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Review of research on chatter stability in milling of thin-walled parts

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Abstract—**Milling is widely used in the processing of thin-walled parts with weak rigidity. As the chatter during the milling of thin-walled parts will cause processing quality problems, some measures need to be taken to suppress chatter. This paper describes the research overview of chatter stability during milling. According to the physical conditions of flutter formation, flutter can be divided into vibration-type coupled flutter, friction-type flutter, and regenerative flutter. In order to solve the problem of flutter, the flutter is firstly modeled dynamically, and then the flutter model is solved by the frequency domain method, the discrete method, etc., and the stability domain lobe diagram can be drawn. In addition, the research on flutter prediction, flutter stability analysis, flutter monitoring and flutter suppression is summarized and analyzed. The research and methods on the flutter problem are continuously proposed, which effectively promotes the processing efficiency and surface quality of thin-walled parts.**

Keywords-thin-walled parts; milling chatter; stability analysis; chatter suppression

I. INTRODUCTION

Thin-walled parts have small weight and high strength, and are common in aerospace structures. Milling, as a common processing method, has the advantages of small milling force and wide processing range, and is widely used in the processing of thin-walled parts. Due to the complex structure of thin-walled parts, high material removal rate and low local rigidity, chatter vibration is prone to occur during milling. When the chip thickness is generated during the machining process, chattering is caused by the self-excited mechanism [1], which manifests as the vibration between the workpiece and the cutting tool, resulting in poor dimensional accuracy and surface finish of the workpiece, and even the damage of the cutting tool or even the machine tool in serious cases [2]. Therefore, in the processing of thin-walled parts, solving the problem of milling chatter has become the focus of research by domestic and foreign scholars.

Scholars' research on chatter in thin-walled parts milling mainly focuses on chatter prediction, stability analysis, chatter monitoring and chatter suppression. Construct milling chatter model and stability lobe diagram from the processing of thin-walled parts to find the main factors affecting chatter; construct chatter stability domain, select appropriate cutting parameters in the stability domain to suppress chatter, and at the same time the real-time online identification and evaluation of milling chatter are realized through the flutter monitoring. In this paper, the problem of milling chatter of thin-walled parts is summarized from the aspects of modeling and prediction, on-line monitoring and suppression.

II. ANALYSIS OF MILLING CHATTER MECHANISM

The research methods for the analysis of chatter stability in the milling process are mainly to construct a model of milling chatter, predict the stability boundary of the milling process, determine the stable milling zone and the unstable milling zone, and select the appropriate milling parameters from the established stability flap diagram to suppress the chatter and improve the milling quality and efficiency.

A. Theoretical research mechanism

According to the formation method of flutter, it can be divided into three forms, namely vibration-type coupled flutter, friction-type flutter and regenerative flutter [3]. Among them, regenerative chatter is the main form of milling chatter, and it is a common self-excited vibration in the machining process. When the tool is cut to the vibration marks on the last residual surface of the workpiece, the dynamic milling force will fluctuate, and the phase difference between the two adjacent vibration marks on the workpiece will cause regenerative chatter. Therefore, the chatter at any moment is not only related to the current tool deflection, but also related to the state of the cutting system at the previous moment. Due to the existence of the regenerative effect, the regenerative flutter model is generally described by a delay differential equation.

B. Stability lobe diagram domain

By simulating the milling process, Li et al. [4] established a milling force model and analyzed the lobe diagram in the stability domain, which could be used to optimize the milling parameters and provide a reference for inhibiting the chatter in the milling process. Fei et al. [5] proposed a dynamic model suitable for predicting chatter during the processing of thin-bottomed flexible bag-shaped structures, and performed modal analysis on it to obtain system parameters. Semi-discrete method was used to draw stability lobe diagram, so as to determine appropriate cutting conditions when milling the thin bottom of flexible chamber structure. Huang et al. [6] proposed a method for calculating the reliability of regenerative chatter stability during milling, and used the full-discrete method to draw the milling stability lobe diagram. Mi et al. [7] simplified the machine tool-tool-workpiece system into a vibration system as shown in Fig. 1, established a dynamic mathematical model for milling processing, and calculated and drew a stable vane diagram by analytical method. Based on it, a milling parameter optimization model that can obtain the best spindle speed, radial feed and axial feed was proposed.

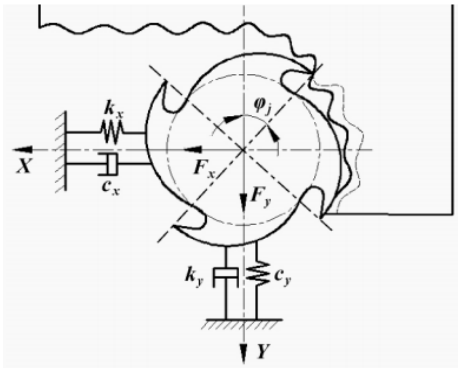

Figure 1. Milling vibration system model

Qu et al. [8] proposed a three-dimensional stability lobe diagram of thin-walled plate milling based on a time-domain flutter model. Since a higher feed rate will produce a greater milling force, as the feed per tooth increases, the surface quality of thin-walled parts will decrease. During processing, the best milling parameters can be selected according to the diagram to avoid vibration and increase productivity. Campomanes [9] proposed an improved milling time-domain model to simulate the vibration cutting conditions under a small radial cutting width, and the improved kinematics model can simulate very small radial immersion. The model can predict the milling force, the surface finish of the workpiece and the vibration stability, so as to accurately solve the nonlinear influence of the modeling.

III. Prediction of Milling Stability

If the chatter that may occur in the milling of thin-walled parts can be predicted in the process planning stage, the machining process parameters can be improved in advance to avoid chatter during the milling process, thereby improving the milling efficiency and machining quality.

Budak et al. [10] proposed a method for predicting the dynamics of the workpiece in the process. The method is based on the dynamic modification of the structure using the finite element model of the workpiece, and the simulation was verified by experiments. Jin et al. [11] established a stability prediction model, which takes into account the dynamic characteristics of the milling process, predicts the stability of the thin-wall milling system through the full-discrete method, and establishes a three-dimensional stability vane Figure, optimize processing parameters and improve processing efficiency. Ding et al. [12] proposed the relative dynamic behavior between the tool subsystem and the workpiece subsystem. According to its dynamic characteristics, the frequency domain method was used to predict the critical conditions of system stability, and the time-varying critical stability of chatter Conditions, a three-dimensional lobe diagram of flutter is established to show the changes in flutter conditions.

Yang et al. [13] proposed a comprehensive dynamics model for predicting SLD in peripheral milling of thin-walled workpiece with curved surfaces. The model and method can accurately predict the stability of thin-walled plates and curved surface milling. Lyu et al. [14] combined the semi-discrete method to predict the stability of milling machining with the change in the meshing condition of the tool workpiece caused by the cavity milling path, and proposed and verified the validity of the prediction of the stability of cavity machining. In addition, the method based on matrix perturbation theory can also be effectively applied to the prediction of modal parameters in the finishing process of thin-walled parts [15]. Sun et al. [16] considered the force-induced deformation effect in the interaction of static and dynamic systems, and combined the stability prediction model with deformation, multi-point contact structure dynamics, material removal and time-varying multi-modal dynamic parameters. The system's 3D-SLD makes accurate predictions. An effective decomposition-condensation method proposed by Yang et al. [17] has a short calculation time and has higher accuracy than the previous method, but it will also have greater memory consumption.

IV. Chatter Online Monitoring

There are some non-linear problems in the processing of thin-walled parts, which make it difficult to predict the machining vibration. Online monitoring of the milling process can obtain the status of the tool and workpiece in real time. This made it possible to study the vibration state of thin-walled parts under the action of alternating cutting forces during milling. therefore, chatter monitoring is an important task to improve the productivity and part quality in the machining process.

A vibration identification method for end milling was proposed in 2015. The vibration signal is adaptively decomposed using the EEMD method, which can effectively avoid the interference to the operator [18]. The author proposed a vibration detection method based on the synchronous compression transform (SST) of the sound signal the following year [19]. This method can effectively monitor online chatter during high-speed milling. Liu [20] et al. used PVDF piezoelectric film sensors, and also proposed a method for on-line monitoring of vibration in the milling process of thin-walled parts without interference. It can also identify different processing stages in the milling process and facilitate real-time decision-making on the processing process. The evaluation index based on the energy entropy of the wavelet packet established by Zhang et al. [21] can also effectively identify the stability and vibration state of milling.

In addition, the use of the dynamic characteristics of the workpiece can better identify regenerative chatter [22], and the chatter detection threshold based on changes in the geometry of the workpiece, tool path and dynamic characteristics can effectively identify chatter. Recently, a dynamic milling stability prediction method for thin-walled parts with a time-varying stiffness system based on the combined method of VPC and VSS was proposed [23]. This method can predict the milling stability of thin-walled parts with a time-varying stiffness system.

V. CHATTER SUPPRESSION STRATEGY

In order to suppress chatter during the milling process of thin-walled parts with weak rigidity, the methods adopted include stiffness lifting, damping lifting and cutting process optimization.

A. Stiffness improvement strategy

Compared with the traditional uniform allowance machining, non-uniform allowance machining in thin-walled parts can improve the machining rigidity of the workpiece and ensure the stability of the cutting process [24]. Thereby, chatter vibration can be suppressed, and the processing efficiency and surface quality can be improved. Matsubara et al. [25] proposed a pivot mechanism, which uses the surface support of the pivot mechanism to have a better effect on flutter suppression. Jiang [26] proposed an auxiliary support method based on magnetorheological fluid, dynamic model and simulation prediction model in view of the weak rigidity and complex structure of thin-walled parts. Through this method, the best parameters of the magnetorheological fluid clamp can be found, which can effectively improve the processing quality of thin-walled parts.

B. Damping promotion strategy

Budak and Altintas [27] proposed an analytical method to solve the problem of chatter stability in end milling operations in order to suppress chatter during milling. This method takes into account structural dynamics in the cutting plane and changes along the axial direction. By modeling the workpiece and the tool as a multi-degree-of-freedom structure, a comprehensive expression of the dynamic milling force is given. Yang et al. [28] proposed a damping vibration reduction scheme based on viscoelastic material, damping layer, constraint layer and mass layer, which can be applied to the five-axis milling of S-shaped thin-walled parts. It has obvious vibration reduction effect and strong adaptability in the process of processing. A method to reduce the chatter of thin-walled parts by immersing the milling system in a viscous fluid has been proposed [29]. Under the condition of viscous fluid, the damping of the system is significantly increased. Tests show that this method can effectively suppress the vibration of thin-walled workpieces and reach a higher stability limit.

C. Cutting process optimization

Seguy et al. [30] conducted a test on a three-axis high-speed milling center as shown in Fig. 2, and the results showed that the milling process can be stabilized by increasing the amplitude of the spindle speed change, and the frequency of the spindle speed change has no effect on the dynamic behavior. Zhang et al. [31] established the time-delay differential dynamics model of the flexible tool-

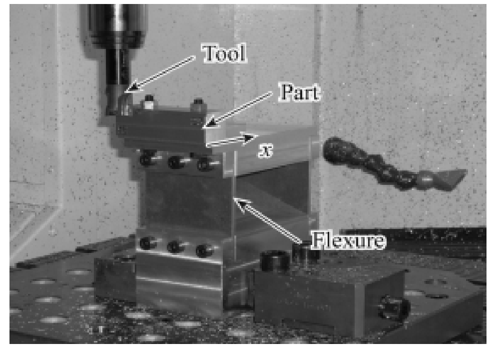

Figure 2. Three-axis experimental device

rigid workpiece dual-degree-of-freedom milling process system, and obtained the stability lobe diagram to predict the stable cutting process parameter domain through the full-discrete method, based on the reasonable selection of process parameters, the flutter can be avoided and the forced vibration can be suppressed.

VI. CONCLUSION

In this paper, the research of chatter problem in the process of thin-walled parts milling is summarized. Vibration coupling, friction, and regenerative flutter theories have been relatively mature. Methods such as frequency domain method, time domain method, semi-discrete method, and full-discrete method have been applied to stability analysis. In recent years, with the research on chatter problems, there are more and more methods for chatter prediction, online chatter monitoring, and chatter suppression. From linear to nonlinear problems, from simple thin-walled parts to complex curved thin-walled parts, all advances in theories and methods are finally applied in production, which can effectively deal with a series of problems caused by chatter and improve the efficiency and quality of thin-walled parts processing. At the same time, as research continues to progress, it will be a great progress to integrate the chatter prediction, real-time monitoring with the suppression and even the surface quality monitoring of thin-walled parts.

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