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Technical note

Radial depth of cut stability lobe diagrams with process damping effects

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ABSTRACT

This paper describes a method to produce analytical radial depth of cut stability lobe diagrams that include process damping. The stability limit was defined using the radial, rather than axial, depth due to the path planning approach for many computer-aided manufacturing (CAM) programs, which remove material layer-by-layer with a varying radial immersion. Experimental validation of the predicted stability limits was performed and the results are presented for both the process damping (low cutting speed) range and higher cutting speeds.

1. Introduction

Milling instability, or chatter, is one factor that limits material removal rates because the stable depth of cut is restricted by the system dynamics. Using the well-known stability lobe diagram, however, preferred (or "best") spindle speeds may be selected that enable the depth of cut to be increased [1–4]. These speeds occur at tooth passing frequencies that are integer fractions of the natural frequency that corresponds to the most flexible structural mode of vibration. Larger stable depths of cut are generally obtained at higher "best" spindle speeds.

A second primary limitation to high material removal rates is tool wear. Because diffusive tool wear is temperature-driven and higher cutting speeds lead to increased cutting temperatures, hard-to-machine materials may cause the higher "best" spindle speeds which provide access to increased depths of cut to be inaccessible due to unacceptable wear rates. Together, chatter and tool wear combine to increase machining costs and are, therefore, the subject of widespread modeling and experimental efforts.

One beneficial phenomenon that occurs at low spindle speeds (cutting speeds) and increases the allowable depth of cut is process damping. Many prior process damping studies have identified it as energy dissipation due to interference between the cutting tool clearance face and machined surface during relative vibrations between the two [5–24]. Because process damping enables increased material removal rates at low cutting speeds, it is an important consideration when modeling machining operations for hard-to-machine materials.

The purpose of machining models is to select optimal operating parameters at the process planning stage. For modern job shops, process planning begins with a solid model of the part to be machined. A computer-aided manufacturing (CAM) software package is then implemented to generate a computer-numerically controlled (CNC) part path from the solid model. For milling operations, the tool geometry, spindle speed, and feed per tooth must be specified in the CAM software. Additionally, the axial depth of cut and radial step-over must also be selected. Because material is often removed layer-by-layer, the axial depth of cut is fixed and the radial depth of cut is defined by the selected step-over. For internal pocketing operations, the radial depth varies with the tool location within the pocket for traditional path definitions, such as the spiral in strategy. In 90 deg corners, for example, the radial depth increases to an instantaneous value equal to the tool diameter regardless of the commanded step-over. For this reason, it is often desired to determine the limiting radial depth of cut as a function of spindle speed for a fixed axial depth; prior

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analytical efforts are described in [25,26]. However, traditional stability analyses assume a fixed radial depth and identify the maximum chatter-free axial depth for the selected range of spindle speeds.

The objective of this paper is to include the effects of process damping in a stability lobe diagram that describes the limiting radial depth of cut as a function of spindle speed. The work is particularly relevant for defining hard-to-machine material part programs. An analytical milling stability model that includes process damping [22–24] is applied to generate spindle speed versus axial depth stability limits for multiple radial depths. These limits are then combined automatically to identify the corresponding spindle speed versus radial depth stability lobe diagram for the selected axial depth. The paper is organized as follows. First, a review of the process damping model is provided. Second, the algorithm for identifying the required stability limit is described. Third, experimental results are provided. Finally, conclusions are presented.

2. Process damping

In descriptions of regenerative chatter in machining, the variable component of the instantaneous cutting force may be written as $F = K_s b(N_0 - N)$, where K_s is the specific cutting force, b is the chip width, N_0 is the vibration amplitude in the surface normal direction, n, from the previous cutting pass, and N is the current vibration amplitude. The underlying assumption in the force equation is that there is no phase shift between the variable force and chip thickness; this is indicated by the real values of K_s and b. However, for low cutting speeds, V, it has been shown that a phase shift can occur. This behavior is captured by the phenomenon referred to as process damping. Practically speaking, the effect of process damping is to enable significantly higher chip widths at low cutting speeds than linear stability analyses predict.

The process damping force in the n direction can be expressed as a function of velocity, chip width, cutting speed, and a constant C [21]: $F_d = -C\left(b/V\right)\dot{n}$. This process damping force was incorporated in Tlusty's stability algorithm in [22–24]. Tlusty's analytical stability solution assumes an average angle of the tooth in the cut, ϕ_{ave}, and, therefore, an average cutting force direction [3]. This assumption produces an autonomous, or time invariant, system. Tlusty then defined directional orientation factors, μ_x and μ_y, to first project the average angle force into the x and y mode directions and, second, project these results onto the surface normal (in the direction of ϕ_{ave}). The limiting axial depth of cut, b_{lim}, and spindle speed, Ω, expressions for milling are provided in Eqs. (1) and (2), where G_{or} is the oriented frequency response function that depends on the directional orientation factors and the frequency responses in the x and y directions, f_c is the chatter frequency, N is the number of complete vibration periods between teeth (i.e., the lobe number), N_t is the number of teeth on the cutter, and $N_t{}^*$ is the average number of teeth in the cut; see Eq. (3), where ϕ_s and ϕ_e (deg) are the start and exit angles defined by the radial depth of cut. The fractional phase between the vibrations from one tooth to the next, ε, is defined in Eq. (4).

$$b_{lim} = \frac{-1}{2K_s Re\left[G_{or}\right] N_t{}^*} \tag{1}$$

$$\frac{f_c}{\Omega N_t} = N + \frac{\varepsilon}{2\pi} \tag{2}$$

$$N_t{}^* = \frac{\varphi_e - \varphi_s}{360/N_t} \tag{3}$$

$$\varepsilon = 2\pi - 2\tan^{-1}\left(\frac{Re\left(G_{or}\right)}{Im\left(G_{or}\right)}\right) \tag{4}$$

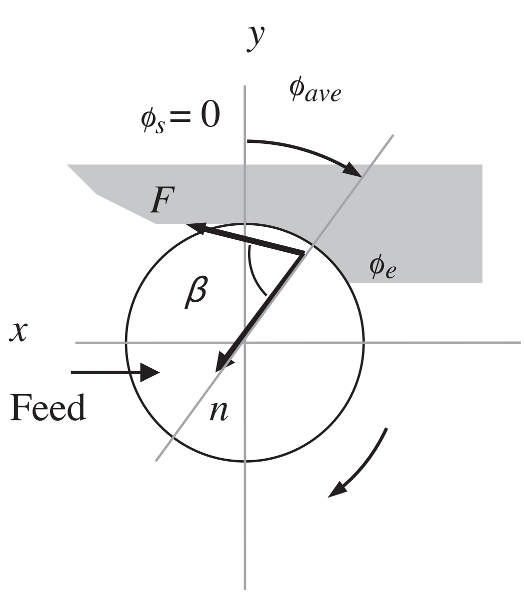

Fig. 1. Up milling geometry.

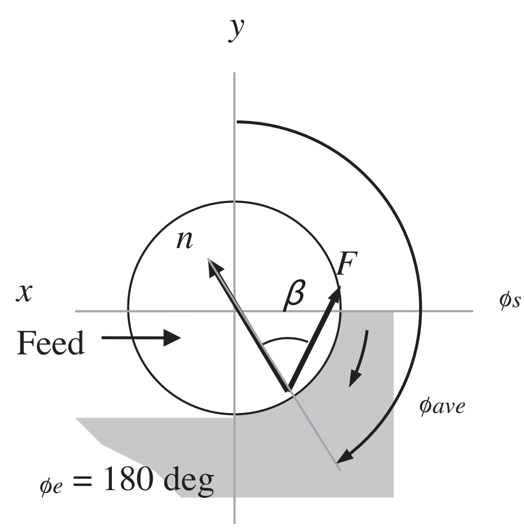

Fig. 2. Down milling geometry.

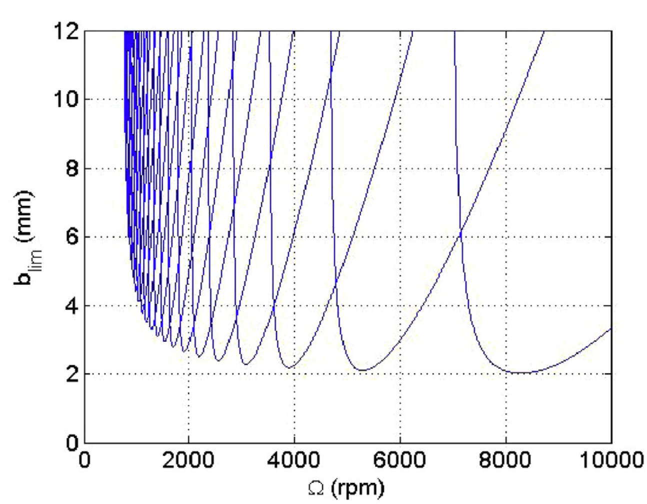

Fig. 3. Limiting axial depth of cut versus spindle speed for a 25% radial immersion.