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Analysis of Spindle Speed for Maximum Chatter Doubling of High Frequency Milling Spindle

Anandkumar Telang
Department of Mechanical Engineering,
BKIT, Bhalki, INDIA

(Corresponding author: Anandkumar Telang)

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ABSTRACT: Machining is a material removal process that alters the dynamic properties during machining operations. In the current paper, spindle speed variation is applied to the high speed milling process, at the spindle speeds where the constant cutting speed results in chatter stability. The stability analysis of triangular and sinusoidal shape variations is made numerically with the semi-discretization method. It is shown that the milling process can be stabilized by increasing the amplitude of the spindle speed variation, while the frequency of the variation has no significant effect on the dynamic behaviour. It is demonstrated that the stability diagram for an application can be modified in a predictable manner in order to maximize the chatter-free material removal rate by selecting favourable system parameters using the analytical model developed. The predictions of the model, which are based on the methodology proposed in this study, are also experimentally verified. Based on the analysis of the machined workpieces, it is shown that the surface roughness can also be decreased by the spindle speed variation technique. Important conclusions are derived regarding the selection of the system parameters at the stage of machine tool design and during a practical application in order to increase chatter stability.

Keywords: chatter, stability, milling, spindle speed variation, surfaceroughness

I. INTRODUCTION

Productivity of machining is often limited by vibrations that arise during the cutting process. These vibrations cause poor surface finish, increase the rate of tool wear and reduce the spindle lifetime. One reason for these vibrations is the surface regeneration, i.e., the tool cuts a surface that was modulated in the previous cut.The theory of regenerative machine tool chatter is based on the work of Tobias and Fishwickand led to the development of the stability lobes theory. Since then several improved modeling and analysis techniques have appeared including detailed analysis of the governing time-periodic delay-differential equation and time domain simulations [2]. These techniques are used to construct the so-called stability lobe diagrams that help in selecting the spindle speeds and the axial depths of cut associated with a chatter free machining. These stability diagrams present the stability boundaries that separate stable machining from chatter.

Close to the stability boundaries, the rate of change of the vibration amplitudes is small (i.e., the exponential time constant is large), consequently, the identification of stable machining or chatter might be not so clear as for parameter points far from the stability boundaries. For instance, in case of a machining operation with parameters just slightly above the stability boundaries, the operation may be terminated before chatter fully develops. In many practical cases, the choice of the optimal speed is difficult because many coupled parameters interact non-linearly in a production.The main source of chatter vibrations is a subtle shift between the vibrations of the workpiece or tool and the tooth passing frequency. This phase shift leads to a chatter frequency slightly lower or higher than a multiple of the tooth passing frequency. In the particular case of chatter doubling period, there is a perfect synchronism between the half tooth passing frequency and the chatter frequency.

One possible way to suppress chatter is the application of variable tool pitches and the other techniqueis to reduce chatter vibrations in the continuous spindle speed variation. Both techniques are based on the disturbance of the regenerative effect by creating varying tooth passing periods. Compared to variable pitch cutters, spindlespeed 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. The study of the stability for variable speed machining requires a special mathematical analysis to compute stability lobes. Tsao *et al.* have developed a model taking the angular coordinates as variables instead of time. Insperger and Ste´pa´n showed that the semi-discretization method can effectively be used for the stability analysis of turning at variable speed [4].

They showed that the critical depths of cut can be increased for low speeds, but for the high-speed domain, no improvement was found. Experimental results were showing gains on surface roughness for turning at low speed. Recently, Zhang et al. presented a systematic stability analysis based on a model of a non-linear delay differential equation. Experimental validations in turning show reduction of the displacement and improvements in the surface roughness at low speed.The modeling of variable spindle 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. used Fourier expansion and applied theFloquet theory to derive stability lobe diagrams for face milling. They obtained some improvements for low spindle speeds. Recently, Zatarain et al. presented a general method in the frequency domain to the problem, and showed that varying spindle speed can effectively be used for chatter suppression.

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) lobe. Theoretical stability predictions are obtained using the semi-discretization method and the results are confirmed by experiments. First themodel of the process is presented. Then triangular and sinusoidal spindle speedmodulations are compared and the selection of the optimal amplitude and frequency is presented. Experimental verifications are provided withdetailed analysis of the machined surface.

II. MECHANICAL MODELLING

A. Variation of the Spindle Speed

In the literature, mostly sinusoidal, triangular or square-wave modulations are considered. Here the sinusoidal and the triangular variations shown in Figure 1 are compared and analyzed. We 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, $N(t)=N(t+T_v)=N_0+N_aS(t)$, where $S(t)=S(t+T_v)$ is the shape function. For a triangular modulation the shape function is defined as[6]:

$S(t) = 1 - 4 \bmod(t, T_v)/T_v$ if $0 < \bmod(t, T_v) \leq T_v/2$ &

$-3 + 4 \bmod(t, T_v)/T_v$ if $T_v/2 < \bmod(t, T_v) \leq T_v$

Here, $\bmod(t, T_v)$ denotes the modulo function. For a sinusoidal modulation S(t) is defined as:

$S(t) = \sin(2\pi t/T_v)$

To normalize amplitude and frequency variation, the parameters RVA and RVF are introduced:

$RVA = N_a/N_0$ & $RVF = 60/N_0T_v = 60f_v/N_0$

RVA represents the ratio of 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% in the spindle speed and a variation of 30% in the feed by tooth at the same time due to the constant feed velocity. RVF is the ratio of the variation frequency fv and the average spindle frequency N_0.

For given spindle speed acceleration, different shape functions result in different maximum amplitude. Figure 1 presents sinusoidal and triangular speed modulations for a fixed maximal spindle acceleration. It can be seen that the triangular modulation provides larger amplitude than the sinusoidal one for a given maximal spindle acceleration.

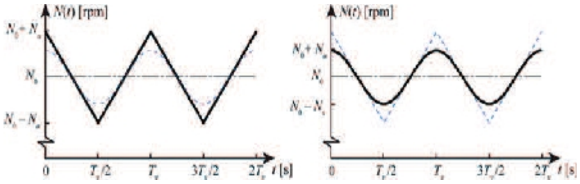

Fig. 1. Typical triangular and sinusoidal shape variation.

B. Mechanical Model

A schematic diagram of the milling process is shown in Figure 2. The structure is assumed to be flexible in the x direction that is perpendicular to the feed.The governing equation for the single degree of freedom oscillator model is:$mx(t) + cx(t) + kx(t)=F_x(t)$

where m is the modal mass, c is the damping, k is the stiffness and $F_x(t)$ isthe x component of the cutting force.

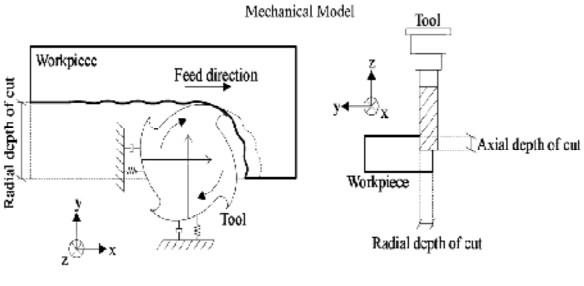

Fig. 2. Mechanical model of the milling process [13].

C. Stability Analysis

Stability of the milling process with variable spindle speed can be estimated theoretically via the analysis of the governing Equations and can be written in the delay-differential equation in the form:$x(t) = A(t)x(t)+B(t)u(t)-(t-\tau(t))$.

If the modulation period T_v is rationally related to the mean time delay ($\tau_0=60/zN_0$), i.e., $pT_v=q\tau_0$ with p and q being relative primes, then the system is purely periodic at period $T=pT_v=q\tau_0$. For this case, the Floquet theory of delayed systems can be applied with the principal period T. However, if $T_v=\tau_0$ is not a rational number, then the system is quasiperiodic, and the Floquet theory does not apply.

A triangular shape variation with p=4 and q=15 is shown in Figure 3. For this example, the amplitude variation is 20% and the RVF=0.8. The evolution of the function H(t) is also presented. The common period is $T=4Tv=15\tau_0$, i.e., 15 tooth passes spaced with variable delays τ(t) occur during the period of four speed modulations.

In the current analysis, parameters are selected so that T_v and τ_0 are rationally related and the Floquet theory can be applied. This assumption may seem restrictive, since these two parameters are in general not rationally related, and the system is therefore quasi-periodic. Still, this assumption will be used in the analysis. The explanation is that for any pair of T_v and τ_0, one can give a rationally related pair $T_v$and τ_0 (i.e., p T_v = q τ_0 with p and q being integers) that are close enough to the original pair T_v and τ_0. From practical point of view, it is reasonable to assume that the behaviour of the two systems are similar, although the mathematical theorems for the stability analysis of the quasi-periodic systems are more difficult than they are for the periodic system with T_v and τ_0.

According to the Floquet theory, the stability of a time-periodic system is determined by the eigen values of the associated monodromy operator. If all the eigen values are in modulus less than 1, then the system is asymptotically stable. In general, this operator is infinite dimensional with infinitely many eigenvalues, but it can be approximated by finite dimensional matrices. Here, we apply the semi-discretization to derive stability properties.

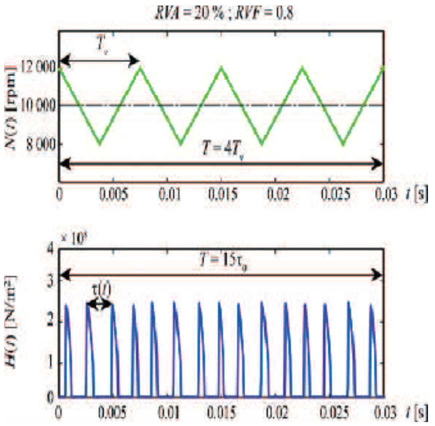

Fig. 3. Principal period determinations.

III. SELECTION OF OPTIMAL PARAMETERS

A. Optimal Area

Stability lobes can be constructed numerically by scanning the cutting conditions (spindle speed and axial depth of cut) for a couple of (RVA, RVF) parameters. Figure 4 presents the lobes for constant, triangular and sinusoidal spindle speeds at the region of the first flip and first Hopf lobes. 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 1mm and a spindle speed of 9100 rpm – that is unstable for constant spindle speed can be stabilized by a speed variation. Globally, the critical depth of cut can essentially be increased in the area of the first flip lobe by spindle speed variation. We did not test all cases to make a complete generalization, but we have given the various simulations that seem to be quite general.

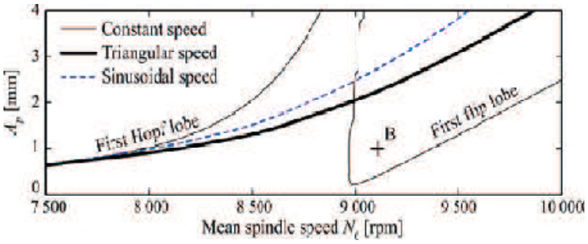

Fig. 4. Stability diagrams for variable speed milling [6].

IV. EXPERIMENTAL WORK

The cutting tests were conducted on a 3-axis high-speed milling centre (Huron, KX10). The tool was an inserted mill with three teeth, 25mm diameter without helix angle. The average feed per tooth was 0.1mm=tooth. The spindle speed modulation was controlled by a sub-programusing a synchronous function. A removable part in aluminium alloy (2017A) was machined with aradial depth of cut (A_e) of 2 mm. For such a small radial immersion, thenumber of cutting teeth engaged to the workpiece is changing between 0and 1. Figure 5 shows the experimental setup. The workpiece was fixed toa flexure that was compliant in the x direction in order to assure thesingle degree of freedom system. The tool was considered to be rigid compared to the flexure. The vibrations of the part were measured by a laservelocimeter (Ometron, VH300+). Filtering was achieved with a high pass filter, Butterworth 14 order type, with a 50 Hz cutoff frequency. This numerical filtering was followed by a numerical integration with the ode45 solver. The measurement of the static displacements is not possible using a velocimeter signal, especially for machining conditions where laser beam may be crossed by particles. This filtering is coherent with the chatter phenomenon studied, mainly over 100 Hz.

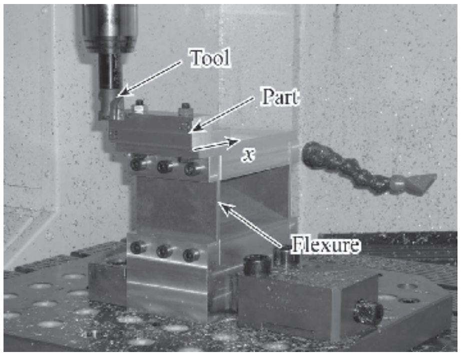

Fig. 5. Experimental setup.

A. Constant Spindle Speed Test

To verify the model, a series of tests at a constant speed has been conducted. The experimental results have been superimposed onto a plot of the theoretical stability predictions in Figure 6. Cutting tests were declared stable if the 1=rev sampled position of the part approached a steady constant value and this information was also correlated by frequency analysis. Stable cutting tests are denoted by circle while unstable tests by crosses. The predicted behaviour of the system agrees well with the experiments. The classical Hopf lobes were just checked by some focused tests, while the area of period doubling chatter at the firstflip lobe was explored using a finer resolution of the spindle speed.

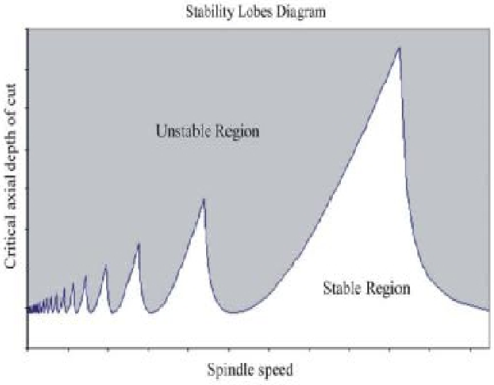

Fig. 6. Stability lobe diagram[13].

B. High Frequency Spindle Speed Variation

Cutting tests were conducted at spindle speed of 9100 rpm with RVA=0.005, RVF=0.15 and a depth of cut of 1mm. In this range of variation, the maximum acceleration of the spindle was measured: 70 rev/s^2, i.e., 4200 rpm/s. The results are presented in Figure 7.The envelopes of the measured displacements are approximately the same for both the constant and the varying spindle speeds, and both machining operations have generated similarly poor surface roughness on the workpiece. These cases demonstrate that high frequency of the spindle speed modulation has a minor effect on the performance.

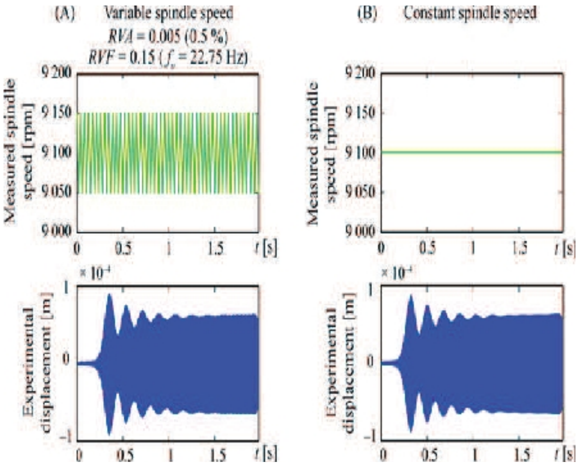

Fig. 7. Two machining unstable for A_p=1mm and N_0=9100 rpm [6].

C. Low Frequency Spindle Speed Variation

Here the cutting tests are presented where the frequency of the speed modulation is low, about 1 Hz. Consider the machining process with spindle speed 9100 rpm and depth of cut 1mm. For constant spindle speed, this process is unstable and for high frequency spindle speed variation with low amplitude (RVA=0.005, RVF=0.15), the chatter still develops, i.e., the system is still unstable. Thus we apply the spindle speed variation and the corresponding parameters with RVA=0.2, RVF=0.0046875 (f_v=0.71 Hz). Based on the theoretical predictions, the corresponding critical depth of cut is about 2 mm, thus the machining operation with depth of cut 1mm is predicted to be stable. Figure 8 presents the experimental results obtained for the cutting test with low frequency spindle speed variation that confirms the theoretical prediction.

At constant spindle speed (Figure 9), chatter was clearly identified. The amplitude of the vibrations was about 0.07 mm. While theapplication of high frequency spindle speed variation with RVA=0.005and RVF=0.15 does not result in any improvement in the stability for the low frequency modulation of the spindle speed with RVA=0.2 and RVF=0.0046875 stabilizes the process and reduces the amplitudes of the vibrations to 0.01mm as shown in Figure 8).

The feed per tooth was 0.1mm for all machining operations. Without vibrations, the three fluted tool would leave a machined profile of pitch 0.3mm due to the runout (since the profile is generated by the tooth with the maximum radial runout). For the constant speed cutting in Figure 9, this pitch is 0.6 mm, which refers to the period doubling phenomena, i.e., this mark is left after two complete rotation of the tool. The corresponding surface roughness was 3.7 mm.

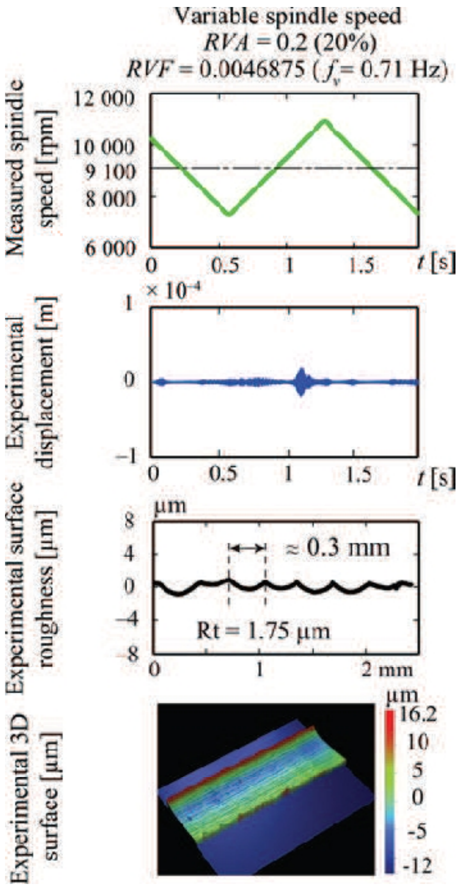

Fig. 8. Chatter suppression by spindle speed variation for A_p=1mm and N_0=9100 rpm.

This phenomenon is clearly presented on the 3D view of the machined surface in Figure 9. During the tests with low frequency spindle speed variation, no chatter was observed (shown in Figure 8). In this case, the pitch is 0.3 mm, i.e., the profile was generated during a single rotation of the tool. The surface roughness was reduced to 1.75 mm that corresponds to 50% improvement. The 3D view in the Figure 8 shows a smoother machined surface, as well.

V. CONCLUSIONS

In this paper, variable spindle speed machining, on a single DOF system, was investigated for high-speed milling at the first flip lobes. Based on both numerical simulation and from experiments using specific cutting operation parameters, the following points can be concluded:

1. Spindle speed variation technique was analyzed for different variation amplitudes and frequencies. It was found that the critical depth of cut increases mainly with the amplitude of the variation, while the frequency of the variation has no significant effect on the dynamic behaviour of the process even in the case of high frequency variation reaches RVF≈1. The amplitude of the speed variation is more important from stability point of view than its frequency.
2. The semi-discretization method is an effective and reliable method for the prediction of stability properties for milling operations with spindle speed variation.
3. Triangular and sinusoidal speed modulations were compared in order to find the optimal technique to suppress chatter. It was found that the sinusoidal shaped modulation is more effective than the triangular one, for the same amplitude and frequency parameters. However, for the same spindle dynamics the triangular shape allows larger modulation amplitude. In fact, the triangular shape allows the maximal gain for the machinist.
4. The surface roughness of the machined workpiece was improved when the spindle speed variation was applied.
5. The stabilization effect of spindle speed variation was confirmed by experiments. Chatter was effectively suppressed by applying low frequency spindle speed variation, while the process was unstable both for constant speed variation and for high frequency spindle speed variation.

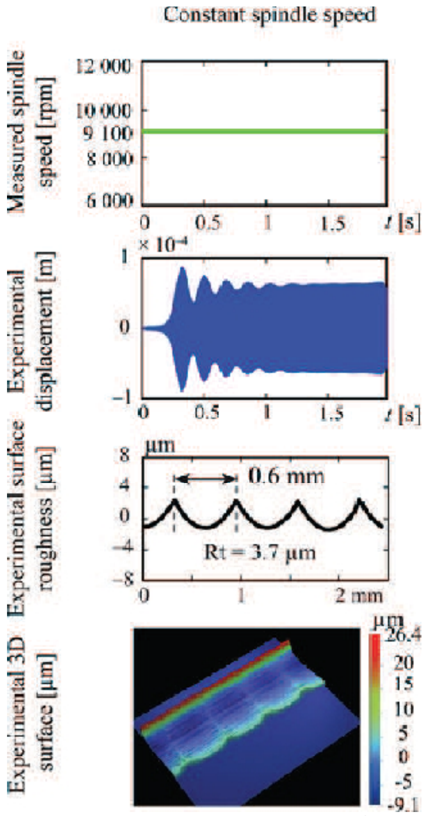

Fig. 9. Constant spindle speed machining for A_p=1mm and N_0=9100 rpm.

6. Finallyit should be noted that in practice it might be easier to change the spindle speed to stable parameter domains rather than applying spindle speed variation, which is highly power consuming. However on a complex part with multiple modes, the structure of the stability diagram is complex and usually unknown for the machinist.

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