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Modeling dynamics and stability of variable pitch and helix milling tools for development of a design method to maximize chatter stability

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ABSTRACT

Chatter is one of the major limitations in milling operations causing poor quality and reduced productivity. Stability diagrams can be used to identify deep stable pockets which usually occur at high spindle speeds. However, the required high cutting speeds may not be applied in some cases due to machinability or machine tool limitations. It is known that variable pitch and helix tools help suppressing chatter even at low cutting speeds. These tools may offer high productivity if they are properly designed. The literature on variable geometry milling tools is mainly limited to modelling and simulation whereas for industrial applications design guidelines are needed for selection of variation pattern and amount which is the focus of this paper. Dynamics and stability of variable pitch and helix tools are modelled and solved in frequency domain as well as using Semi-Discretization Method employing multiple delays. A practical but accurate design method is presented for selection of the best variation combination to maximize chatter free material removal rate without using time consuming computer simulations. Increased stability with the tools designed using the proposed method is demonstrated by several examples which are verified experimentally.

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1. Introduction

Productivity of milling operations can be substantially increased when the machine tool is operated at high spindle speeds corresponding to deep stability pockets predicted by stability diagrams [1]. Increased dynamic cutting forces due to self-excited, regenerative chatter vibrations in unstable zones generate poor surface quality and damage to the machine tool parts (i.e. tool and spindle bearings) [2]. Stability pockets providing increased productivity at high speeds and depths may not be utilized in some cases due to low machinability of hard-to-cut materials and machine tool limitations. Special milling tools having uneven pitch or helix angles between consecutive teeth can be profoundly effective by altering the delay in dynamic system and disturbing the regeneration mechanism [3–6]. Therefore, proper design of special milling tools utilizing stability models is crucial to increase productivity.

The effectiveness of variable pitch cutters in suppressing chatter vibrations in milling was first demonstrated by Slavicek [7], who applied orthogonal cutting stability theory to irregular pitch milling tools by assuming rectilinear motion. Assuming an alternating pitch variation, he obtained a stability limit expression as a function of the pitch variation. In a later study, Opitz et al. [8] considered milling tool rotation using average directional factors. Their experimental results and predictions showed significant increase in the stability limit using cutters with alternating pitch. Vanherck [9] considered different pitch variation patterns in the analysis by assuming rectilinear tool motion. Simulations showed the effect of pitch variation on stability limits. These studies mainly concentrated on the effect of pitch variation on the stability limit; however, they do not address cutting tool design, i.e. determination of the best pitch variation to maximize stability. Altintas et al. [3] adapted the analytical milling stability model to the case of variable pitch cutters which can be used more practically to analyze the stability of variable pitch cutters. Later, Budak [4] proposed an optimization methodology for design of variable pitch tools considering the chatter frequency and spindle speeds. He showed that the selection of pitch variation is very critical for increasing chatter stability limits. Olgac and Sipahi [10] developed an optimization model for similar tools by analyzing the characteristic equation of the dynamic system using cluster treatment method. Later, Ferry [11] developed a model to predict stable cutting regions for serrated variable pitch milling tools using the Nyquist criteria. Turner et al.

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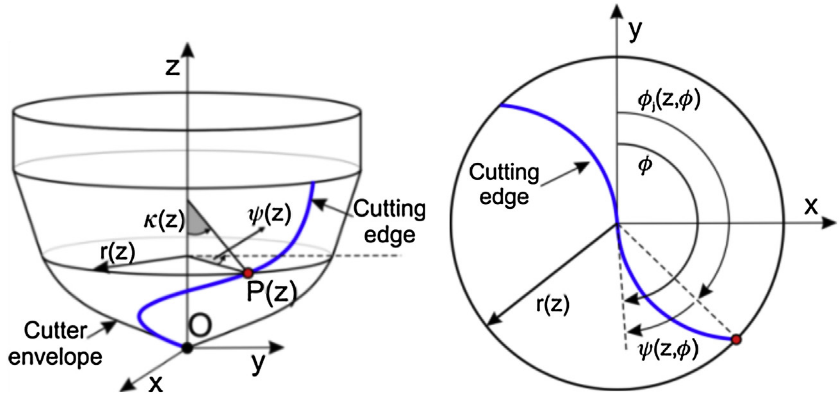

Fig. 1. Cutting flute geometry and corresponding parameters.

[12] obtained coherent results for low radial cutting cases by applying the method [4] developed for variable pitch cutters to variable helix cutters. Similarly, Sims et al. [13,14] investigated the chatter stability of variable helix and variable pitch cutters analytically, and proposed an optimization methodology by comparing three different modeling approaches, i.e. semi-discretization [15], time averaged semi-discretization with similar assumptions to Budak's model [4], and temporal-finite element method (TFEA) [14]. Finally, Dombovari and Stepan [16] investigated the effect of the helix angle variation on the chatter stability by semi-discretization method. In a recent study, Shamoto et al. [17] presented an optimization method based on multi-mode regeneration mechanism.

The objective of this paper is to demonstrate the optimal design of variable geometry milling tools for maximized chatter stability. First, the geometric model developed for generalized milling tools is presented. This is followed by the presentation of two stability formulations used for generalized milling tool chatter analysis, namely, semi discretization method and zero order approximation. Then, the optimal selection of pitch and helix angle variations is demonstrated through example cases which are experimentally verified. The procedure presented can be used for the design of variable milling tools to maximize chatter stability limits for desired spindle speeds. Finally, a novel design methodology for variable pitch tools is presented to determine the best pitch geometry for a given cutting condition to increase stability in a time efficient manner.

2. Variable tool geometry

All possible milling tool shapes and cutting edge forms can be defined geometrically by considering the tool envelope as an axially and radially organized point cloud. For instance, a point $P(z)$ on a helical cutting flute is defined in cylindrical coordinates in terms of its radial distance $r(z)$ to the tool axis, the axial immersion angle $\kappa(z)$, i.e. the angle between the tool axis and the normal vector of the cutting edge, and the radial lag angle $\psi(z)$ as shown in Fig. 1.

The immersion angle of the corresponding cutting tooth is written in terms of the lag angle $\psi(z)$ and the cutter rotation angle $\phi(z)$. For the general cutting tools with variable helix and pitch angles, the generalized local immersion angle $\phi_j(z)$ for the j^{th} cutting edge is written as follows;

$$\phi_j(z) = \phi + \phi_{p,j} - \psi_j(z) \tag{1}$$

where, $\phi_{p,j}$ and $\psi_j(z)$ represent the pitch angle of the j^{th} cutting edge with respect to the previous $j-1^{th}$ one and the axial lag angle of the j^{th} cutting edge at level z generated by the helix angle of the j^{th} flute $i_{0,j}$, respectively. The formulation to construct a generalized milling cutter profile with variable cutting edge geometry is given in [18].

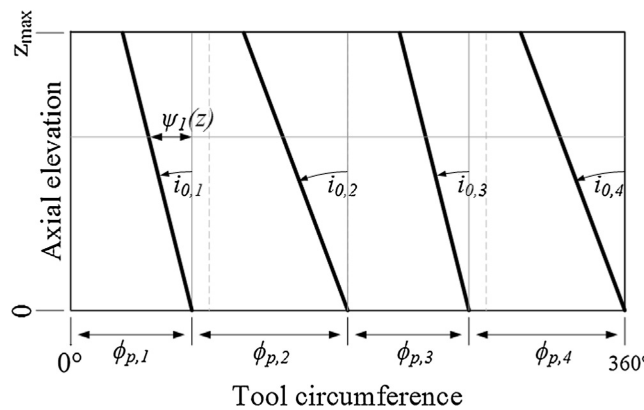

Fig. 2. Unfolded tool geometry and variable flute parameters.

Since the helix and pitch angles may change between consecutive flutes (see Fig. 2), instantaneous chip thickness at any axial level along the cutter axis depends on the helix and pitch angles of the corresponding flute. Therefore, effect of pitch $\phi_{p,j}$ and helix variations $\psi_j(z)$ along the cutter axis has great importance on the modeling of variable geometry milling tools.

The time delay between successive cutting passes at elevation (z), can be written as the difference of immersion angles of j^{th} and $j+1^{th}$ flute;

$$\delta\phi_j(z) = \phi_{j+1}(z) - \phi_j(z) \tag{2}$$

In this study, two common variation patterns are considered for both pitch angle and helix angles; linear and alternating. For non-uniform pitch distribution, a pitch angle variation measure, ΔP, is introduced and the initial pitch angle is found as described in [4].

For the helix angle variation for both alternating and linear distributions, the helix variation measure is denoted by ΔH. This variation measure has to be tuned to assure no crossing occurs between consecutive teeth due to the lag effects of helix and pitch angles. This constraint is noted as;

$$\phi_j(z) > \phi_{j-1}(z) \quad \forall z \tag{3}$$

3. Dynamics and stability of variable geometry tools

The stability of milling operations depends on the dynamically varying chip thickness. For variable geometry milling tools, as the time delay between consecutive edges is different, the phase angle can be disturbed resulting in higher stability.

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