Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 56 (2016) 115 – 118

www.elsevier.com/locate/procedia

9th International Conference on Digital Enterprise Technology - DET 2016 – "Intelligent Manufacturing in the Knowledge Economy Era

Effect of cutter runout on chatter stability of milling process

Yingchao Ma[a], Min Wan[a,]*, Weihong Zhang[a]

[a]*School of Mechanical Engineering, Northwestern Polytechnical University, 710072 Xi'An, Shaanxi, People's Republic of China*

* Corresponding author. Tel.: +86-029-88493914-1212; fax: +86-029-88495774. *E-mail address:* m.wan@nwpu.edu.cn

Abstract

Chatter-free cutting parameter selection is a very important topic in milling process. Thus, numerous researches have been done to predict the stability lobes of milling process. Practical milling process is always influenced by multiple modes and cutter runout which may induce multiple delays. However, in most previous work conducted in time domain, stability lobes were traditionally predicted by only selecting the most flexible mode, which inevitably loses the accuracy in some speed ranges. Especially, combined effect of multiple modes and cutter runout makes stability analysis more difficult. To this end, this paper aims at revealing the influence of cutter runout on milling stability when multiple modes occur. Numerical and experimental studies are carried out to study this issue. Prediction algorithm is established by taking into account the physical status of process. Simulated and measured results confirm that the occurrence of cutter runout can locally increase the stable region, as shown in Fig. 2. Besides, numerical studies are also conducted to investigate the combined effects of feed rate, helix angle and cutter runout.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Chatter stability; Milling process; cutter runout

1. Introduction

Milling process has been extensively applied in die components, aeronautical, astronautical and automobile parts and other products in manufacturing industry. However, the occurrence of chatter vibration will lead to poor surface finish, rapid tool wear and even damage of machine tools. Therefore, chatter-free cutting parameter selection is a very heated issue in milling process, and has been attracting numerous researchers' attention. Altintas[1-3] have done very good work and pointed out that the wave shift of the adjacent cutting surfaces may give rise to the exponentially growing chip thickness and unstable cutting process, i.e., the well-known chip-regenerative chatter. Modeling of machining chatter has been a heated topic of vast amounts of studies in literature. Altintas and Budak[2] formulated the chip regeneration and developed a zero-order approximation (ZOA) method, which proved to be efficient and analytical in determining stability lobes from the frequency domain. Later, Merdal and Altintas[4] found that the ZOA method would fail in the case of low radial immersion, and a multi-frequency solution was proposed by considering not only the average but also several harmonics of directional coefficients to overcome this shortcoming.

In contrast, time domain simulation is more powerful in predicting the stability of milling process since the kinematics of milling process, cutting mechanism and cutter geometry are reflected. Among others, Mann and co-workers[5,6] proposed a temporal finite element analysis aiming to predict stability lobes. From a numerical viewpoint, Insperger et al.[7] proposed the so-called 'semi-discretization (SD) method', which was widely adopted by the following research work. Wan et al. [8]proposed an improved and unified SD method for milling process with multiple delays, and then they employed the method to thread milling[9] and multifunctional tools[10]. Similarly, Ding[11] proposed a full-discretization method. Then, Guo et al. [12] developed a third-order full-discretization method to enhance the convergence efficiency. However, the above work mainly focused on the stability lobe construction for the ideal cutting conditions, cutter runout influence combined with feed rates ,helical angle and multiple modes effect had rarely been investigated. In this paper, the

2212-8271 © 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.10.034

authors focused on revealing the influence of cutter runout combined with feed rates and helical angle on milling stability when multiple modes occur. Experimental work has been carried out as well.

Nomenclature

K_t, K_r	Tangential and radial cutting force coefficient
a_p	Axial depth of cut
$\varphi(i\omega_c)$	Transfer function of milling system
N	Number of cutting teeth
M	Modal mass matrix of milling system
C	Damping ratio matrix of milling system
K	Modal stiffness matrix of milling system
Q	Displacement of the cutter
τ	Time delay
ρ, λ	Runout offset and its orientation angle

2. Chatter prediction with multiple delays under multiple modes

2.1. Stability limit with multiple modes

In practical milling process, the milling system is always dominated by multiple modes. According to the authors' previous study[13], the stability boundary of multiple modes dominated system can be treated as a combination of the boundaries of each single-mode case. For the completeness of description, the theoretical proof is given in brief.

According to Ref.[1], the critical axial depth of cut $a_{p,\lim}$ for chatter stability limit can be determined by

$$a_{p,\lim} = -\frac{2\pi\Lambda_R}{NK_t}(1+\kappa^2) \qquad \kappa = \Lambda_I / \Lambda_R \tag{1}$$

where Λ_R and Λ_I are the real and imaginary parts of the eigenvalue of the following characteristic equation.

$$a_0\Lambda^2 + a_1\Lambda + 1 = 0 \tag{2}$$

where the variables have same meaning with the ones in Altintas' book[1]. By solving Eq.(2), we obtain:

$$\Lambda = \frac{-1}{2\upsilon\varphi_{XX}(i\omega_c)\varphi_{YY}(i\omega_c)}\left(\begin{array}{l}\alpha_{XX}\varphi_{XX}(i\omega_c)+\alpha_{YY}\varphi_{YY}(i\omega_c)\\ \pm\sqrt{\begin{array}{l}(\alpha_{XX}\varphi_{XX}(i\omega_c)+\alpha_{YY}\varphi_{YY}(i\omega_c))^2\\ -4\upsilon\varphi_{XX}(i\omega_c)\varphi_{YY}(i\omega_c)\end{array}}\end{array}\right)$$
$$\upsilon = \alpha_{XX}\alpha_{YY} - \alpha_{XY}\alpha_{YX} \tag{3}$$

Assuming that, the milling tool-spindle assembly is a symmetric system, i.e. $\varphi_{XX}(i\omega_c) = \varphi_{YY}(i\omega_c)$, and then Eq.(4) is obtained.

$$\Lambda = \frac{\chi}{\varphi_{XX}(i\omega_c)} \qquad \chi = -\frac{\alpha_{XX}+\alpha_{YY}\pm\sqrt{\alpha_{XX}^2+\alpha_{YY}^2+2\alpha_{XX}\alpha_{YY}-4\upsilon}}{2\upsilon} \tag{4}$$

Obviously, Λ directly varies with respect to $\varphi_{XX}(i\omega_c)$ as χ in Eq. (4) is a constant for a certain cutting condition. Actually, $\varphi_{XX}(i\omega_c)$ can be rearranged as follows.

$$\begin{aligned}\varphi_{XX}(i\omega_c) &= \sum_{j=1}^{N_m}\frac{1}{-m_{X,j}\omega_c^2+2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i+m_{X,j}\omega_{X,j}^2}\\ &= \sum_{j=1}^{N_m}\frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2)-2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^4+\omega_c^4)-2m_{X,j}^2\omega_{X,j}^2\omega_c^2+4\xi_{X,j}^2\omega_{X,j}^2m_{X,j}^2\omega_c^2}\end{aligned} \tag{5}$$

Generally, $\xi_{X,j}$ is very small for a metal structure. Hence, $4\xi_{X,j}^2\omega_{X,j}^2m_{X,j}^2\omega_c^2$ can be dropped from the denominator, i.e.

$$\varphi_{XX}(i\omega_c) \approx \sum_{j=1}^{N_m}\frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2)-2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2} \tag{6}$$

Since the chatter frequency ω_c is around natural frequency of some certain mode $\omega_{X,j}$, we obtain the following equation:

$$\frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2)-2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2} \gg \sum_{\varsigma=1,\varsigma\neq j}^{N_m}\frac{m_{X,\varsigma}(\omega_{X,\varsigma}^2-\omega_c^2)-2\xi_{X,\varsigma}\omega_{X,\varsigma}m_{X,\varsigma}\omega_c i}{m_{X,\varsigma}^2(\omega_{X,\varsigma}^2-\omega_c^2)^2} \tag{7}$$

According to Eq.(7), Eq.(6) can be approximated as:

$$\varphi_{XX}(i\omega_c) \approx \frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2)-2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2} \tag{8}$$

Then, the following equation is obtained,

$$\begin{aligned}\Lambda &= \frac{\chi}{\varphi_{XX}(i\omega_c)}\\ &= \chi\frac{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2}{m_{X,j}(\omega_{X,j}^2-\omega_c^2)-2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}\\ &= \chi m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2\frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2)+2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2+4\xi_{X,j}^2\omega_{X,j}^2m_{X,j}^2\omega_c^2}\end{aligned} \tag{9}$$

Combining Eq. (9) with Eq. (6) yields

$$\begin{aligned}\Lambda &\approx \chi[m_{X,j}(\omega_{X,j}^2-\omega_c^2)+2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i]\\ &= \frac{\chi}{\varphi_{XX,j}(i\omega_c)}\end{aligned} \tag{10}$$

Because the limit axial depth of cut is determined by Λ, and Λ is proportional to the jth mode term $1/\varphi_{XX,j}(i\omega_c)$, that is to say, the limit axial depth for multiple mode case can be approximated as the one obtained by the selected single mode case. In other word, the stability lobes directly obtained from multiple modes can be approximated by the combined envelop of the stability lobes corresponding to different vibration modes. With this conclusion, a multiple modes