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Control of chatter by spindle speed variation in high-speed milling

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Abstract. High-speed milling operations are often limited by regenerative vibrations. The aim of this paper is to analyze the effect of spindle speed variation on machine tool chatter in high-speed milling. The stability analysis of triangular and sinusoidal shape variations is made numerically with the semi-discretization method. Parametric studies show also the influence of the frequency and amplitude variation parameters. This modeling is validated experimentally by variable spindle speed cutting tests with a triangular shape. Stable and unstable tests are analyzed in term of amplitude vibration and surface roughness degradation. This work reveals that stability must be considered at period variation scale. It is also shown that spindle speed variation can be efficiently used to suppress chatter in the flip lobe area.

Introduction

The productivity of cutting processes is severely limited by vibrations that arise during the material removal process. One reason for such vibrations is the surface regeneration. The theory of regenerative machine tool chatter is based on the work of Tobias and Fishwick [1]. This knowledge initially dedicated to the turning process has been adapted to milling [2] and led to the development of the stability lobes theory. Since then several improved model and analysis techniques have been appeared including detailed analysis of the governing delay differential equation and time domain simulations, see, for example [3,4]. These models all use the so-called stability lobe diagrams, which allows to choose the spindle speed associated with the axial depth of cut with a chatter free machining. In many practical cases, the choice of the optimal speed is difficult because contradictory parameters interact with productivity [5].

Another technique to reduce chatter vibrations is the spindle speed variation. As opposed to variable pitch cutters, spindle speed variation can effectively be used in a wider spindle speed range, since the frequency and the amplitude of the speed variation can easily be adjusted in CNC machines even during the machining process. In the 1970's, Takemura et al. [6] presented the first simple model to study the stability of variable speed machining; they predicted significant shift of the stability lobes to higher depth of cuts, but the experimental tests showed only small improvements. Sexton and Stone [7] developed a more realistic model, and they found some improvements in the stability properties for low spindle speeds. Moreover, they showed that the presence of transient vibrations may further reduce these gains.

The study of the stability for variable speed machining requires a special mathematical analysis to compute stability lobes. Tsao et al. [8] have developed a model taking the angular coordinates as variables instead of time. Inspirger and Stépán [9] showed that the semi-discretization method can effectively be used for the stability analysis of turning at variable speed. They showed that the critical depths of cut can be increased for low speeds, but for the high-speed domain, no

improvement was found. Recently, Zhang et al. [10] presents a systematic stability analysis of spindle speed variation based on a machining chatter model of non-linear delay differential equation. Experimental results were presented by Al-Regib et al. [11] showing gains on surface roughness for turning at low speed.

The modeling of variable speed milling is more complex than that of turning, since the speed variation frequency and the tooth passing frequency interact and the resulting system is typically quasi-periodic. Still, there are mathematical techniques to determine approximate dynamic properties. Sastry et al. [12] used Fourier expansion and applied the Floquet theory to derive stability lobe diagrams for face milling. They obtained some improvements for low spindle speeds. Recently, Zatarain et al [13] presented a general method in frequency domain to the problem, and show that varying spindle speed can effectively be used to chatter suppression. Another approach is to use time domain simulation [14] that makes it possible to obtain more detailed information like the amplitude of vibrations, the chip thickness or the cutting forces. Simulations were sometimes made at high speed, but to the best knowledge of the authors, experimental validations are only made at low spindle speed [11, 12, 13, 14, 15].

In this paper, the stability of variable speed milling is analyzed in the high-speed domain, for spindle speeds corresponding to the first flip (period doubling). Theoretical stability predictions are obtained using the semi-discretization method based on [4], and the results are confirmed by experiments.

Milling modeling

Variation of the spindle speed. In the literature, mostly sinusoidal, triangular or square-wave modulations are considered [16]. Here, the sinusoidal and the triangular variation shown in Fig. 1 are compared and analyzed. Assume that the spindle speed variation is periodic at period T_v with a mean value N_0 and an amplitude N_a , that is, $N(t) = N(t + T_v) = N_0 + N_a S(t)$, where $S(t) = S(t + T_v)$ is the shape function. For a triangular modulation the shape function is defined as:

$$S(t) = \begin{cases} 1 - 4 \text{mod}(t, T) / T & \text{if } 0 < \text{mod}(t, T) \leq T/2 \\ -3 + 4 \text{mod}(t, T) / T & \text{if } T/2 < \text{mod}(t, T) \leq T \end{cases} \quad (1)$$

Here, $\text{mod}(t, T)$ denotes the modulo function, for example, $\text{mod}(12, 5) = 2$. For a sinusoidal modulation $S(t)$ is defined as:

$$S(t) = \sin\left(\frac{2\pi t}{T_v}\right). \quad (2)$$

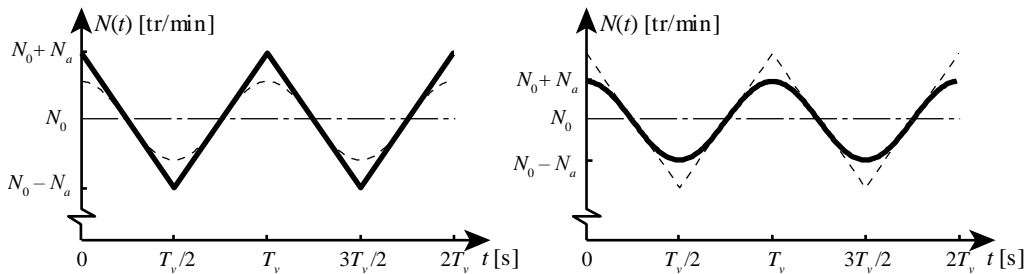


Fig. 1: Typical triangular and sinusoidal shape variation

In order to normalize amplitude and frequency variation, the well know, parameters RVA and RVF are introduced:

$$RVA = \frac{N_a}{N_0}, \quad RVF = \frac{60}{N_0 T_v} = \frac{60 f_v}{N_0}. \quad (3)$$

RVA represents the amplitude ratio between the amplitude N_a and the mean value N_0 , it is always less than 1. In order to have reasonable cutting conditions, its value was limited at 0.3. This

represents a variation of 30% of the spindle speed. This represents also a variation of 30% of the feed by tooth due to the constant feed velocity. RVF is the ratio between the variation frequency f_v and the average spindle frequency N_0 . It may be higher than 1. If RVF equal to 1, then the spindle makes one variation period during only one revolution of the tool.

Mechanical model. A schematic diagram of the milling process is shown in Fig. 2. The structure is assumed to be flexible in the x direction, while the feed is parallel to the y direction.

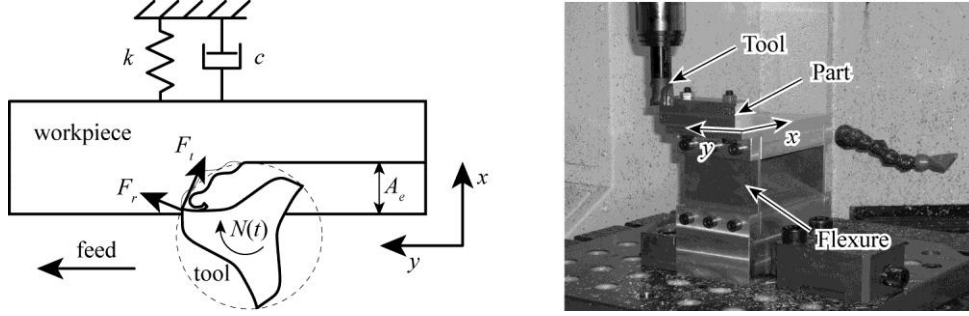


Fig. 2: Mechanical model of the milling process

The dynamic model is given by the following equation:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_x(t), \quad (4)$$

where m is the modal mass, c is the damping, k is the stiffness and $F_x(t)$ is the cutting force in the x direction. According to a linear cutting law, the x component of the force is given by:

$$F_x(t) = A_p \sum_{j=1}^z \left[(K_R \cos \varphi_j - K_T \sin \varphi_j) h_j(t) \right], \quad (5)$$

where A_p is the axial depth of cut, φ_j is the angular position of the j th cutting edge and K_T and K_R are the specific tangential and radial cutting coefficients. The chip thickness is expressed by:

$$h_j(t) = g_j(t) \left\{ f_z \sin \varphi_j + [x(t) - x(t - \tau(t))] \cos \varphi_j \right\}, \quad (6)$$

where the function $g_j(t)$ is a unit function, it is equal to 1 when the tooth j is cutting, otherwise it is equal to 0. Here, f_z is the feed per tooth, $x(t)$ is the current position of the tool and $x(t - \tau(t))$ is the position at the previous cut. The regenerative delay $\tau(t)$ is periodic in time due to the spindle speed variation.

Stability analysis. Stability of the milling process with variable spindle speed can be estimated theoretically via the analysis of the governing Eqs. (4), (5) and (6). According to the Floquet theory of delayed differential equations [4], an infinite dimensional operator Φ (monodromy operator) can be associated with the system that gives the connection between the current state of the cutter and the state one period earlier:

$$x(t+T) = \Phi x(t). \quad (7)$$

This period T is equal to the principal period of the system. Thus, for the milling model with spindle speed variation, the regenerative time delay τ and the spindle modulation period T_v are periodic. We assume that the ratio of the modulation period T_v and the mean time delay τ is a rational number, i.e., $qT_v = p\tau$ with p and q being relative primes. Thus, the system is periodic at the principal period $qT_v = T$ consequently, the Floquet theory of periodic DDEs can be applied. Note that if the ratio of T_v and τ is not rational, then the system is quasi-periodic and the Floquet theory cannot be used. Stability properties are described by the eigenvalues of the monodromy operator. If all the characteristic multipliers are in modulus less than 1, then the system is asymptotically stable. Here, the semi-discretization method [4] is used. The basic point of this method is that they provide a finite dimensional matrix approximation of the monodromy operator and the eigenvalues of this

matrix can be determined numerically. This method was validated by time domain simulation [17].

Selection of the optimal parameters

Optimal area. Stability lobe can be constructed by scanning the cutting conditions (spindle speed and axial depth of cut) for a couple of (RVA , RVF) parameters and for a given shape. Fig. 3 presents the lobes for constant, triangular and sinusoidal spindle speed.

The critical depth of cut can be seen to be increased by speed variation for some ranges of spindle speeds, but for some other ranges, the critical depth of cut is less than that of the constant spindle speed. For example, a cutting process with an axial depth of cut of 1 mm and a spindle speed of 9100 rpm – that is unstable for constant spindle speed – can be stabilized by a speed variation. But globally, the critical depth of cut can be seen to be increased essentially in the area of the first flip lobe by spindle speed variation.

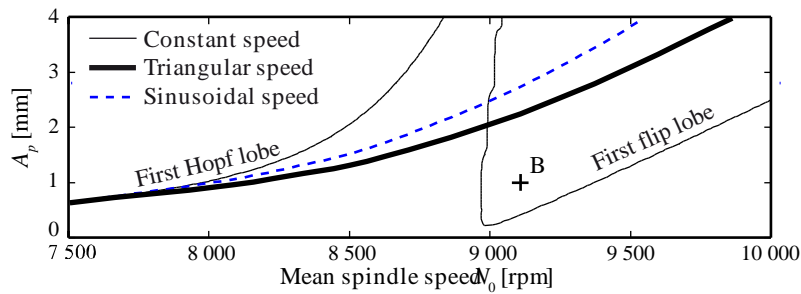


Fig. 3: Stability diagrams for variable speed milling with $RVA = 0.3$ and $RVF = 0.003$

Comparison of the shape variation. The effectiveness of the spindle speed variation is tested on a flip lobe area ($N_0 = 9100$ rpm) with a triangular and sinusoidal shape variation.

Fig. 4 shows a contour plot presenting the maximal depth of cut available without chatter for the amplitude (vertical axis) and frequency (horizontal axis) with an average spindle speed of 9100 rpm. At constant speed, the maximal depth of cut is 0.5 mm. It can be seen that the triangular shape always increase the critical depth of cut A_p for any RVA and RVF values. For some domains, even $A_p = 2.4$ mm can be achieved that corresponds to 380% improvements. As mentioned earlier, the choice of the frequency and the amplitude variation is limited by the spindle dynamics. Within the range of variation, the maximum acceleration of the spindle is 100 rev/s^2 , i.e., 6000 rpm/s. Considering the limits of the dynamic spindle for the triangular shape, the optimal choice is to use low frequency modulation with high amplitude. Such a point is denoted by point D or E.

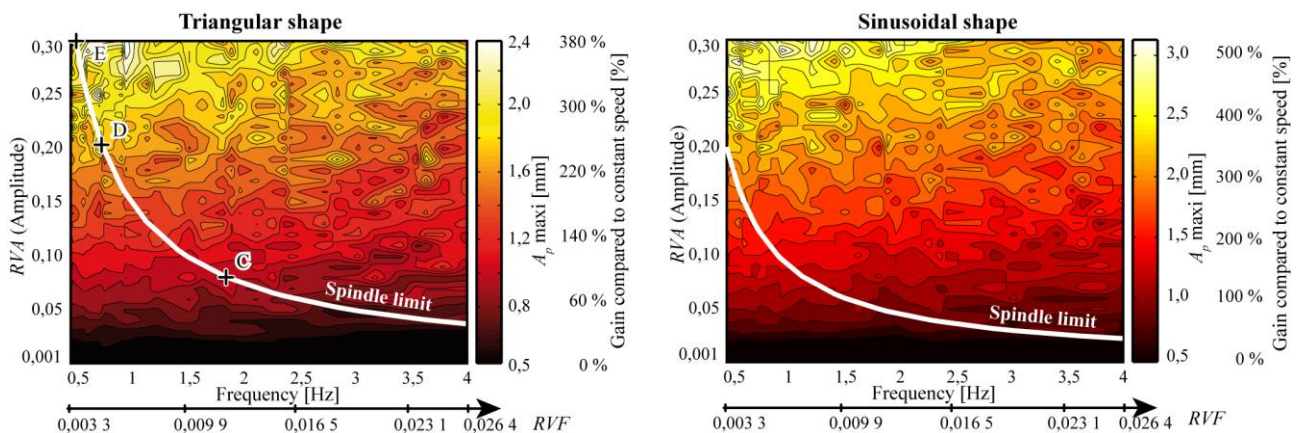


Fig. 4: Parametric study for triangular and sinusoidal shape ($N_0 = 9100$ rpm and $A_e = 2$ mm)

A similar plot is determined for a sinusoidal shape in Fig. 4. Like the triangular shape, the sinusoidal shape always increases the critical depth of cut. For some area, an improvements of 500% can be achieved ($A_p = 3$ mm). In fact, for a same frequency and amplitude parameters, the

sinusoidal shape is more effective than the triangular shape. But if we consider the limit of the spindle, the sinusoidal shape gives – for the machinist – only an improvement of 300%. In fact, the sinusoidal shape needs more acceleration than the triangular shape (see Fig. 1). For a given spindle dynamic, the sinusoidal shape allows no more improvements.

Surprisingly, a high frequency of variation, coupled with a low amplitude variation, produce a little gain. The most effective parameter is the amplitude variation.

Because triangular shape allows – for a given dynamic spindle – the maximal gain for the machinist, only this spindle speed variation was analyzed in the experimental part.

Experimental work

The machining tests were carried out on a high-speed milling center. The average feed by tooth is 0.1 mm/tooth. The tool is an inserted mill with 3 teeth, 25 mm diameter without helix angle. The spindle speed rotation is managed by a sub-program using a synchronous function.

A removable part in aluminum alloy (2017A) is machined in contouring with a radial depth of cut (A_e) of 2 mm. Fig. 2 shows the experimental set-up of the single degree of freedom flexure, compliant in the x direction. The tool is considered infinitely rigid compared to the workpiece. The vibrations of the part were measured by a laser velocimeter.

Collected in Table 1, the dynamic characteristics of the system were determined by hammer impact test and the cutting force coefficients were determined in coherence with previous work [5].

Table 1: Flexure modal parameters and cutting coefficients

m [kg]	f_0 [Hz]	ξ [%]	K_T [MPa]	K_R [MPa]
1.637	222.5	0.50	700	140

Some special cases. Firstly, cutting tests were conducted at spindle speed of 9100 rpm with $RVA = 0,005$, $RVF = 0,15$ ($f_v = 22,75$ Hz) and a depth of cut of 1mm. This test uses the maximum acceleration of the spindle with high frequency variation and low amplitude. The results thus obtained are presented in Fig. 5. Test (A) refers to the variable speed machining, test (B) to the constant spindle speed machining (note that these cutting parameters are in the first flip lobe, see point B in Fig. 3). Based on the theoretical predictions, these two tests are unstable.

The displacement measured with and without spindle speed variation is the same. Moreover, these two unstable machining generates exactly the same poor surface roughness on the workpiece. For this unstable machining, chatter is clearly identified.

Both machining shows also the minor importance of the variation frequency, like simulation predicts. It is not necessary to change very fast the spindle speed, even with maximum acceleration, because this is not the most important parameter.

Then, other cutting tests were performed at spindle speed of 9100 rpm and depth of cut of 1 mm using variable spindle speed with $RVA = 0.08$, $RVF = 0.0125$ ($f_v = 1.9$ Hz). This variation corresponds to point C in Fig. 4. Based on the theoretical predictions, the critical depth of cut is about 0.8 mm, i.e., the process is unstable.

Fig. 6 shows the recorded displacement history and the surface roughness variation during the cutting process. After about two periods of speed variation, the amplitude of the displacement increases very strongly. The envelope curve of the vibrations is illustrated by dashed lines. This behaviour corresponds to the predicted instability. However, chatter does not appear suddenly – some time is needed for it fully develops. In the case of our cutting test, this time span is about 0.7 s. If the duration of the machining process is less than this period, then large amplitude vibrations do not develop. In a sense, this case can be considered as "practically stable" machining, in spite of the fact that the process itself is globally unstable. If the duration of the machining process is longer, then chatter develops.

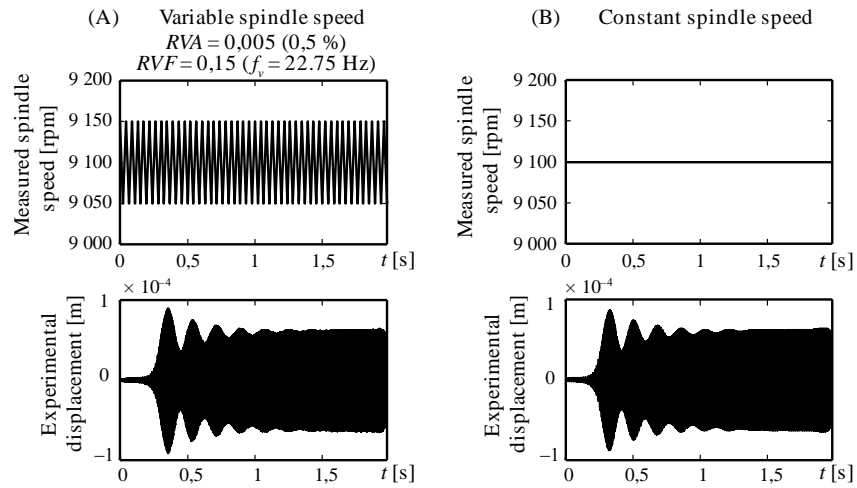


Fig. 5: Two machining unstable ($A_p = 1$ mm and $N_0 = 9100$ rpm)

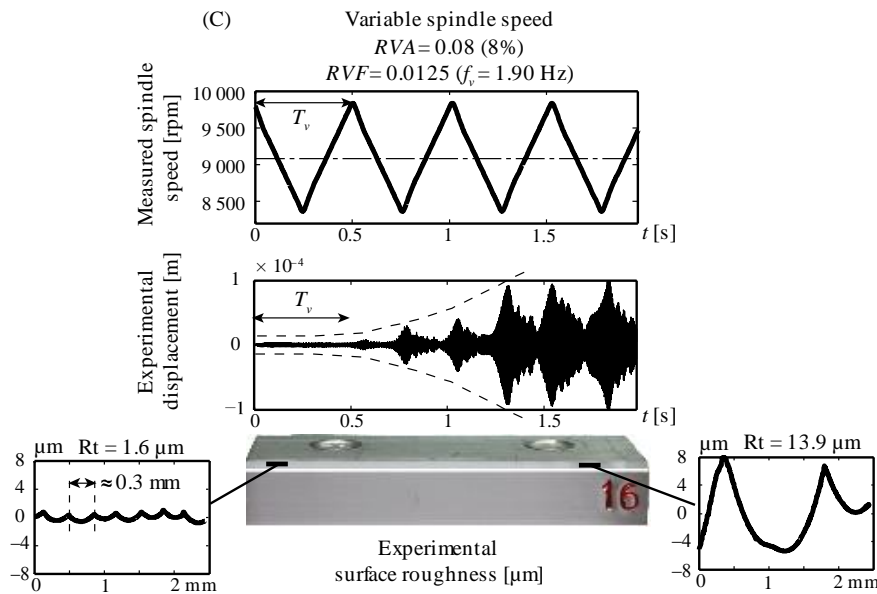


Fig. 6: Analysis of an unstable machining ($A_p = 1$ mm and $N_0 = 9100$ rpm)

This effect can also be observed on the surface roughness of the workpiece. The left hand side of the machined profile, where the cutting was started, has a pitch of approximately 0.3 mm, with roughness of 1.6 μm . For an ideally symmetric tool, the pitch of the machined profile is equal to the feed per tooth. However, if the tool has a runout greater than the roughness of the surface, then it leaves only one mark per revolution. The tool used in the tests had a runout of 10 μm , the feed per tooth was 0.1 mm and the tool had 3 teeth, thus the pitch of the machined profile is expected to be approximately 0.3 mm for stable machining. In fact, the pitch varies slightly around 0.3 mm, since the constant feed velocity and the variable spindle speed produce a varying feed per tooth. As the tool passes over and chatter develops, the surface roughness gets worse and worse. By the end of the workpiece, the roughness increased to 13.9 μm .

Stabilization by spindle speed variation. Consider the unstable machining process with spindle speed of 9100 rpm and depth of cut of 1 mm. Spindle speed variation is applied according to point D in Fig. 4. The corresponding parameters are $RVA = 0.2$, $RVF = 0.0046875$ ($f_v = 0.71$ Hz). Based on the theoretical predictions, the critical depth of cut is about 2 mm, i.e., the system with variable spindle speed is predicted to be stable. In Fig. 7, test (D) refers to the variable speed machining and test (B), to the constant spindle speed machining.

During the test with variable spindle speed, no chatter was observed. The amplitude of the vibrations was less than 0.01 mm, the roughness was 1.75 μm and the pitch of the machined profile was 0.3. For a 3 fluted tool with runout of 10 μm and feed per tooth 0.1 mm, this corresponds to stable machining. These all refer to a stable cutting process.

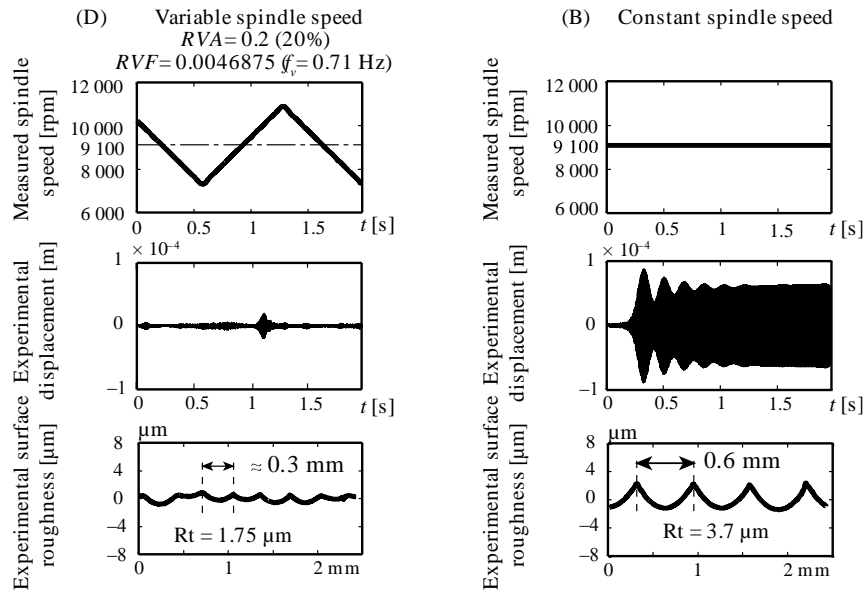


Fig. 7: Chatter suppression by spindle speed variation ($A_p = 1$ mm and $N_0 = 9100$ rpm)

For constant spindle speed, chatter was clearly identified. The amplitude of the vibrations was about 0.07 mm, the roughness was $3.7 \mu\text{m}$ and the pitch of the machined profile was 0.6 mm that refers to the period doubling chatter (see point B in Fig. 3). In these cases, identification of chatter was unambiguous, the pitches of the machined profiles were uniform all along the workpiece.

Conclusions

Variable spindle speed machining was studied for high-speed milling at around the first flip lobes. Stability properties were predicted using the semi-discretization method. Moreover different combinations of the amplitude and the frequency of the speed modulation were analyzed in order to find the optimal technique to suppress chatter. It was found that the stability properties can always be improved (i.e., the critical depth of cut can always be increased) by spindle speed variation within the unstable domain of the first flip lobe. Amplitude was also shown to have a greater effect on the stability of the process than frequency. In this way, for a given dynamic spindle, the triangular shape allows the maximal gain for the machinist.

Cutting tests were performed for certain spindle speeds in the flip domain in order to verify the theoretical predictions. The concept of stability for variable spindle speed machining was shown to differ slightly from than of constant spindle speed, since the principal period of the system is equal to the spindle variation period (or to its integer multiple) instead of the tooth passing period. If the machining process is unstable, but the development of chatter requires more time than the duration of the process, then it can be considered as "practically stable" machining. The stabilizing effect of spindle speed variation was clearly verified experimentally, a period doubling chatter was suppressed by applying a proper spindle speed variation.

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