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Analytical Modeling, Design and Performance Evaluation of Chatter-Free Milling Cutter With Alternating Pitch Variations

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ABSTRACT Machining efficiency could be increased and chatter vibrations could be suppressed by employing irregular pitch angles onto milling cutters. Applying variable pitch cutters could improve machining stability by disrupting the regenerative chatter mechanism and reducing cutting forces due to decreased nonlinear dynamic chip thicknesses. Previous studies on variable pitch cutters have been mainly investigating vibration suppression and dynamic modeling. There is a lack of efficient and practical variable pitch cutter design methods for practical industrial applications. An analytical method for designing milling cutters with alternating variable pitches has been proposed in this paper. In this method, a new variable, the generic sum of phase difference between the inner and outer waves, has been defined to model the machining dynamics and the stability of the variable pitch cutter. The phase difference value has then been investigated to obtain its generic optimal solution to the stability limit considering different cutting conditions. Based on this, the analytical variable pitch cutter design method is derived. The experimental results have manifested that, compared with uniform pitch cutter, the variable pitch cutter, designed using the proposed method, was able to achieve: 1) a critical stable axial depth of cut improvement of 126% under the desired spindle speed; 2) a cutting force reduction of 53%; 3) a decrease of 75% and 52% in Sq (the root mean square length of the scale limited surface) and Sz (the maximum height of the scale limited surface) of the machined surfaces, respectively. These significant improvements approved the superiority and robustness of the proposed design method for chatter suppression and may promote the application of variable pitch cutter technologies.

INDEX TERMS Manufacturing processes, cutting tools, stability, vibration control, pitch control.

I. INTRODUCTION

Vibrations, which affect the machining productivity and quality [1], [2], occur often in milling operations. Metal cutting vibrations can be categorized as free vibrations, forced vibrations and self-excited vibrations, among which self-excited vibrations are key factors influencing the milling safety and quality [3]. The most common form of self-excited vibrations is regenerative chatter, which is aroused by the phase difference between the two adjacent machined surfaces. Undesired chatter leads to low machined surface integrity and limited tool service life [4]. It is, therefore, necessitated to predict and suppress milling vibrations [5].

For the milling vibration prediction, Altintaş and Budak [6] predicted the stability limit in the frequency domain. Stability lobes could be generated quickly by this prediction. This prediction, however, is not applicable for the milling operation with small radial immersions. Insperger and Stépán [7] developed a semi-discretization (SD) method for chatter stability prediction. Compared with the frequency domain method, the SD method provided a more accurate stability prediction at the cost of higher computing volume. Luo *et al.* [8] employed a time domain method to predict system dynamics for the slot milling process considering vibrations of the cutter exit workpiece.

These studies, however, have apparently ignored the chatter avoidance.

To suppress chatter, three major methods have been proposed including (i) the utilization of dampers, (ii) the selection of appropriate spindle speeds and (iii) the creation of non-standard milling cutters. For the methods (i), the limitation comes from the damper design and experimental tuning [9]. For the methods (ii), there is a lack of theoretical supports for selecting appropriate spindle speeds to suppress chatter vibration [10]. In addition, optimal spindle speeds may not be achieved in real industrial machining. For the methods (iii), the non-standard milling cutters, i.e. milling cutters with variable helix angles or variable pitch angles, have been proposed to suppress chatter through disrupting the regenerative mechanism [11].

For the variable helix milling cutters, Yusoff and Sims [12] developed an optimization procedure, to suppress chatter by using tools with variable helix angles. The optimization procedure was based on a semi-discretization method to obtain the optimal variable helix end mill. Dombovari and Stepan [13] investigated the effect of variable helix cutters on chatter suppression and obtained an obvious increase of stability limit at the low spindle speed domain. However, compared with variable pitch cutters, variable helix cutters are more expensive and difficult to be manufactured. In addition, when machining difficult-to-cut materials where small depth of cuts are employed, the cutting performance of these two cutters are nearly identical [12]. Variable pitch cutters, therefore, are more preferable.

For the variable pitch cutters, the seminal work of variable pitch cutter design and its chatter suppression study was completed by Slavicek [14]. Altintaş *et al.* [15] proposed a solution to provide optimal variable pitch angles based on specific cutting conditions. The designed variable pitch cutter, however, could only be employed in a small range around the desirable spindle speed. Olgac and Sipahi [16] presented a 'Cluster Treatment of Characteristic Roots' approach to determine the pitch angle formation and optimum cutting conditions. Suzuki *et al.* [17] proposed a 'Regeneration Factor' parameter to obtain the variable pitch cutter design method considering the multi-mode regenerations. However, experimental validation of these two methods are missing. Budak developed an analytical variable pitch cutter design method to suppress chatter vibration, resulting in a high material removal rate and smooth surface finish [18].

However, there are three distinctive disadvantages of the reported variable pitch cutter design methods. Firstly, the designed cutters could only improve the stability limit in a narrow spindle speed range. Secondly, some calculated pitch angles may be too small to provide the desirable chip evacuation, and the small pitch angles also lead to the difficulty in the cutter fabrication. Thirdly, previous work did not consider decreasing cutting forces and vibration amplitude via analytically designing variable pitch cutters to reduce dynamic chip thicknesses.

In this study, a new alternating variable pitch cutter design method has been proposed. Chatter vibration can be suppressed and dynamic cutting forces can be reduced by using the designed cutter. In addition, the designed cutter can be applicable in a wide range of cutting conditions. The method therefore is promising to facilitate the modern high-performance and high-precision manufacturing, where satisfactory machining efficiency and perfect machined surface integrity are simultaneously required.

This paper starts with introducing the critical axial depth of cut for variable pitch cutter and the geometrical relationship between adjacent pitch angles. After this, the relations between phase differences and chip thicknesses is clarified and the generic sum of phase difference is defined. The globe optimal phase difference value to the stability limit under different milling conditions is then derived. Following this, the variable pitch angle design method is proposed based on the optimum value and feasible pitch variations. Finally, the reported method is both analytically and experimentally validated.

II. DEVELOPMENT OF THE NEW VARIABLE PITCH CUTTER DESIGN METHOD

A. STABILITY LIMIT CALCULATION OF VARIABLE PITCH CUTTERS

The milling process is generally illustrated in Figure 1(a), considering that milling cutters have two orthogonal degrees of freedom (DoF) [6] (see Figure 1b). As can be seen from the arc $\widehat{P_1P_2}$ in Figure 1(c), a wavy surface can be produced due

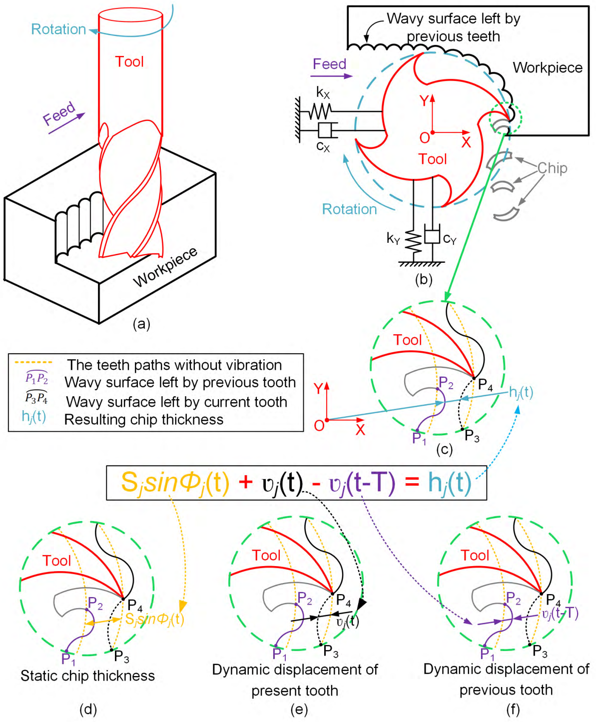


FIGURE 1. Regenerative chatter model with two DoFs.

to relative cutter-workpiece displacements induced by system vibrations.

The total chip thickness $h_j(t)$ consists of the static $S_j sin\varnothing_j(t)$ (see Figure 1d) and dynamic $v_j(t) - v_j(t-T)$ parts (see Figure 1e and Figure 1f). This is because a new wavy surface (see the arc $\widehat{P_3P_4}$ in Figure 1e) is generated by the next tooth after removing the previously machined surface (see the arc $\widehat{P_1P_2}$ in Figure 1f). The resultant chip thickness $h_j(t)$ can be expressed as:

$$h_j(t) = S_j sin\varnothing_j(t) + v_j(t) - v_j(t-T) \tag{1}$$

where $v_j(t)$ and $v_j(t-T)$ are the relative dynamic displacements of the current and previous tooth between the cutter and workpiece, respectively. The static component of the chip thickness $S_j sin\phi_j(t)$ can be neglected in the stability analysis since it does not affect the dynamic chip regeneration mechanism [3]. Therefore, the dynamic chip thickness, which contributes to the dynamic chip load regeneration mechanism, can be described as:

$$h_j(t) = \Delta x sin\varnothing_j(t) + \Delta y cos\varnothing_j(t) \tag{2}$$

where Δx and Δy represent the difference of dynamic displacements between the present and previous tooth periods, respectively. Thus the dynamic milling forces can be derived as:

$$F_{tj} = K_t a h_j(t) \quad F_{rj} = K_r F_{tj} \tag{3}$$

where K_t and K_r are the tangential and radial cutting constants, respectively. According to the zero-order theory [6], the critical axial depth of cut is derived as:

$$a_{lim} = -2\pi \Lambda_R (1+k^2)/N K_t \tag{4}$$

with

$$k = \Lambda_I/\Lambda_R = sin\omega_c T/(1-cos\omega_c T) \tag{5}$$

where ω_c is the chatter frequency (rad/s), Λ_R and Λ_I are the eigenvalue's real and imaginary parts of characteristic equation.

For variable pitch cutters, the phase difference ε_j between the inner and outer waves corresponding to the pitch angle P_j is defined as:

$$\varepsilon_j = \omega_c T_j \tag{6}$$

where T_j and ε_j are the jth tooth period and phase difference, respectively. Therefore, the critical axial depth of cut for variable pitch cutter is:

$$a_{lim}^{vp} = -4\pi \Lambda_I / K_t S \tag{7}$$

where

$$S = \sum_{j=1}^{N} sin\omega_c T_j = \sum_{j=1}^{N} sin\,\varepsilon_j \tag{8}$$

Therefore, it could be observed from (7) that the variable pitch angles should be designed to minimize S for the purpose of increasing the stability limit (i.e. the critical axial depth of cut).

B. GEOMETRICAL RELATION BETWEEN ADJACENT PITCH ANGLES

For the cutters with alternating variable pitches, the pitch angles can be generally described as:

$$P_1, P_2, P_1, P_2, \ldots, \tag{9}$$

where P_1 and P_2 represent the two different pitch angles of cutter.

Hence, for a cutter with N teeth, the alternating variable pitches should satisfy the following relation:

$$\sum_{i=1}^{N} P_i = 2\pi \Rightarrow \begin{cases} N(P_1+P_2)/2 = 2\pi, & N \text{ is even} \\ [(N+1)P_1 + (N-1)P_2]/2 = 2\pi, & N \text{ is odd} \end{cases} \tag{10}$$

Considering that the tooth number of the variable pitch cutter N is an even value, the relationship between the two adjacent pitch angles can be expressed as:

$$P_1 + P_2 = 4\pi/N \tag{11}$$

Based on (6), the phase differences corresponding to the two pitch angles are:

$$\varepsilon_1 = 60\omega_c P_1/2\pi \quad \varepsilon_2 = 60\omega_c P_2/2\pi n \tag{12}$$

where n is the spindle speed (rpm), $60/n$ is the spindle period, and $60P_j/2\pi n$ is the tooth period T_j corresponding to the pitch angle P_j.

Substituting (11) into (12), the following equation could be obtained:

$$\varepsilon_2 = 120\omega_c/Nn - 60\omega_c P_1/2\pi n \tag{13}$$

To simplify (13), $120\omega_c/Nn$ can be represented by the symbol ε_s, referring to the phase difference corresponding to pitch angle $4\pi/N$ (i.e. the sum of the pitch angle P_1 and P_2). Therefore, (13) could also be expressed as:

$$\varepsilon_2 = \varepsilon_s - \varepsilon_1 \tag{14}$$

Substituting (14) into (8), the following expression of S could be obtained for an even N value.

$$S = N\left[sin\varepsilon_1 + sin(\varepsilon_s - \varepsilon_1)\right]/2 \tag{15}$$

The variable pitch cutter design here is based on the pitch angle variation with fixed numbers of teeth. Indicating that in (15), N is a constant value. Only the $sin\varepsilon_1 + sin(\varepsilon_s - \varepsilon_1)$ influences the value of S, and hence, the value of a_{lim}^{vp} in (7). Therefore, $sin\varepsilon_1 + sin(\varepsilon_s - \varepsilon_1)$ could be considered as the generic sum of phase difference. A new variable $\bar{S}$ could thus be defined to represent it as shown in (16):

$$\bar{S} = sin\varepsilon_1 + sin(\varepsilon_s - \varepsilon_1) \tag{16}$$

Then the (15) could be rewritten as:

$$S = N\bar{S}/2 \tag{17}$$

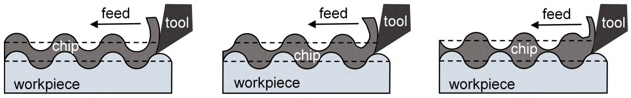
Substituting (17) into (7), a_{lim}^{vp} could be derived as a function of $\bar{S}$:

$$a_{lim}^{vp} = -8\pi \Lambda_I / K_t N \bar{S} \tag{18}$$

Therefore, to design a chatter free milling tool, the $\bar{S}$ needs to be minimised via varying the pitch angle to maximise the a_{lim}^{vp}. In addition, as shown in (12), the phase differences not only depend on the pitch angle, but also the chatter frequency and spindle speed. This indicates that the cutting condition also has a bearing on the phase difference. Hence, cutting condition variations are suggested to be considered to ensure the robustness of the proposed method.

C. RELATION BETWEEN PHASE DIFFERENCES OF ADJACENT MACHINED SURFACES AND DYNAMIC CUTTING FORCES

Milling vibrations lead to random and low-quality machined surfaces. The stochastic nature of this brings further machining deviations, leading to different phase differences between the waves left by previous and current teeth. In addition, such deviations left by the previous tooth serve to change the effective chip thickness for the current in-cut edge within one revolution of the cutting tool. Different chip thicknesses bring varying cutting forces [3] that may further exacerbate the vibration and the induced chatter.



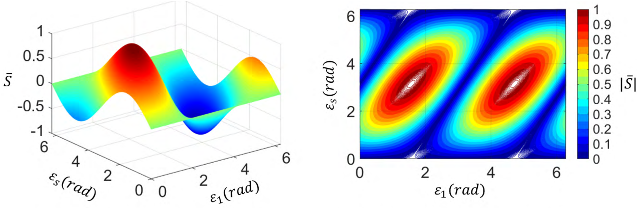
(a) (b) (c)

FIGURE 2. The variation of chip thickness when the phase difference is (a) 0 *rad*, (b) $\pi/2$ *rad* and (c) π *rad*.

The relation between phase differences and chip thicknesses is demonstrated in Figure 2. When the phase difference is zero, the dynamic chip thickness is zero, resulting in the minimum peak and oscillating cutting forces. When the phase difference is π, the system would have the maximum peak and the most severe oscillating cutting forces. Variable pitch angles should, therefore, be adopted to avoid the phase difference π.

D. DESIGN OF VARIABLE PITCH ANGLES BASED ON THE GLOBAL OPTIMAL PHASE DIFFERENCE

For the design of variable pitch milling cutters, minimising the value of $\bar{S}$ is always the aim. The value of $\bar{S}$ is determined only by the values of ε_s and ε_1, as shown in (16), in which the value of ε_s depends only on given milling conditions. Variable pitch angle can only influence the value of ε_1. The challenge is that ε_s varies due to different machining systems and cutting conditions. The variation of ε_s should, therefore, be considered to ensure the robustness of the variable pitch design method whilst selecting a right/general value of ε_1 in order to increase the stability limit.



(a) (b)

FIGURE 3. The effect of ε_s and ε_1 on $\bar{S}$ for alternating pitch variations, including (a) three-dimensional surface of $\bar{S}$ and (b) two-dimensional contour of $|\bar{S}|$.

To investigate the influence of the variation of ε_s on $\bar{S}$, and obtain a general optimised solution of ε_1 to increase the stability limit and reduce dynamic forces, $\bar{S}$ is plotted as a function of ε_s and ε_1 (see Figure 3a). The selection of the value of ε_1 should be based on the fact that the $\bar{S}$ is a general optimised solution even when ε_s changes from 0 to 2π. In (18), the value of a_{lim}^{vp} should be positive since it is the critical axial depth of cut, hence the sign of $\bar{S}$ does not influence the value of a_{lim}^{vp}. Only the absolute value of $\bar{S}$ affects a_{lim}^{vp}. The two-dimensional contour of $|\bar{S}|$, to investigate the effect of ε_s and ε_1 on the absolute value of $\bar{S}$, is presented in Figure 3(b), where, overall, $\varepsilon_1 = 0, \pi, 2\pi$ result in the same minimum of $|\bar{S}|$. When $\varepsilon_1 = \pi$, as shown in Figure 2, milling systems experience the maximum peak and the most severe cutting force oscillations. $\varepsilon_1 = \pi$, therefore, cannot be used to decrease the cutting forces. As such, $\varepsilon_1 = 0$ and $\varepsilon_1 = 2\pi$ are the general solutions which could be used to minimise the value of $\bar{S}$ and milling forces for different cutting conditions. To be general, $\varepsilon_1 = 2k\pi$ (where k is natural number) can be the solution with satisfactory robustness to increase the stability limit and reduce the cutting forces simultaneously.

Substituting $\varepsilon_1 = 2k\pi$ into (12), the pitch angle design method for alternating variable pitch cutters with even number of teeth is obtained as follows:

$$P_1 = 2k\pi \times 2\pi n/60\omega_c \quad P_2 = 4\pi/N - P_1 \qquad (k = 1, 2, 3, \ldots) \tag{19}$$

It should be noted that, since k corresponding to the number of lobes and the desirable spindle speed may be included in multiple lobes, a series of variable pitch design proposals can be obtained from (19). Larger pitch variations bring smaller pitch angles, which may not provide a desirable chip evacuation and increase the difficulties of grinding the flutes. The difference between adjacent pitch angles should, therefore, be minimised. As such, the minimum pitch increment obtained from the series of variable pitch design proposals leads to the final variable pitch pattern.

III. EXPERIMENTAL SETUP AND VARIABLE PITCH CUTTER DESIGN

A. EXPERIMENTAL SETUP AND PROCEDURE

A four-axis milling machine (YHVT850Z machining centre, Qinchuan Machine Tool Group) was used to perform

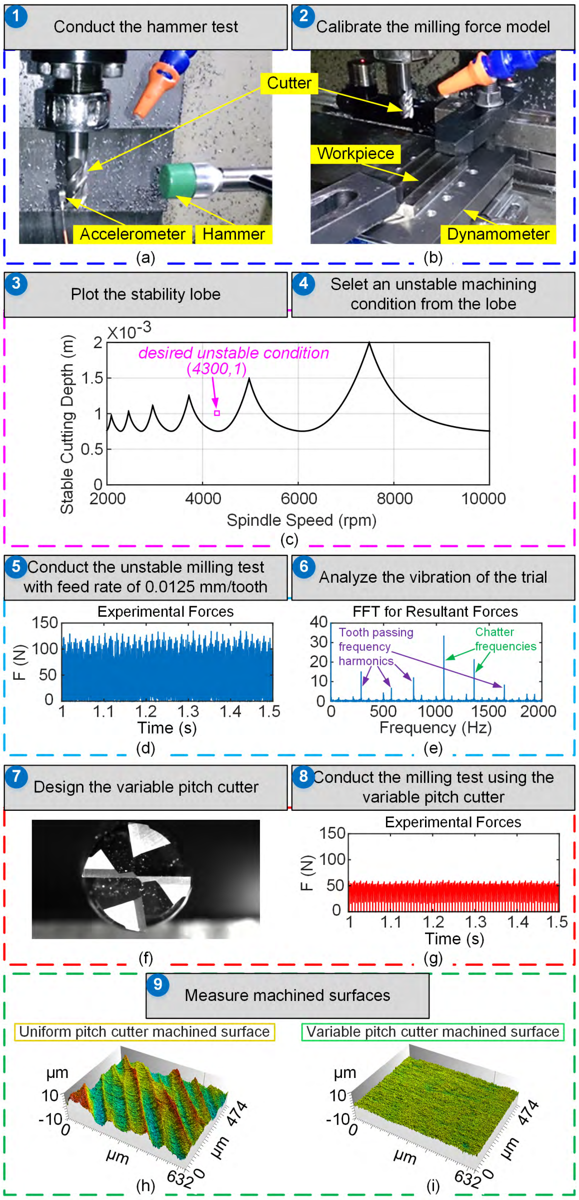


FIGURE 4. Experiment setup and procedure.

the milling trials. A Ti_6Al_4V material, with the size of 60 mm (length) × 140 mm (width) × 15 mm (height), was used as the workpiece. A 3-component dynamometer (9257B, Kistler) was employed to log the milling forces with the sampling frequency of 10 kHz. The uniform end milling cutter (diameter of 10 mm and helix angle of 45°) with four teeth was applied as a benchmark. The experimental setup and procedures, as demonstrated in Figure 4, are:

(i) conducting the hammer test to calibrate the modal parameters of the system (see Figure 4a);

(ii) conducting the milling force coefficient calibration based on the milling tests (see Figure 4b);

(iii) visualising the stability lobe under the half-immersion up-milling based on (i) and (ii) (see Figure 4c);

(iv) selecting an unstable cutting condition from the stability lobe as shown in Figure 4(c);

(v) conducting the milling trials based on (iv) with the feed rate of 0.0125 mm/tooth;

(vi) analysing vibration of the unstable milling process in (v) to obtain the cutting forces (see Figure 4d) and chatter frequencies (see Figure 4e);

(vii) designing the variable pitch cutter (see Figure 4f);

(viii) conducting the variable pitch cutter milling test under the same machining condition used in (v) and evaluating the designed cutter in terms of stability limit and cutting force (see Figure 4g);

(ix) characterising the machined surface topography (see Figure 4h and Figure 4i) using a white light interferometer, Bruker GT-I and surface texture data analysis software, Mountainmap.

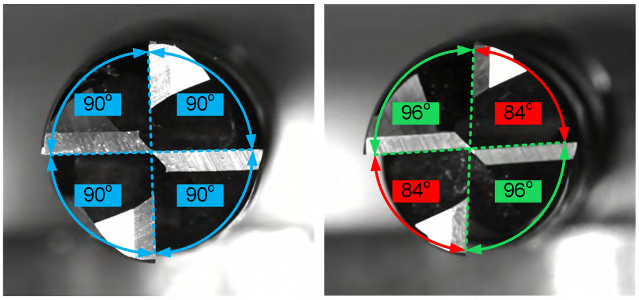
B. VARIABLE PITCH CUTTER DESIGN

After the procedure (i), the modal parameters in the hammer tests can be obtained and are presented in Table 1. After the procedure (ii), the calibrated milling force coefficients are $K_{tc} = 3300MPa$, $K_{rc} = 1438.4MPa$, $K_{te} = -1.9001 \times 10^4 Nm^{-1}$, $K_{re} = 3.8920 \times 10^4 Nm^{-1}$.

After the procedure (iii) and (iv), the unstable machining condition (i.e., spindle speed of 4300 rpm and axial depth of cut of 1 mm, see Figure 4c) for uniform pitch cutter is selected. After the procedure (v) and (vi), the chatter frequencies of the unstable milling process are obtained: $\omega_{c1} = 1071\ Hz$ and $\omega_{c2} = 1358\ Hz$. Then, the variable pitch cutter angles can be derived based on (19) and the selection strategy provided in section II. These angles are 84°, 96°, 84°, 96° (see Figure 5). Since the modal parameters mainly reflect the characteristics of the machine tool system,

TABLE 1. Modal parameters of the experiment milling system.

Direction	$\omega_n(Hz)$	$\xi(\%)$	$k(N/m)$
X	1035	3.768	2.3899×10^7
Y	976	5.990	9.1930×10^6



(a) (b)

FIGURE 5. The four-fluted end milling cutters with (a) uniform and (b) variable (84°, 96°, 84°, 96°) pitch angles.

the variable pitch angles have lightly effect on the system modal parameters and could be ignored.

IV. RESULTS AND DISCUSSIONS

A. COMPARISON OF MILLING FORCE STABILITY BETWEEN THE DESIGNED AND UNIFORM MILLING CUTTERS

The stability lobes and cutting forces of milling cutters with uniform (90°, 90°, 90°, 90°) and variable pitches (84°, 96°, 84°, 96°) are shown in Figure 6 and Figure 7, respectively. As shown in Figure 6, when the uniform pitch cutter is employed, the desired cutting condition, with spindle speed of 4300 rpm and depth of cut of 1 mm, is in the unstable area. When the designed variable pitch cutter is employed, the desired cutting condition is in the stable area, which analytically ensures the chatter suppression of the variable pitch cutter.

Furthermore, as demonstrated in Figure 6, compared with the uniform pitch cutter, the variable pitch cutter showed distinctive advantages on the stability limit improvement, including that:

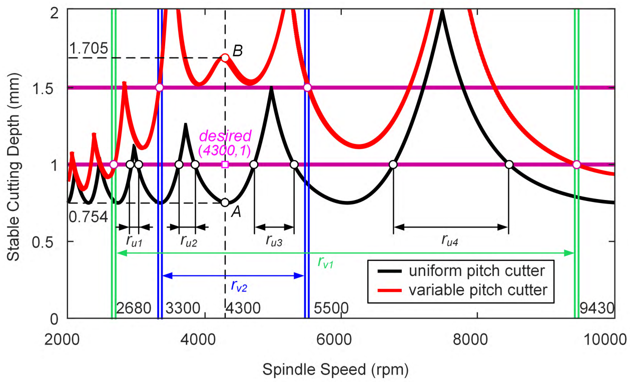


FIGURE 6. Stability analysis of uniform and variable pitch cutters for half immersion up milling.

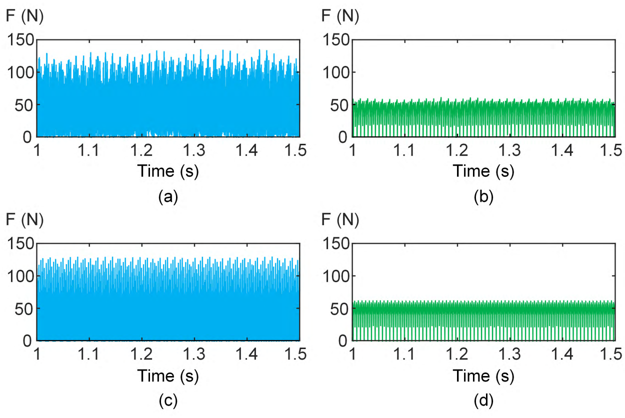


FIGURE 7. The resultant milling forces under the desired cutting condition (spindle speed of 4300 rpm and axial depth of cut of 1 mm), including: the experimental forces of (a) the uniform and (b) the variable pitch cutters, the simulated forces of (c) the uniform and (d) the variable pitch cutters.

(i) when the cutting depth was 1 mm: for the uniform pitch cutter, to obtain the stable milling process, the spindle speed only could be selected from the range of r_{u1}, r_{u2}, r_{u3} and r_{u4} as shown in Figure 6. For the variable pitch cutter, the stable spindle speed area was expanded to the range from 2680 rpm to 9430 rpm (see the r_{v1} in Figure 6). There was a relative improvement of 151 % in the stable spindle speed area. Please note that the relative difference is defined here as: (improved result – conventional result) / conventional result ×100 %.

(ii) when the spindle speed was 4300 rpm: for the uniform pitch cutter, the maximum stable depth of cut was 0.754 mm (see point A in Figure 6). Thus, the desired cutting depth, 1mm, was unstable for this cutter. For the variable pitch cutter, the maximum stable depth of cut improved from 0.754 mm to 1.705 mm (see point B in Figure 6). A relative improvement of 126 % was observed.

(iii) when it was close to the desired cutting spindle speed, 4300 rpm, the maximum stable depth of cut improved from 0.754 mm to 1.500 mm in the range of the spindle speed from 3300 rpm to 5500 rpm (see the r_{v2} in Figure 6). A relative improvement of 99 % was observed.

(iv) previous results showed that the stable depth of cut can only be improved during a small range (less than 1000 rpm) of spindle speeds, whereas a significant larger range (6750 rpm), from 2680 rpm to 9430 rpm, can be improved using the proposed variable pitch cutter. This ensures the effect of variable pitch will not be affected by the variety of cutting condition to a certain extent. Although it has to be noted that previous machining conditions were different, this step-change improvement will apparently improve the robustness of the proposed method and enhance the applicability of the variable pitch cutter.

The experimental milling forces of the uniform and the variable pitch cutters are presented in Figure 7(a) and (b), respectively. The simulated milling forces of the uniform and the variable pitch cutters are separately presented in Figure 7(c) and (d). As demonstrated in Figure 7(a) and (c), there were significant chatter vibrations in the milling process by using the uniform pitch cutter, the severe oscillation of cutting forces were both observed from experimental and simulated results. Figure 7(b) and (d) indicate that by using the variable pitch cutter, it is obvious that cutting force oscillations were disappeared due to the chatter free machining process and the phase difference away from the π. In addition, the maximum cutting force was decreased by 53% compared with the uniform pitch cutter.

B. COMPARISON OF MACHINED SURFACE QUALITY BETWEEN THE DESIGNED AND UNIFORM MILLING CUTTERS

Surface texture measurement of the machined surfaces from the uniform and the variable pitch cutters were conducted based on a white light interferometer, Bruker GT-I. Five random areas of both the machined surfaces were measured, each area (0.632 mm × 0.474 mm) was measured three

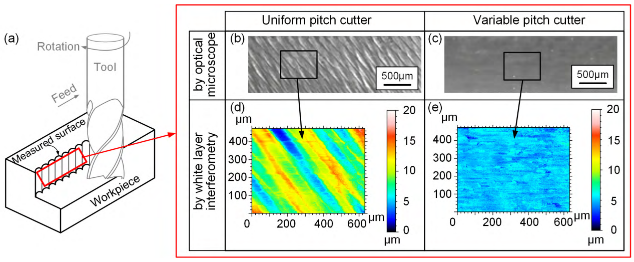


FIGURE 8. Measurement results of the machined surfaces: (a) the location of measurement area, (b) optical microscope image of the machined surface using the uniform pitch cutter, (c) optical microscope image of the machined surface using the variable pitch cutter, (d) surface texture of the machined surface using the uniform pitch cutter, (e) surface texture of the machined surface using the variable pitch cutter.

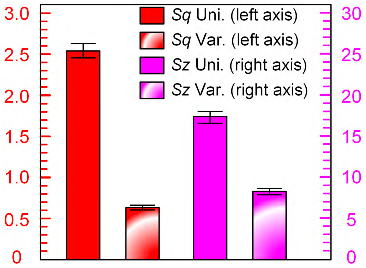
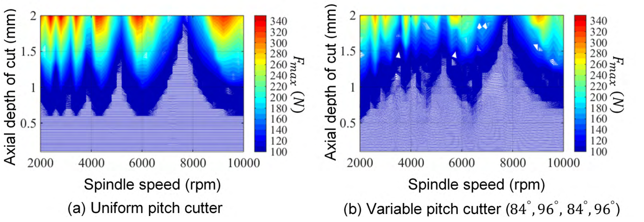


FIGURE 9. Comparison of the Sq and Sz values between the surfaces machined by the uniform and the variable pitch cutters.

times. The machined surface measurement location can be seen in Figure 8(a). MountainsMap software was then used to characterise the data from the Bruker GT-I. The results shown in Figure 8(b) to Figure 8(e) manifest that a substantially better surface quality can be achieved by the variable pitch cutter. The comparison of *Sq* (the root mean square length of the scale limited surface) and *Sz* (the maximum height of the scale limited surface) between the machined surface using the uniform pitch cutter and the machined surface using the variable pitch cutter can be seen in Figure 9. As demonstrated in Figure 9, when the variable pitch cutter is employed, a relative decrease of 75% and 52% can be seen in *Sq* and *Sz*, respectively.

C. FURTHER DISCUSSION

The cutting forces presented in Figure 7 were obtained only under the desirable machining condition. To validate the robustness of the variable pitch cutter on cutting forces decrease in different machining conditions, the maximum milling forces of each machining conditions are plotted as a two-dimensional contour in Figure 10. The cutting forces are plotted with spindle speeds for given axial depth of cuts. Within the two diagrams, in the areas where the milling processes are stable, the forces will not vary with small change of spindle speeds. Favourable combinations of spindle speeds and depth of cuts that could be extracted after multiple lines are plotted for a variety of axial depth of cuts. Compared with uniform pitch cutter in Figure 10(a), around the desirable spindle speed, 4300 rpm, the variable pitch cutter brought significantly smaller forces from 3000 rpm to 5500 rpm (see Figure 10b). This manifests that the variable pitch design method is robust against a range of different milling conditions.



(a) Uniform pitch cutter

(b) Variable pitch cutter (84°, 96°, 84°, 96°)

FIGURE 10. The two-dimensional contour of the maximum cutting forces under each milling conditions for the (a) uniform pitch cutter and (b) variable pitch cutter.

V. CONCLUSIONS AND FUTURE WORK

A method for designing alternating variable pitch cutters, with improved chatter stability, decreased dynamic milling forces, and enhanced robustness against various machining conditions, has been presented and validated analytically and experimentally. The key findings from this work are that:

1) compared with the uniform pitch cutter, the variable pitch cutter showed a relative improvement of 151 % in the stable spindle speed area when the depth of cut was 1 mm. Also, a relative improvement of 126 % in the maximum stable depth of cut was observed when the spindle speed was 4300 rpm. In addition, a relative improvement of 99 % in the maximum stable depth of cut was observed in the range of the spindle speed from 3300 rpm to 5500 rpm. Furthermore, a significant larger stable spindle speed range (6750 rpm) can be achieved.

2) compared with the uniform pitch cutter, the maximum cutting force was decreased by 53% using the variable pitch cutter under the desired cutting condition. Also, severe cutting force oscillations were significantly decreased.

3) compared with the uniform pitch cutter, a substantially better surface quality can be achieved by the variable pitch cutter. A relative decrease of 75% and 52% were observed in Sq and Sz respectively.

4) compared with the uniform pitch cutter, the variable pitch cutter brought significantly smaller forces from 3000 rpm to 5500 rpm, approving that the proposed design method could be robust against a range of different milling conditions.

The findings reported in this paper indicate that the developed variable pitch cutter design method could be applied to obtain step-change improvements on machining stability, cutting forces decrease, and machined surface quality over a large range of different cutting conditions. However, the results of this research not only allow the chatter-free milling cutter design, but also open avenues for clarification of other scientific queries such as:

1) Applying the proposed method to design diamond milling cutters for composite machining. Vibrations can

easily lead to the high wear and fracture of the diamond tools [19]. Protection of diamond cutters might be achieved via chatter suppression and cutting force variation reduction.

2) Quantifying the temperature effect of the milling process using the designed cutters. Lower milling temperatures can be achieved by the alternating variable pitch cutters. This may help to avoid the phase transformation of metal workpieces, especially for difficult-to-cut and high-value metals such as aerospace titanium turbine bladed discs.

3) Quantifying the energy consumption of the milling process using the designed cutters. The energy consumption by milling cutters plays a major part in the total input manufacturing energy. This consumption can be significantly reduced due to the fact that decreased cutting forces and lower machining temperatures (thus reduced energy dissipations) can be achieved using the designed variable pitch cutter.

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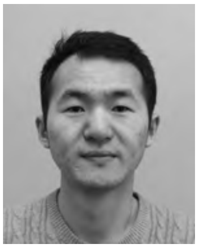

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