An Analytical Design Method for Milling Cutters With Nonconstant Pitch to Increase Stability, Part 2: Application

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Chatter stability in milling can be improved significantly using variable pitch cutters. The pitch angles can be optimized for certain chatter frequency and spindle speed ranges using the analytical method presented in the first part of this two-part paper. In this part, the improvement of productivity and surface finish are demonstrated in three example applications. It is shown that chatter stability can be improved significantly even at slow cutting speeds by properly designing the pitch angles. A roughing example demonstrates substantially reduced peak milling forces which allows higher material removal rate. [DOI: 10.1115/1.1536656]

1 Introduction

Chatter is one of the most critical limitations in machining for productivity and part quality. Many models have been developed and applied in milling and other machining operations within the last half-century [1–7]. The most important outcome of these stability models is the stability lobe diagrams which can be used to determine the cutting conditions where chatter-free material removal rate is maximized. This can be a very effective way of improving productivity. However, large chatter-free depth of cuts are usually available for high cutting speeds which may not be possible to attain for some processes due to work material and machine tool limitations. High temperature alloys used in aerospace industries such as titanium and nickel are common examples. Variable pitch cutters, on the other hand, can be used to suppress chatter in those cases. One of the advantages of the variable pitch cutters is that they can be quite effective even at low cutting speeds. In fact, the stability limits at low speeds can be further increased due to combined effects of process damping and the variable pitch.

The stability of milling cutters with nonconstant pitch has been studied in detail in several previous studies [8–12]. These studies used different approaches in explaining the principles of variable-pitch effect on stability, and predicting the stability limit with variable pitch cutters. Optimal design of the pitch angles to maximize stability limit, on the other hand, is very important in practice which is the subject of this paper. An analytical method, developed for the optimal design of pitch angles based on the chatter frequency and spindle speed, is given in the first part of this two-part paper [13]. In this part, the application of the method to practical chatter examples is demonstrated.

2 Application

The variable pitch cutters designed by the method presented in [13] have been implemented in a variety of milling operations and resulted in significant improvements in productivity and quality [14]. The most significant gains are obtained for the cases where the process is highly unstable due to very flexible parts and tools, and large axial immersions. The axial depth of cut in some of these operations is much higher than even the highest stability lobe with equal pitch cutters. The work materials such as titanium alloys impose limitations on the cutting speed as well. The usual practice in these operations is to use extremely low cutting speeds to increase process damping which helps suppress chatter vibrations. This results in reduced productivity. In highly unstable processes chatter may still develop even at very low speeds that can practically be used. The resulting chatter marks on the surface are usually removed manually which increases cost and lead-time, and causes surface quality variations. Variable pitch cutters suppress chatter vibrations eliminating these additional operations. Furthermore, in some roughing operations the material removal rate (feedrate) is limited by the cutting force capacity of the long end mills. The variable pitch cutters can reduce milling forces by suppressing vibrations which may lead to significant increase in feedrate. Additionally, in both roughing and finishing operations, variable pitch cutters lead to increased tool life. This is expected as vibrations increase wear, particularly for carbide which is highly brittle. These are significant savings especially considering the fact that variable pitch cutters do not introduce additional cost except the initial measurement and analysis.

Some test and production application results are shown in the following. Note that in these examples the main focus is to suppress chatter and increase material removal rate without having to reduce the depth of cut.

2.1 Example 1. In this example, chatter tests are performed on a 5-axis machining center to improve the productivity by suppressing chatter. The machine has a quill type spindle which is highly flexible and generates so much chatter that very low spindle speeds are used even for magnesium alloys which have very low cutting pressure. The cutter used was a 3-fluted, 9.52 mm diameter carbide end mill with 50 mm gauge length which was held in a 125 mm long, 35 mm diameter tool holder. When the spindle extension was 180 mm, the modal parameters in Table 1 were identified by impact testing at the free end of the end mill.

The first mode is mainly due to the spindle mode whereas the second one is due to the tool assembly. The stability lobe diagram for slotting is generated by using the analytical stability method for equal pitch cutters and is given in Fig. 1. Only the second mode is considered in the simulations as it is significantly more flexible than the first one. Note also that process damping has been neglected in the predictions. Higher stability lobes could not be utilized since the maximum spindle speed available on the machine is 4000 rpm. As can be seen from the diagram, the stability limits are extremely small which reduces the productivity significantly. Very low spindle speeds are used to increase process

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Contributed by the Manufacturing Engineering Division for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received September 2000; Revised July 2002. Associate Editor: S. Kapoor.

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Table 1 Modal parameters of the end mill used for slotting tests.

Direction	Mode	k (N/mm)	m (kg)	f_n (Hz)	ζ
X	1	7700	0.95	453	0.13
	2	6500	0.17	984	0.038
Y	1	22000	3.4	405	0.04
	2	4600	0.124	969	0.093

damping and stabilize the process. Therefore, this process is a very good candidate for the application of variable pitch cutters.

Figure 2 shows sound spectrums measured for different spindle speeds in slotting of the magnesium block. Chatter developed at the second mode, i.e., close to 955 Hz. The axial depth of cut and the feed per tooth were 5 mm and 0.038 mm, respectively. As can be seen from Fig. 1, 5 mm depth of cut is much higher than the stability limit, and the process can only be stabilized at low speeds (<750 rpm) with the help of process damping. A variable pitch cutter can be designed to suppress chatter and increase chatter free material removal rate. The feedrate can further be increased using a 4-fluted cutter which could not be used as equal pitch due to more severe chatter was experienced. Design procedure given in [13] is quite straightforward; however, one critical decision is the selection of the spindle speed for a newly designed variable pitch cutter. This is especially important for the cases where the process is stabilized by process damping using slow speeds. In these cases, higher speeds can be used with the introduction of a variable pitch cutter. Considering the chatter test results shown in Fig. 2, the target speed was selected as 2500 rpm. The optimal ΔP is determined from Eq. (48) in [13] (for $N=4$, $n=2500$ rpm and $\omega_c=6000$ rad/s or 955 Hz) as 8 deg. From Eq. (50) in [13], $P_0=78$ deg is obtained, and thus the pitch angles are: 78, 86, 94, 102. This end mill was tested in slotting the same magnesium alloy within the speed range of 2000–4000 rpm and axial depth of cuts up to 25 mm without chatter. Therefore the chatter free axial depth of cut was increased at least 5 times, but due to the increases in rpm and feedrate (result of higher number of flutes with the same feed per tooth), the chatter free material removal rate was increased more than 30 times. Sound spectrums for different depths and spindle speeds are shown in Fig. 3.

2.2 Example 2. In this example, the milling of an airfoil made out of a titanium alloy, Ti6Al4V, is considered. The stability limit of the process is extremely small due to highly flexible workpiece and cutting tool. A 6-fluted carbide taper ball end mill with length-to-average diameter ratio of over 10 is used on a 5-axis machining center (Fig. 4). The long extension and the tapered profile makes the cutter almost as flexible as the blade. For one of the finishing passes, the axial depth of cut is over 100 mm. This is very much higher than the stability limit of the process, thus a very low spindle speed is used to maximize process damping. However, even at 300 rpm severe chatter vibrations are experienced with the equal pitch cutter. The sound amplitude and the spectrum are shown in Fig. 5. For chatter frequency of 420 Hz and spindle speed of 300 rpm, P=55, 57, 59, 61, 63, 65 pitch variation is obtained. This cutter suppresses chatter completely, as it can be seen from the sound measurement in Fig. 6. As a result, the surface finish is significantly improved as shown in Fig. 7.

2.3 Example 3. In this example, the effectiveness of the variable pitch cutters in roughing is demonstrated. For roughing operations where the axial depth of cut is very large, the feedrate is limited due to the high cutting forces which may cause tool shank breakage. Similar to finishing operations (Example 2), chatter vibrations may not be suppressed even at very low speeds. For unstable cutting operations, cutting forces increase with increased feedrate at a much higher proportion due to increased vibration amplitudes. Therefore, chatter suppression in roughing can lead to significant increase in material removal rate as high feed rates can be used. For one of the roughing cycles on a titanium alloy part (similar to the one shown in Fig. 4) the sound spectrum is shown in Fig. 8. The depth of cut varies between 100–125 mm in this 5-axis cutting cycle. The cutting tool has 6 flutes and the spindle speed is 600 rpm. For the dominant chatter frequency of 367 Hz

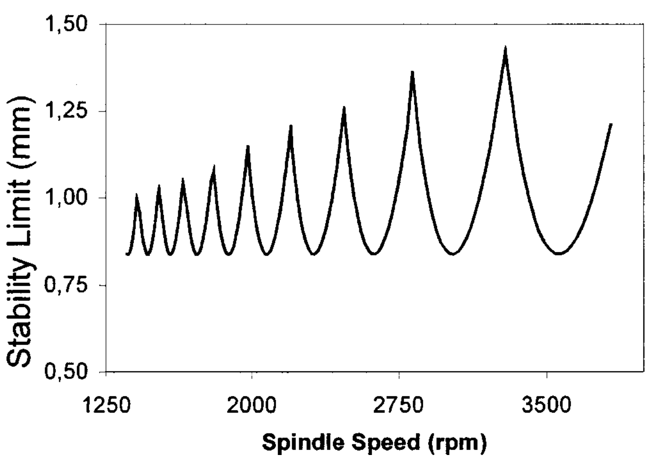

Fig. 1 Stability lobe diagram for the end mill with modal parameters shown in Table 1 for slotting magnesium

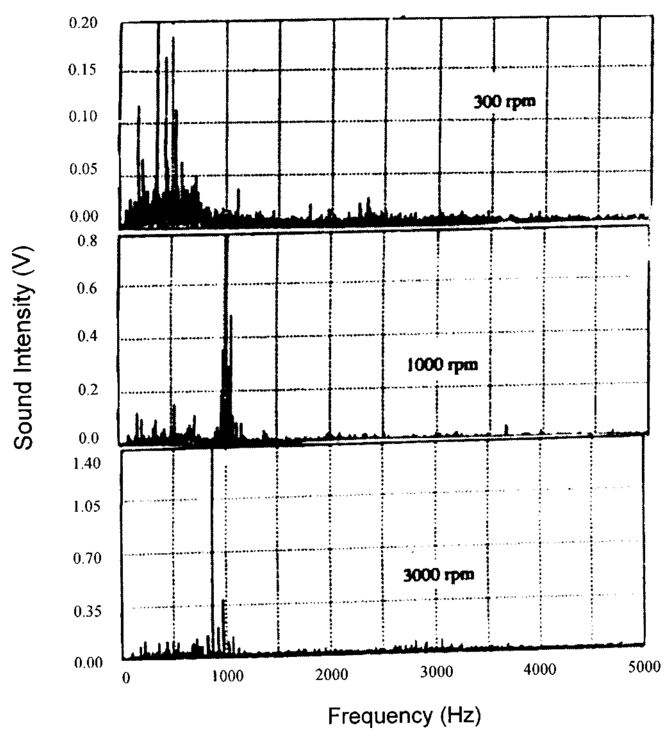

Fig. 2 Sound spectrums at different rpm's using regular pitch cutters for the slotting tests in example 1. Note different scales on Y-axis.

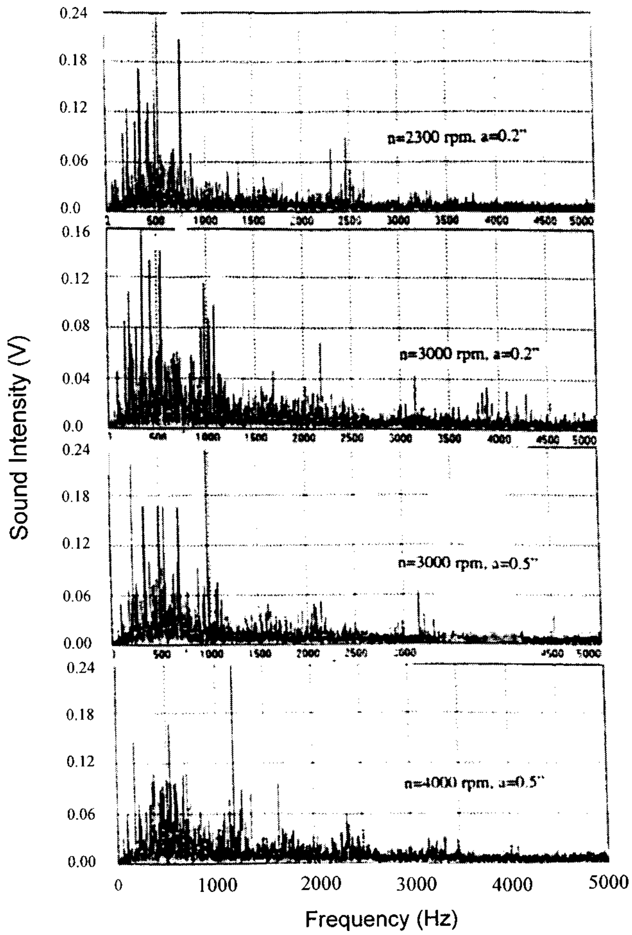

Fig. 3 Sound spectrums using the variable pitch end mill in example 1. Note different scales on Y-axis.

(as can be seen from Fig. 8), the pitch variation is determined from Eq. (48) in [13] as $\Delta P = 4.8$ deg, and the pitch angles $P = 48$, 52.8, 57.6, 62.4, 67.2, 72. When the variable pitch cutter with this configuration is used for the same roughing cycle, chatter is eliminated completely.

In order to demonstrate the effect of the variable pitch cutter on the cutting forces, force measurements were performed using a

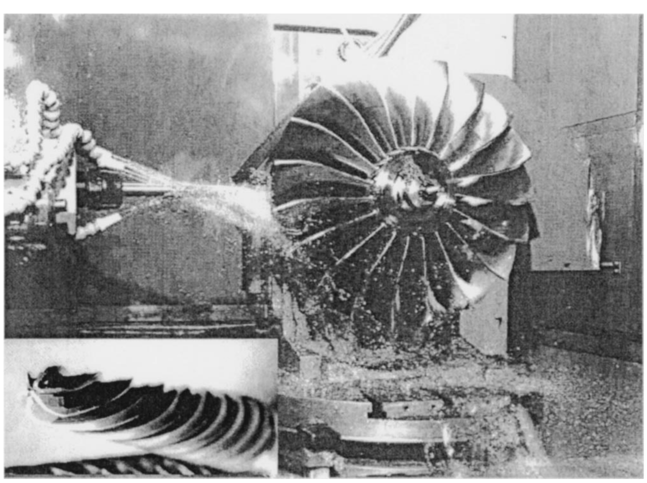

Fig. 4 Machining of the compressor and the cutting tool used in example 2

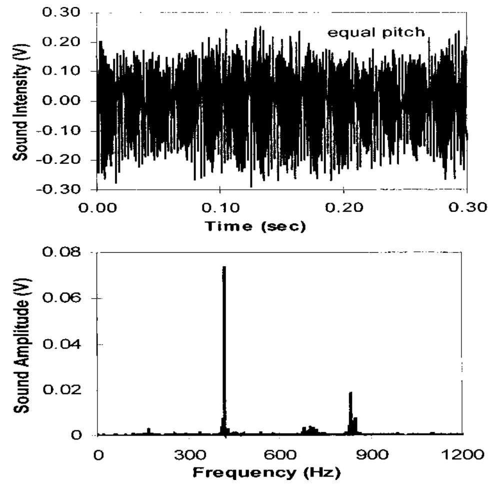

Fig. 5 Sound amplitude and spectrum with the regular cutter in example 2

Kistler rotary dynamometer. Figure 9 shows the peak resultant force variations with the original and the variable pitch end mills for the whole cycle. The pitch variation worked well even with the added flexibility on the tool due to the dynamometer. The peak cutting force varies along the tool path as a result of the changes in the depth of cut, and the angular orientation of the cutter due to 5-axis motion. As it can be seen from the figure, the peak cutting forces can be reduced up to 40% by suppressing the chatter using the variable pitch end mill. As a result, the feedrates in roughing could be increased significantly by using variable pitch roughers. In addition, some of the semi-roughing operations could be eliminated due to much better surface finish and dimensional control obtained with variable pitch cutters.

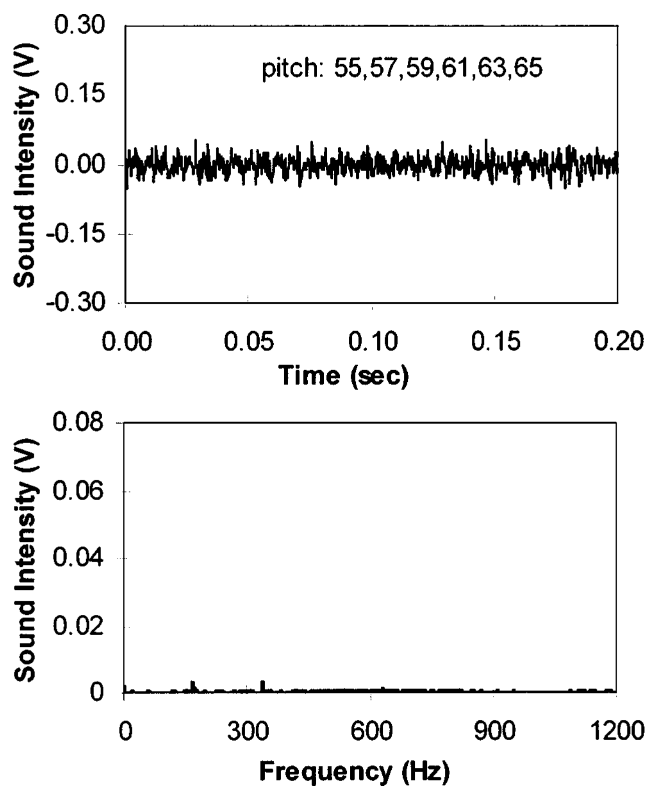

Fig. 6 Sound amplitude and spectrum with the variable pitch cutter in example 2

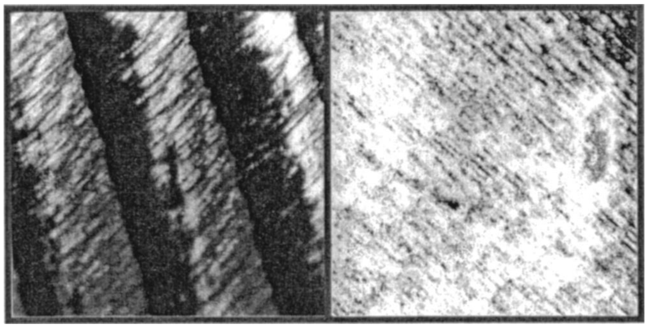

Fig. 7 Surface improvement due to variable pitch cutter in example 2

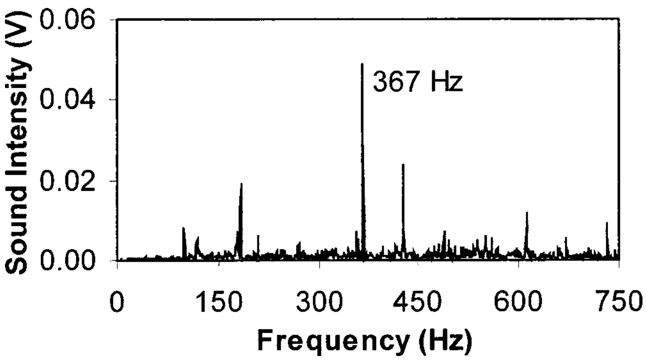

Fig. 8 Sound spectrum for example 3

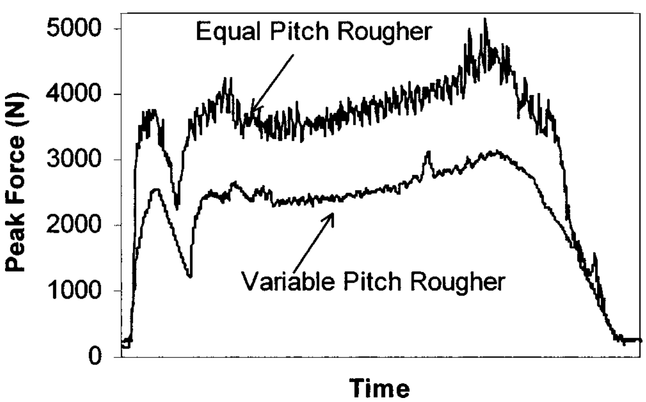

Fig. 9 Cutting forces with regular and variable pitch cutters in the 5-axis roughing cycle in example 3

3 Conclusions

In this paper, it has been demonstrated that milling cutters with nonconstant pitch can be very effective in suppressing chatter. Three examples given in the paper demonstrate increased material removal rate and improved surface finish using variable pitch cutters. Due to their effectiveness in suppressing chatter, variable pitch cutters have been implemented in production processes extensively in turbine engine manufacturing where most of the parts and tools are very flexible. When designed properly as outlined in [13], variable pitch cutters are very effective in production environment even with the some changes in chatter frequencies due to variations in machine, part and cutting tool conditions.

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