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Stiffness variation method for milling chatter suppression via piezoelectric stack actuators

Chenxi Wang, Xingwu Zhang *, Yilong Liu, Hongrui Cao, Xuefeng Chen

State Key Laboratory for Manufacturing System Engineering, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

In cutting process, chatter is an inevitable phenomenon that greatly affects workpiece surface quality, tool life and machining efficiency. The stiffness variation (SV) method has been proposed and applied in chatter suppression for a long time. However, the early studies focused on boring and turning with one degree of freedom. For milling process with two degrees of freedom, there is no related research about SV. In this paper, SV method is employed through modulating the stiffness around a nominal value in order to suppress milling chatter. The milling dynamic model of SV with two degrees of freedom is constructed. In this model, the classical delay differential equation (DDE), which governs the milling process, is replaced with a DDE with a time-varying stiffness term. The stability analysis with different SV is completed using the semi-discretization method (SDM) and results show that the stable region with SV is larger than that under most of the traditional conditions. The results of stability analysis are verified by time domain simulation. In addition, the influences on stability lobe diagram (SLD), which is caused by different waveforms, amplitudes and frequencies of SV, are also analyzed specifically. The analysis results can provide the optimal parameters combination for milling. Cutting experiments are implemented on a three-axis milling machine to validate the effectiveness of SV. In the experiment, piezoelectric stack actuators are used to modulate the stiffness with time-varying preload. The milling forces signals are acquired by data collecting instrument, whose root-mean-square (RMS) is used as the metric of cutting vibrations. Experiment results are in good agreement with theoretical prediction.

1. Introduction

With the development of manufacturing industry, chatter is gradually becoming the great obstacle of obtaining higher machining efficiency, improved working environment, better surface quality and less tool wear, which will cause huge economic losses. Experiments show that the tool life will reduce 30% to 70% due to chatter [1,2]. As reported in Ref. [3], the cost due to chatter on a recent cylinder block is estimated to be about 0.35€, which causes much additional expense owing to its annual production of around 3 million.

In order to suppress or avoid chatter, a vast amount of research work has been done for a long time [4,5]. There are mainly three kinds of techniques for chatter avoidance or mitigation: analytical prediction technique, passive control technique and active control technique. The analytical prediction technique focuses on how to construct SLD more accurately [6–9] and rapidly [10–14] so that better cutting parameters can be selected. However, the accurate prediction of SLD can only be used for parameters selection, which cannot enlarge the stability region and improve the milling efficiency. The passive control strategies can suppress chatter by improving machine tool structure design [15–18] or using additional devices [19–22], such as variable pitch or helix mills, passive vibration absorbers and mechanical dampers. However, under the complexity and uncertainty of machine tool and cutting process, the passive control cannot show good performance without extra energy input. The active technique can expand or modify the SLD with active vibration reduction systems including computers, sensors and actuators. For example, the spindle speed variation can achieve the goal of increasing the stability limit [23–25]. However, this technology can't be widely used in the production process because of its huge energy consuming and large shock to motors. The other active methods, including model predictive control, robust control, adaptive control and so on, require complex control algorithms or expensive corollary equipment [26–30], which cannot be widely applied in the practical production process as well.

In order to suppress chatter, SV method is employed through modulating the stiffness around a nominal value in this paper. As an active

* Corresponding author. Xi'an Jiaotong University, No.28, Xianning West Road, Xi'an, Shaanxi, 710049, PR China.
E-mail address: xwzhang@mail.xjtu.edu.cn (X. Zhang).

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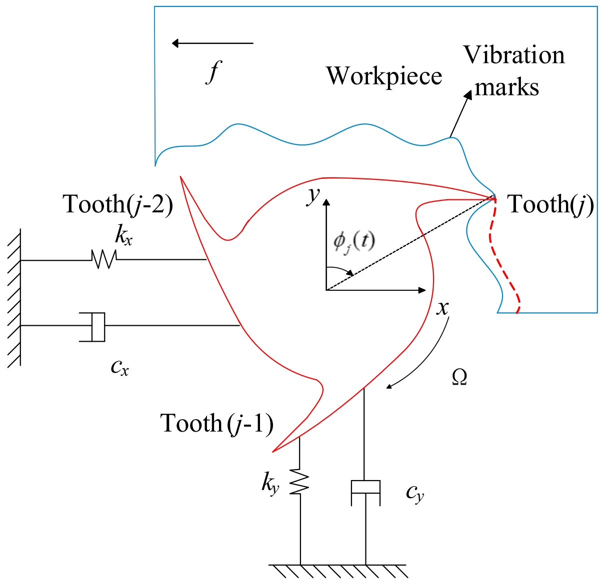

Fig. 1. Dynamic model of milling process with two degrees of freedom.

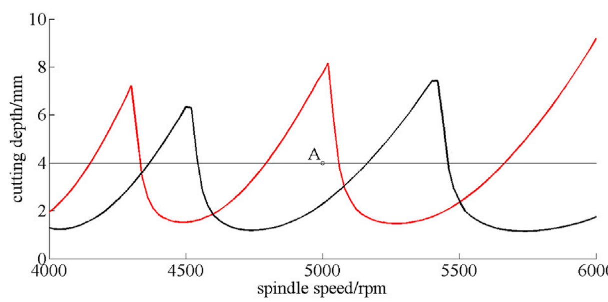

Fig. 2. SLD with two different natural frequencies.

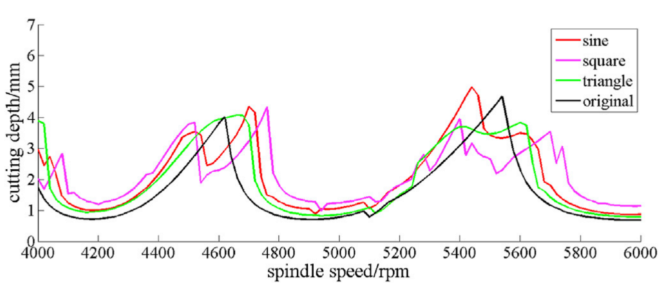

Fig. 3. The SLD with different SV.

control method, SV won't request huge energy consuming, complex algorithms and expensive devices. In Refs. [31,32], impedance modulation and smart material including electro-rheological fluids and magneto-rheological fluids, are introduced for chatter suppression without dynamic modeling and experimental verification. The electro-rheological fluids are applied in tunable-stiffness boring bar for chatter mitigation [33,34]. However, it focuses on the structure design and experiments without dynamic modeling and stability analysis in detail. Magneto-rheological fluids are used into boring bar with time-varying stiffness [35–37], which concentrate on boring chatter suppression without stability analysis. In Ref. [38], a high-order full-discretization method for stability analysis of time-varying stiffness turning is introduced without experimental verification. As described above, it can be known that SV is mainly used in turning or boring in previous research. Besides, the

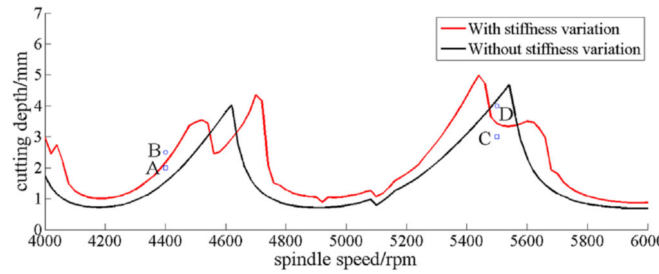

Fig. 4. Stability lobe diagram with and without SV.

influences of SV on cutting stability aren't analyzed. In this paper, the milling dynamic model of SV with two degrees of freedom is constructed, analyzed, discussed and verified in experiments.

The remainder of this paper is arranged as follows. In Section 2, the milling dynamic model of SV with two degrees of freedom is described in detail. Section 3 analyzes the stability in milling process with SV and the effect of different types of SV on SLD is discussed. The contrast milling experimental verification is presented in Section 4. Finally, several conclusions are drawn in Section 5.

2. Milling dynamic model of SV with two degrees of freedom

2.1. Dynamic model of milling process

As shown in Fig. 1, considering the flexible tool and relatively rigid workpiece, the milling process can be simplified as a mathematical vibration model with two degrees of freedom [39]. Without considering the coupling effect in two orthogonal directions, the governing equation can be given by

$$\begin{bmatrix} m_x & 0 \\ 0 & m_y \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix}+\begin{bmatrix} c_x & 0 \\ 0 & c_y \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}+\begin{bmatrix} k_x & 0 \\ 0 & k_y \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}=\begin{bmatrix} F_x(t) \\ F_y(t) \end{bmatrix} \tag{1}$$

where m_x, m_y, c_x, c_y, k_x, k_y, F_x and F_y, are the modal mass, damping, stiffness and milling forces in the flexible directions, respectively. Moreover, the subscript x represents the feed direction and the subscript y is perpendicular to the feed direction.

In Eq. (1), given the tooth number N, the axial cutting depth a, the linearized cutting coefficients K_t and K_n, the spindle speed Ω, the feed per tooth f, the tooth passing period or time delay $\tau = 60/N/\Omega$, then the milling forces F_x and F_y can be respectively given by

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \sum_{j=1}^{N} g(\phi_j(t))a\left(f\begin{bmatrix} -K_t sc - K_n s^2 \\ K_t s^2 - K_n sc \end{bmatrix} + \begin{bmatrix} K_t sc + K_n s^2 & K_t c^2 + K_n sc \\ -K_t s^2 + K_n sc & -K_t sc + K_n c^2 \end{bmatrix}\begin{bmatrix} x(t-\tau) - x(t) \\ y(t-\tau) - y(t) \end{bmatrix}\right) \tag{2}$$

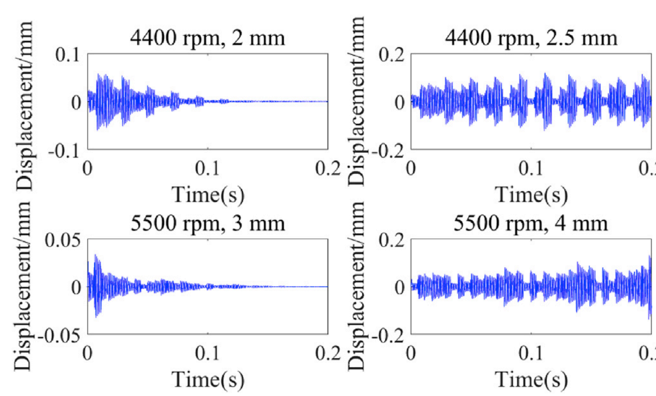

Fig. 5. SLD verification using the time domain simulation.