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A novel stability prediction approach for thin-walled component milling considering the material removing process

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Abstract The milling stability of thin-walled components is an important issue in the aviation manufacturing industry, which greatly limits the removal rate of a workpiece. However, for a thin-walled workpiece, the dynamic characteristics vary at different positions. In addition, the removed part also has influence on determining the modal parameters of the workpiece. Thus, the milling stability is also time-variant. In this work, in order to investigate the time variation of a workpiece's dynamic characteristics, a new computational model is firstly derived by dividing the workpiece into a removed part and a remaining part with the Ritz method. Then, an updated frequency response function is obtained by Lagrange's equation and the corresponding modal parameters are extracted. Finally, multi-mode stability lobes are plotted by the different quadrature method and its accuracy is verified by experiments. The proposed method improves the computational efficiency to predict the time-varying characteristics of a thin-walled workpiece.

1. Introduction

Due to its wide applications in military, energy, and aerospace industries, milling of thin-walled components is of great significance. However, the high flexibility of a cutting tool-workpiece system and improper cutting parameters contribute to severe vibration, and the most important source of the problems that emerge during thin-walled components milling is regenerative chatter.

Regenerative chatter is a kind of self-excited vibrations, and the cutting amount simultaneously depends on the paths left by the tooth tips of the current tooth and the previous tooth,

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so the cutting force varies as well as the chip thickness. There are many methods proposed to predict chatter stability, including frequency-domain methods[1–3] and time-domain methods.[4–8] However, all these studies assumed that the dynamic characteristics of a system did not change during the whole machining process.

As for a thin-walled workpiece, due to the variation of the dynamic characteristic with the motion of the cutter position, the stability also changes during the machining process. Bravo et al.[9] and Sheng et al.[10] divided the milling process into different stages and obtained frequency response functions (FRFs) through an impact test. Although this method would be more accurate, it was almost impractical to conduct enough impact tests to obtain a workpiece's dynamic characteristic during milling. In order to avoid repeated impact tests, a workpiece's FRF was updated by the finite element method (FEM).[11–15] However, this method is of low efficiency since a workpiece should be remodeled and correspondingly, modal analysis should also be re-conducted. In this condition, Budak et al.[16] and Song et al.[17] utilized a structural dynamic modification scheme to improve the FEM-based method, where only a workpiece's initial dynamic characteristic was needed. Similarly, taking into consideration the influence of material removal and the change of the mode shape along the cutting path and tool axis, Yang et al.[18] also obtained in-process workpiece dynamics through structural dynamic modification. Neglecting the influence of material removal, Li et al.[19] obtained position-dependent FRFs through the effective stiffness which was dependent on mode shape. Instead of the commonly adopted FEM, the multispan plate (MSP) mode was proposed to model the varying thickness of a flexible pocket-structure.[20] Compared with FEM-based methods, the MSP model offers 10–20 times higher computational efficiency. Combining the high computational efficiency of the MSP model and the versatility of FEM-based methods, Ahmadi[21] proposed finite strip modeling (FSM) to model thin-walled structures in pocket milling operations.

It is worth noting that due to the change of the mode shape along the cutting path, some specific modes may also affect the stability of a thin-walled workpiece. Based on frequency methods, Budak and Altintas[22] obtained the stability of a flexible multi-mode structure. However, the dynamic characteristic was assumed as unchanged. Thvenot et al.[11,12] took the first several modes into consideration and determined the stability limitation by selecting the lowest envelop of each mode. According to Ref. 23, this lowest envelop method (LEM) may cause some prediction errors when the modes of a workpiece are not well separated. Zhang et al.[24] predicted the stability of a multi-mode cantilever plate and updated the dynamic characteristic by an impact test. Song et al.[25] took the influences of different modes into consideration. However, material removal was neglected.

Based on the above literature review, it can be seen that often the dynamic characteristic of a workpiece was obtained by the FEM. Apart from the MSP method, there is no other independent numerical method which is not involved with the FEM. In addition, Refs. 11,12 considering both multi modes and material removal did not give a clear explanation about the relationship between the position, mode shape, and stability limitation. This paper focuses on the mathematic model of a thin-walled flexible part, and tries to conduct theoretical analysis of the time-variant modal parameters of the workpiece.

The contribution of this paper lies in that the influences of the cutter position and material removal is investigated by theoretical analysis. Since a system does not need to be remodeled during the machining process, compared with the finite element method, the calculation efficiency can be improved a lot. The remainder of this paper is summarized as follows. The equation of motion of the flexible thin-walled part and modal analysis are given in Section 2. Then, the different quadrature method is briefly introduced to calculate stability lobes in Section 3, and the milling stability prediction of flexible part milling and experimental results are presented in Section 4. Conclusions are drawn in the last section.

2. Time-varying model of thin-walled plate

As shown in Fig. 1, during the milling process, the material is continuously removed along the trajectory of the moving cutter. Correspondingly, the workpiece's dynamic characteristics, such as natural frequency and stiffness, also change during this process. In this section, different from Refs. 16–18, where the FEM is used to conduct modal analysis, a more efficient method is proposed to obtain the dynamic characteristics of the workpiece.

2.1. Energy formula

In Fig. 1, a cantilevered thin-walled rectangular plate under milling machining, with a length of L, a width of W, and a thickness of h, is modeled. The spindle speed is Ω and the feed rate is c. The classical plate theory, which is suitable for thin-walled plate analysis, is used, and only the bending effect of the thin-walled plate is considered. Since, during the milling process, the material is removed as the cutter moves along the cutting path, the shape of the plate is varying during this period. However, it is lucky that the shape of the plate is predictable, and the material removal volume is relatively small compared to that of the unprocessed plate. Therefore, it is reasonable to assume that the plate's modal shape is unchanged and correspondingly, the kinetic energy, T, of the machined plate can be expressed as

$$T = \frac{\rho h}{2}\iint_A \dot{w}^2 \mathrm{d}x\mathrm{d}y - \frac{\rho h_{\mathrm{r}}}{2}\iint_{A_{\mathrm{r}}(t)} \dot{w}^2 \mathrm{d}x\mathrm{d}y \tag{1}$$

where ρ is the density, h_{r} is the thickness of the removed part, namely the radial cutting depth, w is the displacement along z direction, and the over-dot denotes differentiation with respect

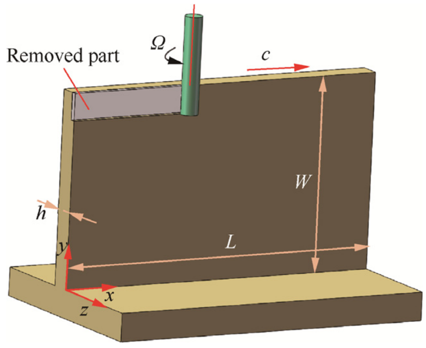

Fig. 1 Model of a cantilevered plate.

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