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Vibration suppression of thin-walled workpiece machining considering external damping properties based on magnetorheological fluids flexible fixture

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Abstract Milling of the thin-walled workpiece in the aerospace industry is a critical process due to the high flexibility of the workpiece. In this paper, a flexible fixture based on the magnetorheological (MR) fluids is designed to investigate the regenerative chatter suppression during the machining. Based on the analysis of typical structural components in the aerospace industry, a general complex thin-walled workpiece with fixture and damping constraint can be equivalent as a rectangular cantilever beam. On the basis of the equivalent models, natural frequency and mode shape function of the thin-walled workpiece is obtained according to the Euler–Bernoulli beam assumptions. Then, the displacement response function of the bending vibration of the beam is represented by the product of all the mode shape function and the generalized coordinate. Furthermore, a dynamic equation of the workpiece-fixture system considering the external damping factor is proposed using the Lagrangian method in terms of all the mode shape function and the generalized coordinate, and the response of system under the dynamic cutting force is calculated to evaluate the stability of the milling process under damping control. Finally, the feasibility and effectiveness of the proposed approach are validated by the impact hammer experiments and several machining tests.

1. Introduction

In aerospace industry, the machining vibration of thin-walled workpiece is an undesirable phenomenon. The analysis of the negative influence caused by machining vibration, especially for machining flexible workpiece such as aeroengine blades, casings, impellers, blisks, has received special attention due to its effects on the accuracy of the final workpiece, the production efficiency and the life of machine spindles and cutters. Milling process, which plays a critical role in manufactur-

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ing, has been extensively used to the finishing machining of the low rigidity and large machining deformation workpiece, and the machining vibration is a serious problem in machining. Therefore, it is necessary to investigate the machining vibration dynamic response of the thin-wall workpiece to suppress vibration in machining.

For the efforts of investigating the milling vibration of thin-walled flexible workpiece, reasonable cutting parameters should be selected in machining according to chatter stability diagram. Recently, in the aspect of chatter stability prediction, numerous theoretical and experimental investigations have been made in model prediction, analysis, and various designs of fixture devices and so on. To accurately study the machining vibration, the prediction and analysis of the dynamic machining stability of the thin-walled workpiece is a fundamental problem. Many research works about this aspect have been developed. Altintas and Budak[1,2] presented an analytical method (ZOA method) based on the dynamic milling coefficients approximated by their Fourier series to predict the milling stability lobes. Merdol and Altintas[3] overcome the existence of additional stability regions and period doubling bifurcations in small radial cut depth during milling process. Zhou et al.[4] proposed an analytical model considering tool-workpiece engagement region and different cutter lead angles for chatter stability prediction in bull-nose end milling of aeroengine casings, and the predicted method is well agreed with experimental results. Insperger and Stépán et al.[5–7] proposed the semi-discretization method to efficiently conduct stability analysis to the linear milling delayed systems. Considering the calculated efficiency, Ding et al.[8,9] presented the full-discretization methods to predict milling stability based on different mathematic theory. Then, this method is extended by Liu et al.[10] based on the Hermite interpolation and the Floquet theory.

In machining vibration suppression, many different passive and active control methods are investigated. Zhang et al.[11] presented a piezoelectric active vibration control method that increases the damping of the thin-walled flexible workpiece to mitigate the milling vibration. Rashid et al.[12] adopted an active controlled palletised workholding system, which is different from traditional approach in machining systems to dampen the unwanted vibration. However, many considerable piezoelectric devices and external system in their method, which take much time and is not suitable for complex parts. Sathianarayanan et al.[13] and Mei et al.[14,15] proposed the method of using magnetorheological fluids to adjust the stiffness of boring bar, which can efficiently improve the stability of boring bar and reduce machining vibration. However, they only investigated the effects of the damping material on the boring bar and the properties of the whole fixture are not considered. Shamoto et al.[16] presented a new method of simultaneous double-sided milling to machine flexible plates and the chatter vibration is efficiently suppressed by the experimental validation. Kolluru et al.[17] presented a novel surface damping solution which took distributed discrete masses as viscoelastic layer to large thin-walled casings for reducing the machining vibration obviously. Zhang et al.[18] proposed a component synthesis active vibration suppression method based on zero-place-ment technique to suppress the vibration of flexible systems. Yang et al.[19] designed a vibration suppression device for the thin-walled flexible workpiece based on the electromagnetic induction principle, and the excitation tests and machining tests are carried out to verify the efficiency of the device. Zeng et al.[20] proposed a novel fixture design approach to suppress the machining vibration of flexible workpiece. In this work, appropriate fixture layout scheme concerned with suppressing the machining vibration of the flexible workpiece is designed based on the proposed dynamic model of workpiece-fixture-cutter system. Later, Wan et al.[21,22] presented a new fixture layout optimization method for the milling of thin-walled multi-framed workpiece to obtain better fixture supports scheme, which took the machining quality and suppression of machining vibration into consideration, in addition, the predicted and experimental results show that the reasonable fixture design can efficiently improve the machining accuracy and significantly suppress machining vibration of flexible workpiece. However, those works only focus on the properties of the fixture support and the effect of the damping properties of the whole fixture on the dynamic machinability is ignored.

Notwithstanding many valuable results aforementioned, current researches on chatter stability prediction and vibration control are mainly concentrated on the effect of the cutting process parameters, while the actual dynamic response properties of the machining system depended on the whole damping properties of the system according to the dynamic differential equation to some extent. However, the dynamic damping properties are not considered in these studies. To address this issue, a semi-active control flexible fixture based on MR fluids is proposed for the complex thin-walled workpiece machining in this paper, which takes the aforementioned missing damping factor into consideration.

Henceforce the paper is organized as follows: Section 2 describes the problem formulation of the thin-walled workpiece in machining considering the equivalent model of the thin-walled workpiece. Then, natural frequency and mode shape function of the thin-walled workpiece based on the Euler–Bernoulli beam assumptions is calculated in Section3 3. Section 4 constructs the dynamic equation of the workpiece-fixture system considering the external damping factor, and the response of system under the dynamic cutting force is calculated to evaluate the stability of the workpiece-fixture system. Milling experimental tests are carried out for validating the feasibility and efficiency of the proposed chatter theory and the flexible fixture, and the experimental results is discussed in Section 5. Following the discussion, some conclusions and future works are summarized in the end.

2. Problem formulation

The machining of thin-walled workpiece is critical to obtain high precision and good quality of the workpiece in aerospace industry. Due to the typical structure of the thin-walled workpiece used in the aerospace industry, the parts with fixture constraint can be approximately equivalent as a rectangular cantilever beam as shown in Fig. 1. Firstly, a solid workpiece with lower precision and larger scattered errors is fixed on the working table of machine tools by the fixture, which can keep the correct position between the cutting tools and the workpiece, and an amount of materials is removed for the required final structure in machining process. In this process, the two stages are divided. One is rough machining, the workpiece with big cutting allowance and the cutter with shank of tool can be regarded as rigid, the cutter with short cutting tool can be