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Mechanistic modeling of milling process damping including velocity and ploughing effects

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Abstract

In this study, a practical method for modeling of process damping in milling process is presented. The cutting forces are decomposed into two components, i.e., the shearing and ploughing forces. The tangential and radial shearing forces are modified considering the direction changing of cutting velocity. With the assumption of small amplitude vibration, ploughing forces are simplified as linear forms through introducing equivalent viscous damper. The effect of cutting velocity and the equivalent viscous damper are integrated into milling forces model since they all have contributions to process damping. The equation governing the dynamics of the milling system is constructed to predict the stability lobe. The prediction is verified by previous researchers' experiments. It is shown that when the proposed process damping model is taken into consideration, the accuracy of stability prediction can be improved significantly at low cutting speeds.

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Keywords: Velocity effect; Ploughing force; Process damping; Stability lobes

1. Introduction

The occurrence of chatter vibration during milling process results in low precision of machining surface and even damages the machine spindle or the cutter. Therefore, selecting the chatter-free cutting parameters based on the predicted stability lobe is of great importance to achieve high material removal rate and high machining quality. The classical chatter theories can achieve good prediction of machining stability for relatively high speed cutting process. However, the critical depth of cut predicted by the classical metal cutting theories is much lower than the experimental values at low cutting speeds, since the additional damping generated in low speed cutting process will enhance the stability.

Das and Tobias[1] expressed the traditional regenerative cutting force considering velocity effect. This modified cutting model only considers the change of direction in the velocity term and does not consider flank contact. Wu[2,3] assumed that the ploughing forces caused by this flank contact are linearly proportional to the total volumes of the displaced material. He also calculated the total indented volume by establishing the relationship between the volume and the tool position. Chiou and Liang[4] simplified the indented volume as a linear model and analyzed chatter stability, it was shown that ploughing forces of worn cutters have positive damping effects that stabilize the cutting systems. Huang and Wang[5] extended the cutting force model including two cutting mechanisms and two process damping effects. Altintas et al.[6] identified the dynamic cutting force coefficients with a fast tool servo, and demonstrated that the process damping coefficient increases as the tool is worn. Recently, Ahmadi et al.[7,8] presented a new method in predicting the material dependent indentation coefficient using output-only modal analysis, and solved the stability of milling in frequency and discrete-time domain.

In this paper, the process damping is mainly consisted of the velocity and ploughing effect. The effect of cutting velocity and the equivalent viscous damper are integrated

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into milling forces model. Small amplitude vibration assumption is used to simplify the model. The stability of milling with process damping can be solved using updated semi-discretization method. For the machining process with damping effect, the predicted stability lobe is validated by the existing experiments from previous researchers' works.

Nomenclature

K_t, K_r	tangential and radial cutting force coefficient
N	tooth number
i	index number of the tooth
a	axial depth of cut
$F_{t,s}$, $F_{r,s}$	theoretical tangential and radial shearing forces
$F_{t,p}$, $F_{r,p}$	tangential and radial ploughing forces
h_s, h_d	static and dynamic uncut chip thickness
V	indented volumes
t	cutting instant time
τ	tooth passing period
l_w	tool wear land length
v_c	cutting speed
K_{sp}	indentation constant
μ	friction coefficient
S	extruded area under flank face
s_t	feed rate of the cutter, mm/tooth

2. Dynamic Milling Model Considering Process Damping

The total cutting forces in dynamic milling process are mainly consisted of two components, i.e., the shearing forces on the rake face and the ploughing forces on the flank face. The shearing force acts on the shear plane, and the ploughing force is a result of the extrusion and friction between the flank face of tool and machining surface.

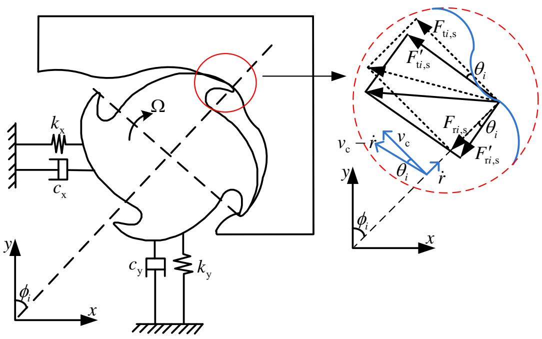

Fig. 1. Process damping due to the velocity effect.

The schematic of a simple model of milling with the velocity effect is given in Fig. 1. The direction of the actual tangential shearing force $F'_{ti,s}$ varies when the tool-workpiece structure vibrates during the cutting process. The actual tangential shearing force is along the direction of cutting velocity, while there is an angle θ_i between the cutting velocity and tangential direction of the cutter. So the theoretical tangential shearing force, which is along the tangential direction of the cutter, is not same as the actual tangential shearing force. The slope of this cutting trajectory is

$$\sin(\theta_i(t)) \approx \tan(\theta_i(t)) = \dot{r}_i(t)/v_c \tag{1}$$

where $\dot{r}_i$ is the vibration velocity, which is coupled in two direction, and can be expressed as

$$\dot{r}_i(t) = \dot{x}(t)\sin(\phi_i(t)) + \dot{y}(t)\cos(\phi_i(t)) \tag{2}$$

The actual shearing forces which are determined by the cutting coefficients, the chip thickness, and the depth of cut, are resolved in the tangential and radial directions of the cutter, and the theoretical dynamic shearing forces can be written as

$$\begin{aligned} F_{ri,s} &= [K_r ah\cos(\theta_i(t)) + K_t ah\sin(\theta_i(t))]g(\phi_i(t)) \\ F_{ti,s} &= [K_t ah\cos(\theta_i(t)) - K_r ah\sin(\theta_i(t))]g(\phi_i(t)) \end{aligned} \tag{3}$$

where $\phi_i(t)$ is the angular position of the ith cutting edge. The window function determining whether the tooth is in or out of cut is expressed as

$$g(\phi_i(t)) = \begin{cases} 1 & \phi_{st} \le \phi_i(t) \le \phi_{ex} \\ 0 & otherwise \end{cases} \tag{4}$$

The uncut chip thickness is consisted of the static and dynamic part

$$h = h_{si} + h_{di} \tag{5}$$

with

$$h_{si} = s_t\sin(\phi_i(t)); \quad h_{di} = r_i(t) - r_i(t-\tau) \tag{6}$$

where $r_i(t)$ and $r_i(t-\tau)$ are the dynamic displacements of the cutter at the present and previous tooth periods, respectively.

The magnitudes of the slope of the wavy surface and the dynamic chip thickness are smaller compared with $\cos(\theta_i(t))$ and the static chip thickness, respectively. By substituting Eq. (5) into Eq. (3) and neglecting the high order terms $h_{di}\sin(\theta_i(t))$, the dynamic shearing forces can be simplified as follows:

$$\begin{aligned} F_{ri,s} &\approx [K_r a(h_{si} + h_{di}) + K_t ah_{si}\sin(\theta_i(t))]g(\phi_i(t)) \\ F_{ti,s} &\approx [K_t a(h_{si} + h_{di}) - K_r ah_{si}\sin(\theta_i(t))]g(\phi_i(t)) \end{aligned} \tag{7}$$

The above discussion is for the influence of velocity changing of shearing forces. When considering ploughing effect, we assume that the ploughing forces are proportional to the volume of material extruded under the flank face of the tool as following equations[2,3]:

$$F_{ri,p} = K_{sp}\cdot V; \quad F_{ti,p} = \mu F_{ri,p} \tag{8}$$