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Optimization and improvement of stable processing condition by attaching additional masses for milling of thin-walled workpiece

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Light weight is the main design requirement for minimizing costs or fuel consumption in mechanical equipments, and it, together with the material removal rate (MRR) requirement, also brings an important source of chatter, which still remains as an essential phenomenon to be suppressed in the future.

This paper investigates the stable cutting region optimization problems in milling of structures with low rigidity. An effective method is proposed to improve the chatter stability by attaching appropriate additional masses to the workpiece, and thorough studies are also carried out to reveal the effect of additional masses on chatter stability. An efficient method based on structural dynamic modification scheme is developed to calculate the varying dynamics of the in-process workpiece under the combined effect of additional masses and material removal during milling process. Typical characteristic of this method lies in that only one modal analysis is needed to be performed on the finite element (FE) model of the initial workpiece, and the mode shape and natural frequency of the workpiece after attaching additional masses and removing material at each tool position can be calculated without the requirement to rebuild the FE model of the in-process workpiece. Based on the proposed dynamic modification scheme, an optimization algorithm is established to obtain the optimized combination of additional masses and the suitable stable cutting region for the achievement of maximum MRR. The proposed method is verified by milling process of a set of thin-walled workpieces, and comparisons of predictions and measurements show the validity and reliability.

1. Introduction

Thin-walled workpiece such as ribs, blades and other aeronautic parts, are mainly manufactured through milling processes. Due to the flexibilities of both workpieces and cutting tools, chatter vibrations are easy to occur. The occurrence of chatter not only brings an unstable machining environment, but also leads to unacceptable geometrical accuracy, poor surface quality and damages of machine tools [1–4]. Thus, the suppression of these kinds of chatter vibrations has become

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one of the major concerns, and it still remains as an essential problem in the future [3]. This paper will present a method to select the optimal stable cutting region to achieve maximized material removal rate in milling of thin-walled workpieces.

Since the description of chatter vibrations has been made by Taylor in 1907, several authors, such as Tobias and Fishwick [5], Minis and Yanushevsky [6], Altinas and Budak [1], Insperger and Stepan [2], have made a lot of studies on this topic. Tobias and Fishwick [5] used turning to approximate milling and developed the linearized theory to predict the stability lobe diagram (SLD), which can be used to select the chatter-free cutting parameters. Based on this excellent work, the method that used Floquet theory was proposed to predict the milling stability in frequency domain [6]. Altinas and Budak [1] used the average item to approximate the Fourier series of the dynamic cutting force coefficients, and proposed a set of linear analytic expressions to calculate the chatter free depth of cut and spindle speed without any digital iteration in frequency domain. Insperger and Stepan [2] proposed a semi-discretization method to predict the stability diagram in milling. Wan et al. [7] theoretically studied the construction mechanism of stability lobes by simultaneously considering multiple modes and delays. All these studies assumed that the dynamic characteristics of tool-workpiece system were unchanging during the whole process, and can give good predictions in the cases that the deflections of cutters and workpieces could be treated as rigid body.

However, in actual milling of thin-walled workpiece, the deformation of workpiece changes the chip thickness, and thus will further have great effect on the machining stability. Therefore, rigidity assumption is inaccurate to predict SLD for this kind of process. Recently, more and more studies focus on the flexibility of tool and part. On the one hand, some authors focused on the flexibility of workpieces by assuming the stiffness of tool is larger than that of the workpiece [8–13]. For example, Arnaud and Dessein [12] used a single degree of freedom system, which only considered the workpiece's flexibility in the direction perpendicular to the cutting speed, to predict the stability lobes of side milling of flexible part. Damir et al. [13] introduced a simulation model to study the dynamics of plunge milling process by considering the variations in axial direction for flexible workpiece. On the other hand, some authors considered the flexibilities of both cutter and workpiece [14–16]. Li and Shin [15] proposed a comprehensive time domain model that considered the dynamic vibrations along the depth of cut for both tool and workpiece. Eksioglu et al. [16] invented a new discrete-time model by considering the structural dynamics of the tool and thin-walled workpiece at the tool-workpiece contact zone.

It should be pointed out that once the flexibility of the machining system is included, it is needed to accurately and effectively obtain the system's dynamic parameters at different cutting instants. Altintas et al. [17] stated that the dynamic parameters of flexible milling system were discrepant along the depth of cut for both the cutter and workpiece, and developed a simulation model to obtain the dynamic responses of workpiece by using finite element modeling (FEM). Li and Shin [15] calculated the dynamic parameters of workpiece based on the frequency response functions (FRF) obtained from modal test experiments. Both works [15,17] ignored the effect of material removal on the dynamic parameters of workpiece. Thevenot et al. [18] concluded that the predicted SLD was not valid for flexible machining if the influence of material removal was ignored. Bravo et al. [19] utilized standard impact tests to obtain the FRFs of thin-walled workpiece at different cutting instant. This means is effective but time-consuming and inefficient since abundant impact tests are required. Some authors [18,20–23] also proposed numerical methods to study the effects of material removal on the workpiece's dynamic responses. Thevenot et al. [18] and Adetoro et al. [20] used FEM to identify the FRFs of workpiece at different tool positions. This method needs a lot of step finite element models and time-consuming modal analyses. For the purpose of increasing the numerical method's efficiency, some researchers [21–23] made outstanding studies based on the structural dynamic modification technique. Budak et al. [21] predicted the in-process workpiece (IPW) dynamics by updating the removed elements of FEM model along the tool path. Yang et al. [23] implemented an efficient method to compute the IPW dynamics of curved parts by reducing system freedom.

All the above researches were mainly focused on the precision and efficiency of stability prediction. Only a limited number of studies carried out vibration controls to improve machining stability. For example, Ertuck et al. [24] established an analytical model to study the effects of system design parameters (e.g. spindle geometry and spindle bearings) and operational parameters (e.g. tool geometry and holder geometry) on the FRF of tool, and then realized increasing chatter stability by optimizing these parameters. Cao et al. [25,26] developed detection methods to discover early signals of chatter vibrations. In order to avoid chatter, Kalinski and Galewski [27] developed a delayed close-loop control system to optimize spindle speed. Smis [28] developed a methodology to analytically tune the stiffness and damping of vibration absorber, which was located on the workpiece to suppress the chatter vibration in machining operations. Bolsunovsky et al. [29] designed an innovative device, i.e. tuned mass damper, to easily and fastly avoid milling vibrations for the selected cutting parameters. Besides, chatter vibrations can also be monitored and controlled by designing intelligent spindles [30].

This paper presents a method to improve the stability domain by adding additional masses to workpiece to change the dynamic characteristics of milling system. Efficient scheme is established in Section 2 to quickly obtain the varying dynamics of IPW under additional masses and material removal effects based on structural dynamic modification scheme instead of rebuilding the finite element model of IPW and re-performing modal analysis. Algorithm to determine the optimal combinations of masses is theoretically formulated. Optimization algorithm is also theoretically developed in this section to find the optimum group of additional masses together with relatively large feasible stable region in stability lobe. Section 3 validates the proposed method and dynamic model by comparing the predictions with the measurements.