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Effects of cutting conditions on dynamic cutting factor and process damping in milling

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ABSTRACT

This paper investigates how cutting conditions affect dynamic cutting factor and system process damping in a dynamic milling process. By considering variation of edge plowing force, a frequency domain method is presented to identify the dynamic cutting factor through measured vibration in a milling process, and cutting conditions most suitable for the identification experiments are also discussed. A series of experiments are carried out to investigate the effects of cutting conditions on the dynamic cutting factor. This factor is shown to be significantly affected by the cutting speed, but relatively independent of the feed per tooth and the radial depth of cut. An average process damping model is further constructed and shown to be effective in representing the time-varying damping function. The average process damping is shown to increase rapidly at lower cutting speed, but remain constant as the cutting speed beyond a critical value.

1. Introduction

Cutting vibration adversely influences the tool life and the productivity, and damping is one of the important factors affecting the vibration amplitude and machining stability. In a cutting system, the source of damping can be mainly classified into two types: the structural damping due to the workpiece, tool, holder and other parts of the machine tool system, and the process damping arising from the machining process itself. The structural damping expends only part of the vibration energy with the rest dissipated through cutting process damping. Due to complexity of the process damping mechanism, many studies used simplified models excluding process damping to analyze machining stability, but found that their simplified models suffer from large errors especially at low cutting speeds. Tlusty and Ismail [1] indicated that the variation of the plowing force in the tool flank is the main source of process damping. Several studies have tried to model this damping mechanism. Jemielniak and Widota [2] assumed that the plowing force is a function in terms of clearance angle and vibration velocity, and predicted the phenomenon of higher machining stability at low cutting speeds. Tarng et al. [3] used Jemielniak and Widota's model to investigate the effects of tool geometries on the machining stability in a two-dimensional turning system. In different ways to model the plowing force, Wu [4] assumed the plowing force to be proportional to the interference volume between the tool flank and the machined surface, but Montgomery and Altintas [5] considered the plowing force to be proportional to the workpiece's yield strength and the interference contact area between the tool flank and the machined surface. However, Elbestawi et al. [6] found that the models given by [4] and [5] both resulted in higher predicted stability limits at high cutting speeds; Wu's model has been modified in [6] by incorporating tool flank wear into the milling dynamics and a more accurate prediction of the stability limit has then been reported.

In milling process, the cutter position and chip thickness change constantly and more than one tooth could be involved in the cutting process, and the effect of cutting condition on the overall damping becomes complicated. Models in [5] and [6] have relied on numerical methods to simulate the complicated process damping forces and predict the milling stability. Without relying on numerical integration and iteration, Huang and Wang [7] presented an analytical process damping model to provide a better insight into the roles of different mechanisms in process damping in milling. Four types of damping mechanism were considered in their model including direction-shearing, direction-plowing, magnitude-shearing and magnitude-plowing damping mechanisms. The direction effect is related to vibration energy dissipation due to directional variation of cutter/workpiece relative motion. The magnitude effect is associated with change in force magnitude due to variation of rake angle and clearance angle. Four dynamic cutting factors were defined to represent the influence of these mechanisms on the damping

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Nomenclature

α, N, R, D cutter helix angle, flute number, cutter radius and cutter diameter
β, β_a radial angular position of cutting point on the cutter and radial angle of axial immersion
C proportional constant between cutting speed and the dynamic cutting factor
$\mathbf{c_{mp}}$ process damping function matrix for magnitude-plowing process damping
c_{mpxx}, c_{mpxy}, c_{mpyx}, c_{mpyy} process damping functions for magnitude-plowing process damping
C_{mpxx}, C_{mpxy}, C_{mpyx}, C_{mpyy} average process damping functions for magnitude-plowing process damping
$C_{mp[n]}$, $F_{[n]}$, $U_{[n]}$, $V_{[n]}$ Fourier coefficients of magnitude-plowing process damping, nominal force, displacement and velocity
cwd chip width density function
d_a, d_r axial and radial depths of cut
db chip width
$\boldsymbol{df_{s0}}$, $\boldsymbol{df_{p0}}$, $\boldsymbol{df_{s1}}$, $\boldsymbol{df_{p1}}$ nominal shearing, nominal plowing, instant shearing and instant plowing forces
$\boldsymbol{df_{ds}}$, $\boldsymbol{df_{dp}}$, $\boldsymbol{df_{ms}}$ $\boldsymbol{df_{mp}}$ direction-shearing, direction-plowing, magnitude-shearing and magnitude-plowing damping forces
df_t, df_r local dynamic cutting forces in tangential and radial directions
df_x, df_y local dynamic cutting forces in x and y directions
$\boldsymbol{f_s}$, $\boldsymbol{f_p}$ nominal shearing and nominal plowing force vectors
f_{su}, f_{pu} nominal shearing and nominal plowing forces
f_x, f_y cutting forces in x and y directions
f_n structure resonant frequency
γ_0 nominal rake angle
H_n structural dynamic stiffness function
η_0 nominal clearance angle
ϕ cutter angular displacement
k_{ts}, k_{ts0} dynamic and nominal tangential cutting coefficients for the shearing mechanism
k_{rs} radial cutting coefficient for the shearing mechanism
k_{tp}, k_{tp0} dynamic and nominal tangential cutting coefficients for the plowing mechanism
k_{rp} radial cutting coefficient for the plowing mechanism
κ dynamic cutting angle
k, n orders of Fourier coefficients
λ vibration wave length
m_x, c_x, k_x modal mass, damping and stiffness of the workpiece in x direction
m_y, c_y, k_y modal mass, damping and stiffness of the workpiece in y direction
μ_s, μ_p dynamic cutting factors for the shearing and plowing mechanisms
$\mathbf{p_{mp}}$ elementary cutting function matrix for magnitude-plowing process damping
p_{mp1}, p_{mp2}, p_{mp3}, p_{mp4} elementary cutting functions for magnitude-plowing process damping
P_{mp1}, P_{mp2}, P_{mp3}, P_{mp4} average elementary cutting functions for magnitude-plowing process damping
$\boldsymbol{p_s}$, $\boldsymbol{p_p}$ elementary cutting function vectors for nominal shearing and nominal plowing forces
θ, θ_1, θ_2 angular position of the cutting point in the workpiece, entry and exit angles
t_c chip thickness function
ts tooth sequence function
t_x feed per tooth
v_c, v_r, v_t cutting velocity as well as relative radial and tangential velocity
w cutting window function
ω_0 angular velocity of tooth passing frequency
Ω spindle rotation frequency in Hz
x, $\dot{x}$, $\ddot{x}$ displacement, velocity and acceleration of the workpiece in x direction
y, $\dot{y}$, $\ddot{y}$ displacement, velocity and acceleration of the workpiece in y direction

force magnitude. A time domain method was proposed to identify the dynamic cutting factors through the vibration signals of the milling process. Their experimental result showed that the magnitude-plowing mechanism is the most significant and about ten times larger than other three mechanisms in milling Al6061-T6 at the cutting speed of 100 m/min, and that the dynamic cutting factors vary with cutting conditions. However, the effects of cutting conditions on the dynamic cutting factors and the overall system damping were not investigated. Moreover, the time domain method for the identification of dynamic cutting factor is not robust enough since the vibration signals are easily contaminated by the measurement noise, bias and drift.

The component of the total cutting force caused by vibration can be decomposed into two orthogonal components with respect to the direction of the vibration—one in line with and the other orthogonal to the vibration vector. The orthogonal component is in line with the displacement vector and reflects the force variation caused by vibration-induced chip thickness change. This component will affect the nominal magnitude of the shearing and plowing force coefficients, and is not considered in this paper. This paper concentrates on the in-line component of the force variation, which is associated with the vibration term and is defined as the process damping force. An in-phase in-line component as indicated by a positive dynamic cutting factor will bring the same dissipative effect as a structural damping while an out-of-phase component, indicated by a negative dynamic cutting factor, presents an undesirable negative damping effect to the system. For the milling conditions investigated so far, the process damping is found to be positive; therefore, the vibration-related force variation shows the positive or dissipative damping effect [7].

Based on the process damping model in [7], this paper first presents an improved method to identify the dynamic cutting factor. Only the vibration signal at the specific frequencies sensitive to the process damping is used in this method. Based on this new method, a series of milling experiments are then carried out to investigate the effect of cutting conditions on the dynamic cutting factor as well as on overall process damping.

2. Analysis of milling dynamics

The local cutting forces can be written as the sum of the shearing and plowing forces through their respective cutting coefficients in the tangential and radial directions [8]

$$\begin{Bmatrix} df_t \\ df_r \end{Bmatrix} = \begin{Bmatrix} 1 \\ k_{rs} \end{Bmatrix} k_{ts} t_c db + \begin{Bmatrix} 1 \\ k_{rp} \end{Bmatrix} k_{tp} db \quad (1)$$

where df_t and df_t are tangential and radial local cutting forces; t_c is the chip thickness and db the chip width; k_{ts} in MPa and k_{tp} in N/mm are the shearing and plowing cutting coefficients in the