ARTICLE IN PRESS

Chinese Journal of Aeronautics, (2016), **xxx**(xx): xxx–xxx

CSAA

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Chinese Journal of Aeronautics

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Time-domain modeling of a cutter exiting a workpiece in the slot milling process

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Received 26 May 2016; revised 21 July 2016; accepted 4 September 2016

KEYWORDS

Cutting force;
Chip thickness;
Dynamic stability;
Machining;
Milling;
Vibration

Abstract In a milling operation, there must be processes of a cutter entering and exiting the workpiece boundary. The cutter exit is usually in the feed direction and the dynamic response is different from that in the normal cutting process. This paper presents a new time-domain modeling of mechanics and dynamics of the cutter exit process for the slot milling process. The cutter is assumed to exit the workpiece for the first time with one tooth right in the feed direction. The dynamic chip thickness is summed up along the feed direction and compared with the remaining workpiece length in the feed direction to judge whether the cutter is ready to exit the workpiece or not. The developed model is then used for analyzing the cutting force and machining vibration in the cutter exit process. The developed mathematical model is experimentally validated by comparing the simulated forces and vibrations against the measured data collected from real slotting milling tests. The study shows that stable cutting parameters cannot guarantee stable cutting in a cutter exit process and further study can be performed to control the vibration amplitude in this specific process.

1. Introduction

In a milling operation, there are frequent cutter entrances into and exits from a workpiece, the two most common processes in a milling operation. While extensive research has been done in the normal milling process,[1] there have been few concerns about the cutter exit process. In practical machining, manufacturers often observe vibration marks left on a machined surface where a cutter exits a workpiece, but the underneath physics is still not clear and corresponding control methods are yet to be developed.

Vibrations happening in a milling operation lead to many negative influences such as poor surface finish, unacceptable machining accuracy, an accelerated tool wear rate, and lower machining productivity. These phenomena will result in low part surface integrity of high value-added components, such as aero-engine blisks or casings. Chatter vibration, which is the most common form of vibration,[2] often occurs because

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

http://dx.doi.org/10.1016/j.cja.2016.10.014

Please cite this article in press as: Luo M et al. Time-domain modeling of a cutter exiting a workpiece in the slot milling process, *Chin J Aeronaut* (2016), http://dx.doi.org/10.1016/j.cja.2016.10.014

of the interaction between a workpiece and a milling cutter.[3,4] Since its first identification and study by Taylor[5], much research work has been done on chatter. Tobias[6] presented the first accurate model to describe self-excited vibrations in orthogonal cutting. Minis et al.[7,8] used the Nyquist criterion to solve the milling stability numerically. Altintas and Budak[9] developed an analytical solution in frequency domain to predict stability lobes, which was proven to be an effective method by experiments.[10] Insperger and Stepan[11] presented a semi-discretization (SD) method and solved the stability boundary problem in discrete time domain. Meng et al.[12] developed a novel criteria of stability analysis for a single degree of freedom (DOF) based on the approximately periodic property of the time delay in a turning process and the delay decomposition method. Ding et al.[13,14] developed a numerical integration method for milling stability prediction. In the above analysis, prediction of the dynamic chip thickness is one of the most important issues, and different chip thickness calculation methods including circular path[15] and cutter runout[16] have been developed. However, the presented research mostly focused on the normal cutting process; dynamic chip thickness calculation for the cutter exit process and vibration analysis is scarce.

As for cutter exits, published research has shown that they have great effects on burr forming.[17,18] Toh[19] studied the effects of entrance and exit of a cutter at a corner in the tool path planning stage. These research works nevertheless focused only on burr forming or its controlling rather than the dynamic response. Wanner et al.[20] studied the exit and post-exit behavior and dynamics of a cutter in milling of a thin-walled workpiece. Their research results show that a small change in the exit angle may result in a considerable improvement in the cutting behavior. Zhang et al.[21] included both the periodical excitation and the regenerative excitation in the stability analysis for milling of a thin-walled workpiece, and an effective cutting parameter optimization method was developed to assure surface location accuracy. However, the above studies mainly focused on a cutter exiting a workpiece in one revolution during a milling process, not the final exit from the workpiece. The mechanics of the cutter exit is quite different from that in the normal cutting process.

Although extensive research has been done in the normal milling process, publications on milling force modeling in the cutter exit process are scarce. This paper provides new ideas in this field. In this paper, a model for the cutter exit process from a workpiece is presented based on the regenerative chatter model.[9] Firstly, an analytical model for this specific process is introduced to estimate the exit time at a certain rotation angle. Next, the chip thickness, which has a significant effect on the dynamic milling process, is updated through the computational method depending on the exit time. The actual chip thickness is then used to analyze the cutting force and vibration during the cutter exit process. Finally, cutting experiments are carried out to validate the developed model.

2. Cutter exit process analysis

A 2-DOF milling system is shown in Fig. 1, which can be described by the model developed by Altintas et al.[22], and it can be represented by two orthogonal degrees of freedom in the X and Y directions as

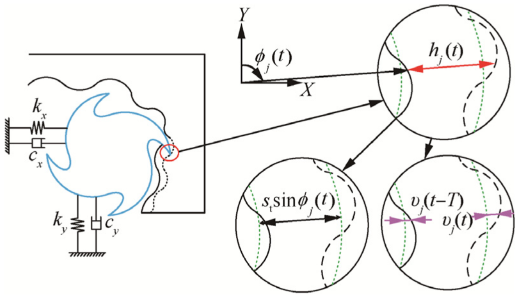

Fig. 1 Dynamic chip thickness of a 2-DOF milling system.

$$\begin{cases} m_x\ddot{x} + c_x\dot{x} + k_x x = F_x(t) \\ m_y\ddot{y} + c_y\dot{y} + k_y y = F_y(t) \end{cases} \tag{1}$$

where m, c, and k are the mass, structural damping ratio, and stiffness, respectively. While the circular tool path assumption with a low feedrate per tooth is used, the model indicates that the cutting tooth leaves a wavy surface because of the vibration between the cutter and the workpiece. When the next tooth begins cutting, it removes the wavy surface left by the previous tooth and generates a new wavy surface. Thus, the total chip thickness consists of three parts, which can be described by the following equation in terms of the static chip thickness, the vibration by the current tooth, and the vibration by the previous tooth:

$$h_j(t) = s_t \sin\phi_j(t) + \upsilon_j(t) - \upsilon_j(t-T) \tag{2}$$

where s_t represents the feedrate per tooth, and $\upsilon_j(t)$ and $\upsilon_j(t-T)$ represent the dynamic displacements generated by the vibrations caused by the current and previous tooth passes at the angular position $\phi_j(t)$, respectively.

However, when the cutter is about to exit the workpiece, the remaining workpiece length in the feed direction becomes shorter. Thus, $h_j(t)$ may be larger than the remaining workpiece length in the feed direction, and hence Eq. (2) is no longer appropriate in calculating the chip thickness. Therefore, a new model should be developed for analyzing this specific process. Since the cutter exit process is still a dynamic process, the dynamic chip thickness expressed by Eq. (2) can be used as the basis for analyzing the chip thickness during the cutter exit process.

As $\upsilon_j(t-T)$ represents the vibration caused by the previous tooth, it has left a wavy surface on the workpiece. When the current tooth rotates to the angular position $\phi_j(t)$, the wavy surface left by the previous tooth is already known. Hence, only $s_t\sin\phi_j(t)$ and $\upsilon_j(t)$ will affect the chip thickness of the current tooth. When the cutter is about to exit the workpiece, the remaining thickness in the feed direction directly affects the current chip thickness. Therefore, the cases when the cutter is going to exit the workpiece should be analyzed first.

As shown in Fig. 2, there are three possible cases for the cutter to exit the workpiece. In Fig. 2(b), when $s_t\sin\phi_j(t) - \upsilon_j(t-T)$ is larger than the remaining workpiece thickness in the feed direction and no vibration occurs, the cutter exits the workpiece along the feed direction. In this case, the feedrate has an important effect on the chip thickness. If vibration occurs in the case shown in Fig. 2(c), the chip thickness is determined by the previously left wavy surface and the feedrate per tooth, as well as the current tooth vibration. Besides,

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