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Investigation of process damping effect for multi-mode milling systems

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Abstract

Process damping acts as a significant cause of increased stability in milling particularly at low cutting speeds, which has been studied only for single-mode systems in the literature. Chatter frequency, which depends on the component causing chatter, strongly influences process damping coefficient, which is expected to vary with modes of the system. In this paper, the effect of process damping on chatter stability is investigated considering multi-mode dynamics of the system. The process damping coefficients are simulated for the fundamental chatter frequency of each significant mode and then used in the stability solution in frequency domain. An iterative milling stability solution is used as the process damping coefficients depend on the cutting depth. The stability lobe diagram is constructed with respect to multiple mode characteristics of the system. The theoretical predictions are verified through representative experimental cases and the results are discussed.

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Keywords: process damping; regenerative chatter, multi modes; milling

1. Introduction

Milling is a commonly used metal cutting process in manufacturing industry. Post-milling operations are required if the desired roughness of machined surface or dimensional accuracy is not achieved, which are mostly influenced by chatter vibration. Thus, prediction of chatter-free cutting conditions is of great importance in machining industry.

Tobias [1] studied the regenerative mechanism and represented it as a function of depth of cut and spindle speed using the stability lobe diagrams. In another early work, Tlusty [2] proposed a stability formulation for end-milling. He adapted the turning formulation to end-milling by taking average number of cutting edges in cut per revolution. Later, Minis and Yanushevsky [3] determined the stability limits using Nyquist stability criterion. The first comprehensive analytical method to predict stable cutting depth and its relation to the spindle speed in end-milling was proposed by Altintas and Budak [4]. They developed zeroth-order approximation method and showed its efficiency in obtaining stability lobes in frequency domain. Tang et al. [5] presented a stability prediction method for high-speed finishing end milling considering multi-mode dynamics. When the system has multiple dominant modes, the stability behavior varies due to interaction among modes [6]. In a recent research, Wan et al. [7] studied the milling system stability with multiple dominant modes. It was theoretically proved that the stability border for a multi-mode system can be effectively predicted by the lowest envelop of the stability lobes constructed for each single mode separately.

Difficult to machine materials such as nickel, titanium, and stainless steel alloys need to be cut at relatively low cutting speeds, causing substantial decrease in material removal rates. However, this may be compensated by the increased stability limits at low cutting speeds with the effect of process damping [8]. Process damping mainly arises from the interaction between the flank face of the cutting edge and the undulations left on the workpiece surface.

The effect of process damping on stability has been studied by several authors in the literature. In an early study, Sisson

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and Kegg [9] tried to find an explanation for chatter behavior at low speeds which is consistent with published experimental observations. Das and Tobias [10] introduced a velocity term into the equations of motion to mimic the process damping effect leading to increased stability limits. Later, there have been significant efforts on modelling of process damping effect considering the tool-workpiece interaction [8]. Chiou et al. [11] developed a model in which process damping force was assumed to be proportional to volume of deformed material beneath the flank face of the tool. In another work, Altintas et al. [12] presented a cutting force model including three dynamic cutting force coefficients related to regenerative chip thickness, velocity and acceleration terms. They used Nyquist criterion to solve stability of the dynamic process. Huang and Wang [13] extended cutting force model to include the effect of process damping and investigated process damping mechanism through time domain simulations. In a recent work, Tunc and Budak proposed a practical process damping identification method for milling using inverse stability solution approach [14]. In this method, the process damping coefficients are identified from experimental stability limits and are further used in identification of the indentation constant and modeling of process damping. They showed that, once the indentation constant is identified, stability limit for different tool geometries and cutting conditions can be predicted, as well. In another identification method [15], the process damping coefficient was predicted from frequency domain decomposition of vibration signal in stable cutting region.

In the literature, the process damping models considered only one dominant mode. However, contribution of multiple modes at distinct natural frequencies may lead to different outcomes as process damping is considered. The effects of fundamental vibration frequency, vibration amplitude, cutting conditions and tool geometry on process damping have been discussed by Tunc and Budak [14] . It was concluded that the process damping effect significantly diminishes at low frequency modes due to the decreased tool-workpiece interaction. This is an important conclusion for multi-mode milling systems, where multiple modes having comparable amplitudes may exist. In such cases, while the expected chatter at higher frequency mode is suppressed by process damping, the low frequency mode may cause chatter, as it may not be suppressed. In this study, process damping effect on stability limits for a multi-mode milling system has been investigated. It is shown that if multiple modes are ignored in prediction of process damping, the stability limits at low frequencies are not predicted accurately. In the experiments, it was observed that after a critical cutting speed region, the chatter mode might shift to the lower frequency mode contrary to theoretical expectation. Henceforth, the paper is organized as follows; the dynamics and stability of milling system with process damping is briefly given in section 2. Then the estimation of process damping coefficients is explained in section 3, which is followed by constructing stability lobe diagrams for multi-mode systems in section 4. The experimental study is presented in section 5, and conclusions are given in section 6.

Nomenclature

m	modal mass
k	modal stiffness
c^s	structural damping coefficient
c^p	process damping coefficient
a_{lim}	stability limit
Λ_I	real part of the eigenvalue
Λ_R	imaginary part of the eigenvalue
N	number of cutting tool teeth
K^d	indentation constant
U(t)	indentation area

2. Dynamics and stability of milling with process damping

The stability of the multi-mode milling system is considered for each mode separately, where stability diagram of each mode with the effect of process damping is simulated. This approach is valid if the modes of the system are well-separated [7]. In this section, the dynamics of single-mode milling system with the process damping term is briefly presented. The equations of motion of milling system are followed by the frequency domain solution of the stability limits [4].

2.1. Equation of Motion

The cross section of a helical end mill, which is flexible in x and y directions with N number of cutting flutes is illustrated in Fig. 1. As the cutter rotates, the cutting tooth indents into the wave left on the surface by the previous tooth. Correspondingly, indentation forces arise in tangential and radial directions on the tool flank face, creating a damping effect. For this system, the equations of motion with the effect of process damping can be written in x and y directions as:

$$\begin{matrix} m_{x,i}\ddot{x} + c_{x,i}^t\dot{x} + k_{x,i}x = F_x; & c_{x,i}^t = c_{x,i}^s + c_{x,i}^p \\ m_{y,i}\ddot{y} + c_{y,i}^t\dot{y} + k_{y,i}y = F_y; & c_{y,i}^t = c_{y,i}^s + c_{y,i}^p \end{matrix} \quad i = 1, \dots, N_t \qquad (1)$$

Where m, c^s and k are the modal mass, structural damping, and stiffness of the system, and c^p indicates the average process damping coefficient in each direction, respectively. N_t stands for the number of dominant modes of the system.

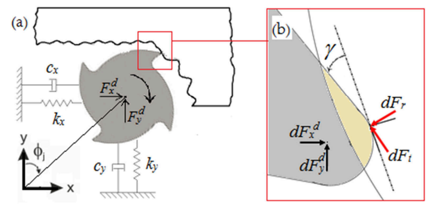

Fig. 1. Dynamic milling with process damping. (a) cross section of a helical end mill, (b) flank-workpiece interaction.

2.2. Milling stability with process damping

After organizing the equations of motion in the frequency domain and solving the eigenvalue problem [4], the stable