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Analysis of Process Damping in Milling

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Abstract

Regenerative chatter has been identified as one of the major limitations on achieving higher material removal rates in milling. There are numerous studies in the literature in which various time and frequency domain models have been developed and successfully employed to predict stability boundaries for different milling operations. However, many of these studies have neglected the dynamics of tool – workpiece interaction that describes process damping. As this interaction becomes prominent at low speeds, it enables substantially higher chatter-free depths that would be of great importance especially for difficult-to-cut alloys. In this study, an alternative process damping model has been presented for flat-end milling on the basis of an equivalent viscous damping approach. Parameters included in the process damping model are cutting speed, vibration amplitude, wear land width and clearance angle. Computed stability diagrams show an agreement with cutting tests which were carried out on Ti6Al4V. The model demonstrates strong dependence to vibration amplitude. Also, it is shown that the spindle's low-frequency vibration mode governs the dynamics of process damping at low speeds.

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Keywords: regenerative chatter; process damping; milling

1. Introduction

In milling, productivity is generally associated with material removal rate (MRR) which is defined as the product of radial depth, axial depth, number of flutes, spindle speed and feed rate. The ultimate objective of a process planner is to maximise the MRR without violating constraints such as tool life, surface quality and form errors. Unfortunately, it is not feasible to achieve this by going through trial and error process. On the other hand, investigation of process dynamics offers valuable solutions on the scientific basis and enables substantial improvements in MRR.

From the perspective of dynamics, instability in machining or so-called as chatter has been one of the major limitations on productivity. There have been various studies in literature focused on understanding, detection and prediction of chatter vibrations in milling. Developed methods are successful to an extent in obtaining maximum chatter-free depths when cutting at higher speeds however experimental data indicate that simulations tend to under predict stability limits as cutting speed decreases. This is caused by the process damping phenomenon that suppresses chatter and is mostly observed at low speeds. Including the process damping into dynamic milling model is critical for machining of difficult-to-cut materials such as titanium and nickel alloys since cutting speed is inherently limited due to tool wear for these alloys. If the maximum depth of cut allowed by the process is correctly determined at low speeds, the productivity lost due to inability of cutting faster can be regained, and this is much appreciated by the machining industry.

Sisson and Kegg [1] were one of the earliest who noticed through experimental studies that the main cause of the increase in damping at low speeds is due to the contact between cut surface and tool flank face. They also discovered that the use of worn cutting edge and reground flank would improve the process stability. These findings were confirmed afterwards by the significant experimental effort conducted by several researchers [2, 3] to introduce process damping into

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analytical stability models within the complex part of dynamic cutting force coefficients. Although this calibration method would facilitate the modeling, Tlusty [3] argued that there were inconsistencies in results even when a standardized set-up had been used. These were mainly attributed to the difficulty in instrumentation. Later on, Tlusty and Ismail [4] established a relationship between surface waviness and process damping which has been used for years as the most practical measure of the process damping performance. As given in Eq. (1) this relationship states that as cutting speed decreases or vibration frequency increases, cut surface becomes steeper and this in turn enlarges the contact area with tool flank and leads to more energy dissipation. On the assumption of harmonic tool vibration, L_c is the wavelength of the cut surface, f is the vibration frequency and V_c is the cutting speed here.

$$L_c = \frac{V_c}{f} \tag{1}$$

Wu [5] developed an indentation force model in which energy loss due to process damping is described by the ploughing forces acting in the tool-workpiece interference. Applying an empirical constant, normal component of the ploughing force is related to the material displaced under tool flank. For tangential component, an average coefficient of friction based on Coulomb Law was assumed between tool and cut surface. Elbestawi et al. [6] adapted Wu's approach into 2-DOF dynamic milling model in order to simulate the ploughing forces and their contribution to stability. Despite that time-domain simulations and experimental results point out a good agreement, authors did not present any direct solution which could be used to predict stability limits.

On the basis of Wu's indentation force model, Ahmadi and Ismail replaced [7] process damping coefficients by linear viscous dampers in the way described in [8] and included them into multi-frequency and semi-discrete solutions of dynamic milling on the assumption of low amplitude vibration.

Tunc and Budak, in connection with their previous research [9-11], recently proposed an inverse stability method for milling in which average process damping coefficients are determined experimentally by deducting structural damping from the total damping [12]. These coefficients are then calibrated iteratively in the forward stability algorithm with respect to cutting conditions and tool geometry.

In this paper, using the equivalent viscous damping approach, process damping in milling is modeled as a function of surface wavelength and included into analytical stability solution. Fundamentals of the approach and parameters used in the model are explained in Section 2. Inclusion of process damping into dynamic milling model and computation procedure of the stability lobes are described in Section 3. Experiment set-up involving impact testing and slotting trials performed on Ti6Al4V are described in Section 4. Discussions on the comparison of computed stability lobes to experimental results are made in Section 4 and 5 respectively.

2. Representation of Process Damping

2.1. Indentation Force Model

It is believed that the primary mechanism of process damping is the ploughing force that occurs due to tool-workpiece contact. The indentation force model developed by Wu [5] relates the components of ploughing force to the volume of material compressed by tool flank into cut surface. If the width of cut b is assumed to be constant, the indentation volume V_i can be expressed as,

$$V_i(t) = bA_i(t) \tag{2}$$

where A_i is the indentation area. In order to derive the normal component of ploughing force F_n^d, the indentation volume is calibrated as follows, using an indentation coefficient K_i which incorporates material properties of tool and workpiece.

$$F_n^d(t) = K_i V_i(t) \tag{3}$$

Assuming an average coefficient of friction μ, the tangential component F_n^t is then expressed as below.

$$F_t^d(t) = \mu F_n^d(t) \tag{4}$$

It can be seen from equations (2-4) that the essential term behind the ploughing mechanism is the indentation area. It can be computed either analytically (by approximating the geometry of indentation) or numerically as described in the following section.

2.2. Computation of Indentation Area

It is a well-known fact that the tool vibrates at a frequency close but not equal to one of its dominant vibration modes under the onset of chatter. In addition, Sims and Turner [13] reported that when process damping becomes prominent over the regenerative vibration, the tool oscillates in a limit cycle. It is therefore reasonable to assume that the tool vibration is harmonic and for one vibratory cycle and it can be defined in Cartesian coordinates as in Eq. (5). Here, A_c is the vibration amplitude, L_c is the wavelength.

$$y(x) = A_c \sin(\frac{2\pi}{L_c} x) \tag{5}$$

It should be noted that as the vibrating tool leaves its imprints onto surface being cut, Eq. (5) also describes the toolpath. As illustrated in Fig. 1, within the boundaries in which slope of the path dy/dx is negative, the tool is said to indent the workpiece surface and ploughing forces acting on the tool flank start dissipating the vibratory energy. As the path is sinusoidal, boundaries can be easily found as $L_c/4$ and $3L_c/4$.