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Dynamics and stability of milling thin walled pocket structure

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In this paper, the multi pocket structure is regarded as a combination of Kirchhoff plates. A semi analytical solutions for the vibration of this thin walled structure are obtained by the subdomain decomposition method which is proposed by the authors earlier. Thereafter, a dynamic cutting model concerning the cutting position and the vibration states is adopted to modelling the milling force. Both the vibration model and the dynamic cutting model are integrated together to establish the governing equation which fully consider the dynamic features for the thin wall milling process. Based on the quasi static hypothesis, the stability of the milling of thin walled structure can be regarded as the stability of cutting at a series of discrete points. And the semi discretization method is applied to analysis the stability for this thin wall milling process. It is found that the critical depth of cut is appropriately inversely proportional to the square of mode shape for each single mode. In addition, the influence of the multimode and the mode coupling effects on the milling stability are discussed. It gives clearer insight into the dynamics and stability for the milling processes of thin walled structure.

1. Introduction

The milling operation is a common technology for material removal in industries. Vast literature exist for the research of dynamics and stability in the milling process. Theoretically, the governing equation for the milling process is a set of Ordinary Differential Equation (ODE) with the delayed milling force, since the rotating cutter is removing the wavy surface left by the previous tooth. Therefore, the stability of the milling process may be determined by the corresponding DDEs with periodic coefficients. Altintas and Budak proposed the frequency method [1] for the milling stability prediction, where for the most simplistic case, only the zeroth order of Fourier series was considered. Merdol and Altintas [2] applied the multi frequency method for the low immersion milling stability analysis, with higher order Fourier expansion components were taken into consideration. Urbikain et al. [3] used the single frequency method and collocation method to study the stability in rough turning by considering different modes. The study on the cutting stability through the frequency method can also be found in literature [4,5]. Different from the frequency method, Insperger and Stepan [6] proposed the semi-discretization method for the delayed system. Insperger [7] and Long [8] applied the semi-discretization method into the milling stability analysis. Mathematically, the semi discretization method is actually studying the stability of periodic solution of the functional differential equation by the Floquet theory [9]. With different discretization and approximation strategies, there also exist the

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higher order semi discretization method [10] and full discretization method [11]. Ahmadi et al. [12] used the semi discretization method to cover the process damping in the milling process. Mann et al. [13] used the Time finite element analysis (TFEA) to determine the stability in milling. Moradi et al. [14] studied the internal resonance of regenerative chatter between two coupled modes. Based on the frequency method and time finite element method, Sims et al. [15] used a fuzzy algorithm to accommodate the uncertainty in the milling process. In addition to these mentioned approaches, the time domain simulation can also be carried out [16,17] for the stability prediction, where more complicated nonlinear effects can be taken into consideration. For example, the force with a power law [18], the milling force with the edge effect [19], and the process damping effect [20] can be integrated into the dynamics and stability analysis model.

For the milling of thin-walled structure, the dynamics analysis became more difficult. Due to the varying stiffness, dynamic properties are changing along the cutting path continuously, which is different from the milling of structures with high stiffness. Besides, modal parameters may be affected by the continuous material removal effect. Campa et al. [21] used the FEM to calculate the FRFs in milling of thin floors, and the tool path is discretized to cover the material removal effect. Ratchev et al. [22] simulated the deflection of thin-walled parts during machining, where the material removal effect was modeled using "voxels". Researchers studied the process dynamics in thin wall milling from different aspects. Adetoro et al. [23] studied the stability lobes in thin wall milling by considering the nonlinearity of the cutting force coefficients. Arnadu et al. [24] numerically and experimentally studied the vibration during machining of thin-walled workpiece, based on a dynamic mechanistic model. Kolluru et al. [25] experimentally studied the coupled dynamic responses in thin wall milling. For the thin wall milling system when both machine structure and workpiece have similar dynamic behaviors, Bravo et al. [26] determined the stability based on the relative movement of the tool and workpiece. Urbikain et al. [27] studied the stability in milling thin walled workpiece with newly developed barrel cutters. Yang et al. [28] studied the thin wall milling dynamics based on the structural dynamic modification scheme. Iglesias et al. [29] analyzed the parameter domains of stability boundaries in the milling system with one dominant mode.

In addition to the characteristics mentioned earlier, another difficulty in thin wall milling come from the modelling of milling force. In the traditional milling process with a high radial immersion ratio, the main source of chatter is the regenerative effect. And the corresponding mechanism leading to instability is the secondary Hopf bifurcation. While in milling with a low radial immersion, the loss of contact effects may also have a tremendous influence, this may lead to another kind of instability in the form of period doubling bifurcation. On the other hand, the force in thin wall milling is not the tradition model only with a low radial immersion, the dynamic features may have larger influence on the milling process than that in a traditional milling process.

Thin-walled structures in an engineering application usually take the form of plates and shells. The pocket structures are commonly used in the aerospace industries, which is characterized by the internal Ribs or Spars, connecting the plates to each other [30]. The pocket structures can be theoretically classified as plates with appropriate boundary conditions. Vibration of plates are actually the structural responses under the excitation of forces. Therefore, during the finish milling process, just like the harmonic excitation for forced vibration, the milling force may be regarded as a kind of external excitation which have the characteristics of time delay. From this point of view, however, by these literature mentioned earlier, one may conclude that the thin wall milling dynamics lacks the theoretical modelling and the calculation for the vibration characteristics, just like that in the forced vibration or random vibration. Besides, this also means that the thin wall milling dynamics may be studied from two aspects, one is the structural dynamics or vibration of plates and shells, the other is the delayed dynamics or milling force models. There both exist different theories for the plate dynamics and for the milling force models respectively. For example, the classical thin plate theory [31], the Reissner-Mindlin plate theory [32], and so on. And there also is the linear and nonlinear milling forces models as summarized in the aforementioned paragraph. By combining different plate theories and milling force models, one can get different equations governing the vibration in thin wall milling. Some work studied the thin plate milling dynamics, however, limited research has been done in pocket milling. For this typical structure combination, Meshreki et al. [30] proposed a model by using the beam shape functions, where the displacement, the rotation, the bending moment and the shear force must be continuous.

For the stability analysis in thin wall milling, the literature mostly regard it as the stability composed with a series of discrete points [33,34]. Therefore, the stability lobe diagram must be calculated at different locations along the tooth cutting path. This is time consuming, especially for a thin walled structure where the higher order modes lead to a high order governing equation. In the case of occurrence of chatter in milling, it is known that the chatter frequency would be close to the natural frequencies of the machine structure [35]. For the thin walled structures, there exist multiple natural frequencies, and the chatter frequency is also modulated by the tooth passing frequency. This means that the vibration components corresponding to the modulated chatter frequencies may cause interactions between modes due to these distributed natural frequencies. This phenomenon is specific to the thin wall milling process and would be discussed in this paper.

This paper developed a model for the typical pocket structures by using the subdomain decomposition method presented in the previous research [36], and which is convenient to incorporate more plates in case of necessary. The thin wall milling dynamics is regarded as the structural vibration under the excitation of milling forces. The remainder of this paper is organized as follows. In section 2, both the vibration model for the pocket structure and the milling force model is proposed. In section 3, the simulation and experiment results are addressed. In section 4, the stability under the influence of multimode and mode coupling effect is discussed. Finally, concluding remarks are given.