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Design of irregular pitch end mills to attain robust suppression of regenerative chatter

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ABSTRACT

This paper presents a design method of irregular pitch end mills, which ensures robust suppression of total regeneration in milling. Firstly, general formulation of irregular pitch angles is explained for simultaneous suppression of multi-mode regenerations. An index named “Regeneration Factor (*RF*)” is introduced to quantify regenerative effect. Minimizing the mean value of the $|RF|$ within a certain frequency range, suppression frequencies are distributed in the proposed method, resulting in robust suppression of regeneration regardless of chatter frequency and/or spindle speed variations. Experimental investigations verified significant robustness of the end mill with the proposed design against the spindle speed variation.

1. Introduction

Chatter vibrations are one of the limiting factors on achievable productivity in machining operations [1]. Typically, regenerative chatter vibrations are the most widely encountered type of chatter vibrations [2]. Influence of regenerative effect on process stability is dominantly determined by the spindle speed and the eigen-frequency of the flexible structure. The long-standing rule is to synchronize spindle speed with the eigen-frequency of vibrating structure to stabilize dynamic uncut chip thickness [3]. This approach generates the well-known stability pockets where relatively large depths of cut are often achieved.

Irregular pitch cutters (IPCs) are proposed to increase chatter stability based on a different mechanism [4]. As compared to regular pitch cutters, in IPCs the pitch angle between two cutting edges is introduced as an extra parameter. This enables cancellation of regenerative vibration of each tooth. Past literatures clarified the importance of the pitch angle design considering the dynamics of mechanical structures [5]. It is well known that regeneration can be completely suppressed when number of teeth is even and difference in pitch angles $\Delta\theta$ in each pair of teeth satisfies the following relationship:

$$\Delta\theta = 2\pi\left(m + \frac{1}{2}\right)\frac{n}{60f_c} \tag{1}$$

where m is an integer, n is a spindle speed, and f_c is the chatter frequency. The relation given in Eq. (1) lays the fundamentals for the design of most commercial IPCs in practice. Typically, a pair of pitch angles θ_a and θ_b determined by Eq. (1) is aligned alternately, i.e., alternating pitch variation (APV). Budak also proposed general formulations for tools with arbitrary number of flutes, i.e., linear pitch variation (LPV) [6], and chatter suppression effect was verified in both analysis and experiments.

As a matter of fact, currently available IPC design mentioned above is oriented towards chatter suppression for structures with single vibration mode. This is strict constraint. In general, machine tool structures vibrate at several modes. For instance, dominant milling spindle dynamics are determined by the vibration modes of tool, tool holder assembly and the whole rotary shaft. Furthermore, current design framework for IPCs does not accommodate dynamics variations of the structure such as changes in the eigen-frequency and damping. In practice, stiffness and damping in machine tool joints [7] are load dependent, and spindle dynamics change with spindle speed [8]. This hinders successful application of IPCs to suppress regenerative chatter. Park et al. has proposed a robust chatter stability prediction to accommodate variations in the structural dynamics and provided robust chatter stability charts for the first time [9]. However, this approach does not allow essential increase in chatter stability. Instead of utilizing conventional IPC design, Suzuki et al. proposed a functional tool design approach suppressing the regenerative effect of more than two vibration modes on systems [10]. The eigen-frequencies, however, need to be given in advance in this approach, which is impractical.

The present research addresses a novel robust IPC design. By extending the design approach of multi-mode suppression in [10], a practical design method of IPCs is proposed in the present study. By distributing regeneration suppression frequencies properly, the proposed design method can attain robust suppression of total regenerative vibrations within certain frequency range. And, instead of analytically solving chatter stability margins, pitch angles for regeneration free milling are calculated regardless of chatter frequency. General formulations for designing pitch angles are explained, and influence of the proposed method on the regeneration suppression is analytically investigated. Experimental verification is

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presented by comparing irregular pitch end mills and an ordinary regular pitch end mill.

2. Quantification of regenerative effect in milling

Fig. 1 illustrates milling process with an irregular pitch end millwith four flutes. When mechanical structure vibrates, relative displacement between tool and workpiece oscillates. The uncut chip thickness oscillates not only due to the present vibration but also by the past vibration left on the surface by the previous tooth. Effect of the past vibration is known as the "regenerative effect". Dynamic uncut chip thickness, i.e., difference between present and previous relative vibrations, causes dynamic variation in cutting force, resulting in excitation of the mechanical structures. The resultant vibration of the mechanical structure affects present uncut chip thickness. Because of this feedback mechanism, machining process may become unstable and vibration at a certain frequency can increase and diverge depending on several conditions. Stability of the process can be estimated by mathematical process modelling [11].

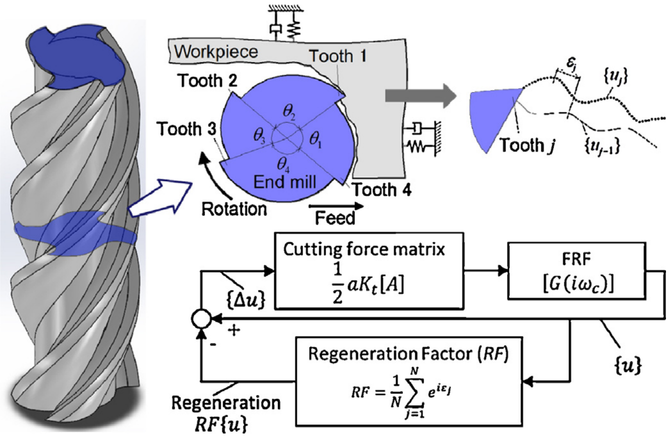

Fig. 1. Illustration of milling process with irregular pitch cutter.

In milling with IPCs, the phase difference between the inner and outer modulations ε varies depending on tooth passing period T_j of jth tooth and chatter frequency f_c. The regenerative vibration $\{u_{j-1}\}$ and the corresponding phase difference ε_j can be derived from present vibration $\{u_j\}$, the chatter frequency f_c, spindle speed n and the pitch angle θ_j as follows:

$$\{u_{j-1}\} = e^{-i\epsilon_j}\{u_j\}, \quad \epsilon_j = 2\pi f_c T_j = \frac{60 f_c}{n}\theta_j \tag{2}$$

where regeneration is represented by a complex phase vector $e^{-i\varepsilon}$.

The key to suppress regeneration is to quantitatively incorporate the contribution of individual pitch angles to the vibration. In order to quantify the regeneration suppression effect with respect to arbitrary chatter frequency, a novel index, so-called "Regeneration Factor (RF)", is introduced in this research by taking an average of complex phase vectors as follows:

$$RF = \frac{1}{N}\sum_{j=1}^{N} e^{-i\epsilon_j} \tag{3}$$

Fig. 2 illustrates relationship of phase differences and complex RF in case of IPCs. Phase differences of regenerative vibrations ε are not uniform. Because of this non-uniformity, average of the regenerative vibrations can be smaller than the current vibration, resulting in smaller cutting force fluctuation due to regeneration. RF represents the average regeneration gain in the nominal process, as shown in Fig. 1. Hence, it can be an indexing factor of regenerative effect. In case of APV design satisfying Eq. (1), paired complex phase vectors point towards opposite directions. The LPV design in [6] allows circumferential alignment of phase vectors with even interval. These vectors cancel out each other. As a result, conventional IPC design makes $|RF| = 0$ at designated conditions, and chatter stability can be increased by minimizing $|RF|$ considering that mode-coupling [5] in the system is negligible. Meanwhile, $|RF| = 1$ in case of a regular pitch cutter.

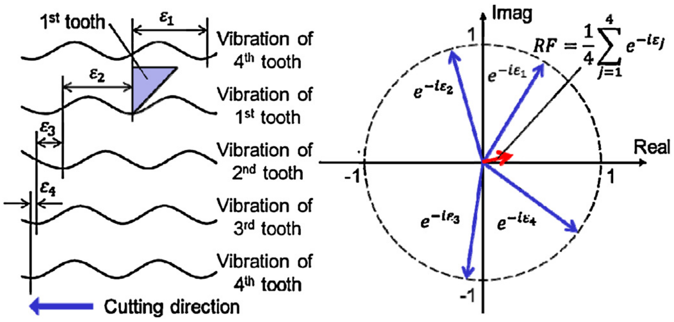

Fig. 2. Complex representation of regenerative vibrations and RF.

3. Pitch angle design for robust regeneration suppression

3.1. Pitch angle design for simultaneous suppression of multi-frequency modes

Regeneration suppression due to multi modes can be accomplished by the method given in [10]. This method plays an important role in the proposed robust design. Here, a brief summary of the method is presented as follows.

It assumes that there are two flexible vibration modes with different eigen-frequencies ${f_c}^{(1)}$ and ${f_c}^{(2)}$. Regenerations from the two modes can be suppressed theoretically by an IPC with four flutes. In this case RF can be calculated as:

$$RF = \frac{(e^{-i\epsilon_1} + e^{-i\epsilon_2} + e^{-i\epsilon_3} + e^{-i\epsilon_4})}{4} \tag{4}$$

In order to suppress the regeneration due to ${f_c}^{(1)}$, the necessary pitch angle difference at spindle speed n is derived from Eq. (1) as:

$$\theta_1 - \theta_2 = \theta_3 - \theta_4 = \Delta\theta = 2\pi\left(m^{(1)} + \frac{1}{2}\right)\frac{n}{60{f_c}^{(1)}} \tag{5}$$

In the same manner, appropriate pitch angle difference for ${f_c}^{(2)}$ can be obtained by utilizing different combination of the teeth.

$$\theta_1 - \theta_3 = \theta_2 - \theta_4 = \Delta\theta = 2\pi\left(m^{(2)} + \frac{1}{2}\right)\frac{n}{60{f_c}^{(2)}} \tag{6}$$

Sum of the pitch angles satisfies the following relation:

$$\theta_1 + \theta_2 + \theta_3 + \theta_4 = 2\pi \tag{7}$$

Finally, the pitch angle of jth flute for making RF zeroat ${f_c}^{(1)}$ and ${f_c}^{(2)}$ can be obtained from Eqs. (5)–(7) as:

$$\theta_j = \frac{\pi}{2} + \frac{1}{2}\left\{(-1)^{j-1}\Delta\theta^{(1)} + (-1)^{\lfloor (j-1)/2 \rfloor}\Delta\theta^{(2)}\right\} \tag{8}$$

It should be noted that this relation can be generalized in case of dynamics with h number of modes. Regenerations can be suppressed and RF can become zero at the same time by use of 2^h flutes IPCs. The optimum pitch angle difference and the corresponding pitch angles can be derived as follows:

$$\Delta\theta^{(k)} = 2\pi\left(m^{(k)} + \frac{1}{2}\right)\frac{n}{60{f_c}^{(k)}}, \quad (k = 1, 2, \ldots, h) \tag{9}$$

$$\theta_j = \frac{\pi}{2^{h-1}} + \frac{1}{2}\sum_{k=1}^{h}(-1)^{\lfloor (j-1)/2^{k-1} \rfloor}\Delta\theta^{(k)}, \quad (j = 1, 2, \ldots, 2^h - 1, 2^h) \tag{10}$$

3.2. Optimization of suppression frequencies and pitch angles for robust regeneration suppression

When regenerative effect is suppressed at a certain combination of frequencies and a spindle speed, RF becomes not only zeroat designated suppression frequencies but also considerably small at