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Milling stability analysis with simultaneously considering the structural mode coupling effect and regenerative effect

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ABSTRACT

Machining stability analysis is important for chatter avoidance and machining efficiency improvement. To accurately predict the stability, the chatter mechanism must be recognized. Chatter is a kind of self-excited vibrations and the two most widely used theories explaining chatter in milling are the regenerative effect and the mode coupling effect. However, these two mechanisms are always separately considered in the previous stability researches, and none of them can explain the great difference between the stability prediction results with the classical model and the experimental results in many cases. This paper investigates the structural mode coupling effect in the regenerative milling stability analysis. Based on lots of experimental data, we found that these two mechanisms actually co-exist during the practical milling process, and the usually neglected structural mode coupling effect has a great effect on the stability lobe diagram in many practical milling cases. The theoretical prediction taking the cross coupled terms into account alters the stability boundary and such prediction is verified by the chatter experimental results.

1. Introduction

Chatter stability predictions are appreciated during many machining operations in modern automotive and aerospace industry. To accurately predict the stability lobe diagram is very important to avoid the machining chatter and improve the productivity. There are vast researches about the stability prediction and various mechanisms are proposed to explain the self-excited chatter in turning and milling. The two most widely used theories are the regenerative effect and the mode coupling effect [1,2].

The regenerative effect is based on the fact that the tool cuts a surface already cut during the previous revolution, the cutting force varies as well as the chip thickness, leading to the time delay of the dynamic equation. The classical regenerative vibration model plays an essential role in machine tool vibrations. For most cases taking the regenerative effect into account, the structural mode coupling effect is neglected. The frequency response function (FRF) matrix of the most flexible structure (machine–tool) is assumed diagonal, *i.e.* the vibration modes in different directions are assumed uncoupled and the cross FRFs are considered as zeros. For the frequency domain methods [3–5], such simplification leads to the analytic expression of the solution [6]. There are also many other methods handling the stability prediction of the regenerative chatter besides the frequency domain methods, such as the time domain methods [7–12], the numerical simulation method [13,14], the semi-discretization method [15,16], the Lambert function based method [17,18], the Chebyshev collocation method [19], the full-discretization method [20], etc.

In fact, the real multiple degree-of-freedom (DOF) system vibrates simultaneously in many directions, with different amplitudes and phases, which is mode coupling. Mode-coupling instability can occur when successive passes of the tool do not overlap, and results from a particular motion of the tool relative to the workpiece in the presence of closely coupled modes of vibration of the structure. Its vibration amplitude has no fixed direction because the tool follows an elliptical path relative to the workpiece, which is different from the regenerative chatter whose vibration amplitude has a fixed direction. The mode coupled mechanism can explain the instability vibration when successive passes of the tool do not overlap, while the regenerative cannot. The theory of mode coupled demonstrates that the cutting stability of the machine tool is not only dependent on the stiffness and damping, but also influenced by the variation and orientation of the interaction of the modes, and the theory is successfully applied to some practical cases to improve the cutting stability without increasing the weight of the machine tool much [21,22].

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However, this type of instability will not be significant for conditions where successive passes of the cutting tool overlap each other [22]. Therefore, it is believed that instability usually takes place as a result of "regeneration principle" earlier than by mode coupling in most machining cases [23]. Moreover, the cross FRFs of the machine–tool structure are neglected since the coupling dynamics (cross coupled terms) are always being considered to have little influence on the cutting stability for a computer numerically controlled (CNC) machine, due to the fact that the structure stiffness is usually hundreds of times of the machining process stiffness [24].

Parallel to the research of the regenerative chatter, there are also many works on the mode coupling chatter analysis. Ismail and Vadari [25] improved their chatter performance in slotting by modifying the regular slender end mills to weaken the contribution of the mode coupling mechanism to chatter. Gasparetto [26,27] analyzed the mode coupling chatter in turning from the viewpoint of the system theory. Gallina and Trevisani [28] explored the mode coupling phenomenon using the state-space form for a wood milling process. Pan et al. [24] analyzed the mode coupling chatter of robot machining, and gave the available explanation that mode coupling chatter may happen if the structure stiffness is not significantly higher than machining process stiffness. Iturrospe et al. [29] proposed a state-space analysis method for mode coupling in orthogonal metal cutting. Hoffmann and Gaul [30] investigated the relationship between the mode coupling instability and the viscous damping of structure. In these works, the mode coupling chatter is analyzed, but the regenerative effect is neglected.

The regenerative effect and the mode coupling effect are always separately considered in the previous researches to explain the self-excited vibrations. To the best of the knowledge of the authors, there are few works in machining about the combination between the regenerative chatter analysis and structural mode-coupled chatter analysis. Kalmár-Nagy and Moon [31] examined the coupling between multiple DOF tool dynamics and the regenerative effect in turning, and the numerical simulation shows the mode-coupled nonconservative cutting tool model with time delay can produce new regions of instability. Gradisek et al. [32] conducted some numerical simulation, and the result reveals that even weak mode coupling influence the predicted stability boundary greatly.

According to lots of milling experimental results in different machine tools, we found that there is still a great difference between the stability prediction with the classical model and the experimental results in many cases, even when lots of factors are excluded, such as big cutter runout (tooth jump-out) [33,34], low speed process damping [35], big impact testing uncertainty [36], etc.

This paper investigates the milling stability with the structural mode coupling effect and the regenerative effect simultaneously and tries to explain the great difference between the stability prediction with the classical model and the experimental results. Compared with the previous stability analysis, the main contributions of the paper lie in the fact that these two mechanisms, which actually co-exist during the practical milling process, are pointed out and verified by the experimental results, and the usually neglected structural mode coupling effect is explored to have a great effect on the stability analysis in many milling cases. Therefore, the structural coupling effect needs to be considered in the regenerative milling stability analysis and such prediction agrees well with the actual milling experimental results. We consider the mode coupled effect in the regenerative chatter mainly based on the following facts:

- The regenerative chatter happens earlier than the mode coupling chatter due to the difference of machine–tool structure in each principle directions being large than the process stiffness [24]. However, in some modal testing experiment of the long flexible cutter, we notice that this condition is not always satisfied. For example, slender end mills are basically axis-symmetric structures [25], and the stiffness difference between principal directions of the machine–tool structure is likely smaller than process stiffness. In this case, mode coupling chatter happens previous to the regenerative chatter. Even if the stiffness difference between principle directions is large than process stiffness, it is at the same quantity level. That means the instability is still influenced by the mode coupling mechanism, though the instability is mainly explained by the regenerative chatter mechanism. The mode coupled mechanism still has an effect on machining process and some vibration energy is transferred by this mechanism, which may change the chatter stability domain.
- The cross coupled terms are not equal due to the nonlinear structure system of the practical machine–tool structure, which means that the modal matrix (M, C, K) are not symmetric according to some modal testing experiments, which is due to asymmetrical machine structure stiffness, asymmetrical clamping conditions, asymmetrical tool holder (spindle) structure stiffness, etc. This is different from the previous analysis about mode coupling chatter.

The structure of the paper is as follows. In Section 2, the dynamic equation of a two-DOF system with the structural mode coupling effect and the regenerative effect is given. In the stability analysis of mode coupling systems, the integration method is briefly reviewed in Section 3. The numerical simulation of milling stability is given in Section 4. The modal parameter calibration and experimental verification are given in Section 5, and some discussions are made in Section 6, especially about the response sensitivity of the stability boundary to the cross coupled terms. The conclusions are drawn in the last section.

2. Modal equation of two-DOF system

To investigate the mode coupling effect on the stability prediction, a two-DOF system is used for illustration. The vibratory model used in this work is shown in Fig. 1. To simplify the milling process dynamics and concentrate on the modeling of cross coupling effect, the tool is assumed to be flexible compared with the rigid workpiece.

The dynamic cutting mechanical model of the two DOFs is described by two-order lumped parameters equations:

$$m_x\ddot{x}+m_{yx}\ddot{y}+c_x\dot{x}+c_{yx}\dot{y}+k_xx+k_{yx}y=F_x(t),$$
$$m_y\ddot{y}+m_{xy}\ddot{x}+c_y\dot{y}+c_{xy}\dot{x}+k_yy+k_{xy}x=F_y(t). \quad (1)$$

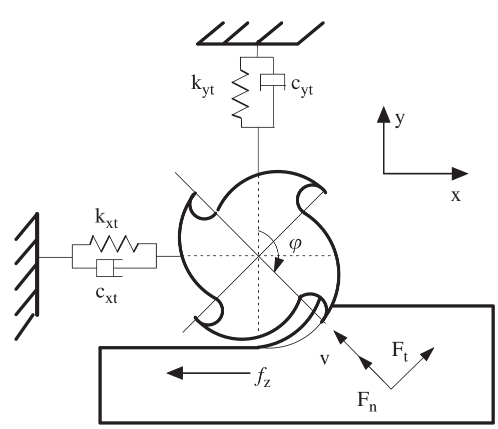

Fig. 1. Mechanical model (down-milling).