-sections. The actual cutting tool motion can be decomposed into the desired vibration and the noise vibration. The former is needed to produce the desired noncircular profile of the workpiece, and the latter reflects the tracking performance of the fast tool servo and the machining stability. For such a machining system equipped with the fast tool servo, it is likely that the most flexible element will be the servo itself, and the impact of this on the machining stability is a primary concern [2].

An effective strategy for increasing noncircular turning stability is to improve the dynamic stiffness of the fast tool servo. This can involve the optimal design of the linear actuator and the control algorithm for the fast tool servo. Woronko et al. [3] developed a piezoelectric-based fast tool servo for precision turning of hardened shafts. The actuator has a 370 N/μm stiffness and 3200 Hz natural frequency. A sliding mode controller is implemented to reject cutting force disturbances and piezoelectric nonlinearity for high dynamic stiffness. Rakuff and Cuttino [4] developed a long-range precision fast tool servo that is driven by a voice coil actuator. A control strategy consisting of linear and nonlinear feed-forward controllers and a proportional, integral, and derivative feedback controller was implemented to accommodate the changed system dynamics and thus improve the stiffness. However, for a given fast tool servo and machine tool structure, the use of variable spindle speed machining (VSM) to enhance the noncircular turning stability has been considered as another attractive solution. VSM refers to machining operations in which the spindle speed is continuously varied in a periodic fashion over the nominal constant speed.

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The concept of VSM was first introduced by Stoeferle and Grab [5] to unevenly distribute the chip load in single point turning in order to improve cutting stability. Since that time, there have been many research efforts to address various topics in VSM. Takemura et al. [6] investigated VSM using the energy balance between the energy generated by the cutting process and the energy dissipated by the structure. The results showed that VSM efficiently reduces the amplitude of regenerative chatter. Hoski et al. [7] experimentally demonstrated the effectiveness of VSM on improving process stability in vertical turning and boring. More analog and digital simulations were performed by Sexton and Stone [8,9] to study the practical effect of VSM on stability charts and transient vibrations in single point machining. The results showed that the stability improvements resulting from the use of VSM are only modest. In a theoretical analysis, Inamura and Sata [10] used the function space theory to investigate the suppression of chatter in cutting by varying the spindle speed, but they found that it cannot be practically implemented. Jemielniak and Widota [11] investigated the influence of VSM on stability using the vibration amplitude amplification coefficient. They concluded that it was necessary to use a spindle speed variation frequency higher than a certain limit value. Tsao et al. [12] used the angle domain concept and the spectral radius approach to investigate the stability of VSM systems in the discretization domain. Al-Regib and Ni [13] applied the energy balance approach to investigate the optimal selection of spindle speed variation parameters. Some analytical stability analysis methods have been developed based on the Fourier analysis and the Floquet theory [14–17]. The problem of delayed differential equations is analytically solved in frequency domain. The stability of dynamic milling was checked by scanning speeds and depth of cuts like in chatter experiments. Budak and Altintas [18,19] had presented an extensive model of chatter where the harmonics of periodic directional matrix was considered. They called the stability model the "Multiple-Frequency-Solution", but did not focus on the intermittent process nor did they notice the added lobes. Moreover, Merdol and Altintas [20] extended the multi-frequency stability approach by modeling the dynamics of low radial immersion milling that is highly intermittent, and proving that the added lobes can be predicted accurately. Insperger and Stepan [21] used the numerical semi-discretization method to analyze the delay-differential equation with time-varying delay in a single-degree-of-freedom model of turning. In addition, the perturbation analysis method was also used to investigate the chatter stability [22,23].

As seen above, the previous investigations of VSM have been focused on the general cutting process where a cutting tool is mounted on a rigid tool post. However, the analysis of chatter stability in the noncircular turning process is more involved than that of the general cutting process. This is due to the fact that the cutting tool motion is controlled by a fast tool servo in a noncircular turning system, and a strong dynamic feedback interaction between the machining process and the fast tool servo drive must be considered. This causes the closed-loop system equation to be more complex. Hanson and Tsao [24] experimentally demonstrated the effectiveness of VSM for increasing noncircular turning stability. They emphasized designing a periodic, discrete-time repetitive controller that was applied to the control of a fast tool servo for variable spindle speed noncircular turning. However, a more theoretical explanation of why VSM has the potential to increase noncircular turning stability has not been provided.

This paper attempts to add insight and value to the approach of VSM by providing a physical explanation as to why VSM can suppress noncircular turning chatter, thus reducing the noise vibration of the tracking motion of the fast tool servo, and how the spindle speed variation parameters influence the noncircular turning stability. The explanation is based on an investigation of the stability limit during constant and variable spindle speed machining.

The remainder of the paper is organized as follows. Section 2 describes the experimental noncircular turning system and the fast tool servo controller. The closed loop model for noncircular turning, which includes the regenerative cutting force model, the structure dynamics model of the linear actuator, and the servo controller model, is also derived in this section. Section 3 develops the analytical methods for stability analysis to predict the stability limit for both constant and variable spindle speed noncircular turning. A theoretical explanation and the effect of amplitude and frequency of spindle speed variation on the stability of the noncircular turning process are given in this section. Section 4 presents the experimental results for both constant and variable spindle speed machining, which demonstrates the ability and mechanism of suppressing chatter in the noncircular turning process using spindle speed variation. Conclusions follow in Section 5.

2. System description and modeling

2.1. System description

The variable spindle speed noncircular turning system is shown schematically in Fig. 1. The voice coil motor driven linear actuator is mounted on the cross-slide of the computer number-controlled lathe, which actuates the cutting tool to reciprocate in the direction normal to the surface of the workpiece. The industrial computer generates the desired cutting tool motion trajectory that is sent to the digital controller as the reference input of the fast tool servo. The actual radial cutting tool's position is collected by the linear raster position sensor with a 0.5 μm resolution. The spindle position is measured using the rotary encoder (LF-1024BM-C05D), which produces the pulse train signal to trigger the sampling control of the fast tool servo. During a sampling period, the digital controller, which is a 16-bit fixed point digital signal processor (DSP, Texas Instruments TMS320LF2407), processes the sensor information and the desired cutting tool trajectory according to the control algorithm, and it generates the control signal that is sent to the power amplifier driving the actuator.

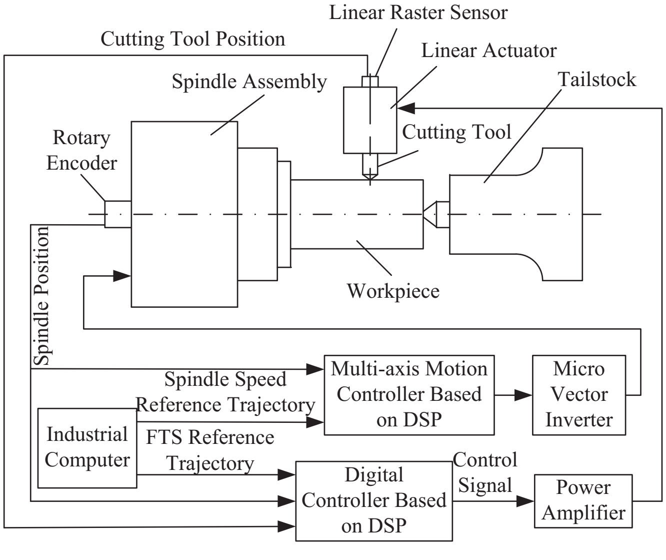

Fig. 1. Schematic diagram of the variable spindle speed noncircular turning system.