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Predictive modeling of chatter stability considering force-induced deformation effect in milling thin-walled parts

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Abstract: Force-induced deformation is an inevitable phenomenon in thin-wall milling operations, which makes the actual radial depth of cut deviate from its nominal value and changes tool-part engagement angle boundaries. This paper presents an accurate modeling of dynamic milling system with the force-induced deformation effect. Both the thin-walled part and the cutter are discretized into differential elements, such that the influences of the force-induced deformation and multi-point contact structure dynamics can be simultaneously considered at the contact zones. A detail flexible iteration strategy is first presented to calculate the force-induced deformation and the resulting tool-part engagement angle boundaries. After that, time-varying multi-modal dynamic parameters with actual material removal effect are obtained by simultaneously modifying structural static and dynamic stiffness at each tool feed position. The system involving regenerative dynamic displacements is formulated as a matrix of time-periodic delay differential equation. Chatter stability of the system is predicted by an extended second order semi-discretization method. Milling experiments are conducted to validate the proposed approach, and two types of parts with different wall thickness are designed. The results show that chatter can be well predicted by using the proposed approach.

Keywords: chatter stability; thin-walled parts; force-induced deformation; multi-point contact; semi-discretization method

1. Introduction

Due to the structural efficiency and light weight, thin-walled parts are widely used in automotive and aerospace industries. In milling of such parts, the low rigidity, weak damp and time-varying dynamic characteristics of the milling system are prone to induce undesirable chatter phenomenon. It is recognized that chatter greatly degrades the machining accuracy, efficiency, surface quality and even causes damages to cutter and spindle units [1,2]. Thus, it is desired to obtain a stable process when milling thin-walled parts. To fulfill this aim, the use of stability lobe diagrams (SLDs) is of great value and has gain considerable attention of scholars.

In the last two decades, much effort has been devoted to the area of stability prediction for milling processes. Various methods for predicting the SLD have been proposed from frequency domain or discrete time domain. In the mid-90s, Altintas and Budak proposed an analytical solution [3] in the frequency domain, namely the well-known single-frequency solution method. By using the method, rapid and accurate SLDs can be predicted in the case of large radial immersions. To improve the prediction accuracy under small radial immersions, the multi-frequency solution [4] is further developed by considering the harmonics of the time-varying and periodic milling coefficients. Insperger et al. [5,6] presented the important semi-discretization methods (SDMs) in discrete time domain, which have been extensively applied to various complex time delay problems. Bayly et al. [7] solved discrete time equations by using temporal finite elements analysis which can also be used to predict the surface location error. Butcher et al. [8] presented a Chebyshev collocation based method to determine stability boundaries. Ding et al. proposed the full-discretization method (FDM) [9] and numerical integration method [10] based on the direct integration scheme. By using an equivalent transformation, Insperger compared the FDM with the first-order SDM [6] under a same scheme and analyzed the rates of convergence of both methods. Subsequently improved SDMs and FDMs with faster rate of convergence, including the methods based on Hermite interpolation [11], Newton interpolation [12], Simpson's rule [13] and least squares approximation [14] were proposed in succession. Recently, Jiang and Sun et al. [15] developed an efficient second-order semi-discretization method (2nd SDM) based on an improved precise time-integration algorithm. Considering the highly intermittent property of the process in milling thin-walled parts, it is essential to develop accurate chatter stability prediction algorithm fully considering the time variations of the process dynamics so as to achieve accurate predictions of SLDs.

Apart from ensuring the accuracy of chatter stability prediction algorithm, much effort has been made on establishing accurate dynamic models for milling thin-walled parts. Davies et al. [16] investigated the effect of impact dynamics in milling of thin-walled components via a mechanics-based model with the assumption of a dominated bending mode and a rigid cutting tool. Two-dimensional-SLD (2D-SLD), only determined by axial depth of cuts and spindle rotation speed, can be obtained from this model. However, in most actual situations, multiple modes participate in the tool-part dynamics at the same time. Moreover, modal parameters of the thin-wall part, which are often represented by natural frequencies and mode shapes, are time-varying at different feed position due to material removal effect. Bravo et al. [17] recommended a three-dime-

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