MACHINING PARAMETERS SELECTION TO AVOID CHATTER IN HIGH SPEED MILLING

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Abstract. High speed milling exerts great demands on the dynamic behavior of machine-tool-workpiece system. The results of the process depend on the amplitudes of the relative vibrations between workpiece and tool, which arise during the operation. Best results can be achieved only if the process is kept in stable conditions free of chatter. In this paper, it is investigated the relative importance of spindle speed, system dynamics, and depth of cut on the stability of the high speed end milling of aluminum through computational simulations and experiments. Slotting operations were performed on aluminum workpieces using carbide endmills. The results showed that the spindle rotations, which permit the use of high axial depth of cuts without chatter are those whose tooth passing frequency approach to the natural frequency of the system. In this case the forced vibrations are at their highest, but the regenerative ones, which are more critical, are at their lowest. The selection of these spindle rotations is one way to minimize chatter problems and increase material removal rate.

Keywords. *high speed milling, chatter, regenerative vibrations.*

1. Introduction

High speed milling is a cutting process, which has a great potential. Its advantages include the production of improved surface finish and burr free edges components at high material removal rates. However, high speed milling exerts great demands on the dynamic behavior of machine-tool-workpiece system. The results of the process depend on the amplitudes of the relative vibrations between workpiece and tool, which arise during the operation. They can achieve unacceptable levels and deteriorate the surface finish and reduce tool life, especially in situations, which there are an inherent lack of rigidity of the system. These conditions are often found in end milling of thin walled aircraft and automotive structures, and machining of moulds and dies, whose geometries demand the use of long tools to mill deep pockets. End milling of these components is a difficult task. The static deformations produce dimensional errors and the dynamic displacements deteriorate the surface finish. To avoid the problem, the material removal rate is often reduced, abdicating the power and torque available on the spindle. Without a clear understanding about what causes chatter, and the available solutions to chatter problems, many existing machines are underutilized.

According to Tlusty (1986), machine tool chatter vibrations are characterized by the oscillation of the system in one or more natural frequencies, without the interference of external forces. The main source is the self-excitation mechanism in the generation of the chip thickness during the operation. Whether or not they happen depends on the structure of the machine and workpiece (rigidity, damping and mass), orientation of its mode of vibration and cutting conditions. According to Altintas (2000), the self excited vibrations chatter vibrations may be caused by mode coupling or regeneration of the chip thickness. The mode coupling chatter occurs when there are vibrations in two directions in the plane of cut. The regenerative chatter results from phase differences between the vibration waves left on both sides of the chip and occurs earlier than the mode coupling chatter in most machining cases. Vibrations can also occur due to an external variable force, like the tooth impacts in interrupted cutting and the spindle run-out.

In this paper, it is investigated the relative importance of spindle speed, system dynamics, and depth of cut on the stability of the high speed end milling of aluminum through computational simulations and experiments. The stability evaluation was based on the workpiece surface finish.

2. Metodology

The cutting tests were conduced on a high-speed milling center, Hermle C800U, with a maximum spindle rotation rate of 16.000 rpm and power output of 15 kW. The workpiece material was an aluminum alloy (7075-T6). Four and six flutes, 16 mm diameter, tungsten carbide endmills were used in the cutting tests. The stability evaluation was based on the workpiece surface finish. The surface roughness was measured by using a Perthometer S8P, Feinpruef Gmb H. The surface roughness values represent a relative measurement of the process stability. A stable process is characterized by a relative fine surface finish, while an unstable process is associated to a deteriorated one.

The system transfer functions or frequency response function were obtained by attaching an accelerometer to the end of the tool, striking the tool in the direction of the accelerometer with an instrumented hammer and recording the signals simultaneously. The fast Fourier transform (FFT) was calculated for each signal and the acceleration over force transfer function obtained by performing the complex division of the accelerometer FFT over the hammer FFT. The displacement over force transfer function were obtained by converting the acceleration to displacement at each point of the frequency domain.

The system transfer functions were used as input to the simulations based on the linear stability theory, and they were helpful to understand the experimental results.

3. Linear Stability Theory

The following analytical chatter prediction model was presented by Altintas and Budak (1995). Figure 1 shows a schematic of a milling operation.

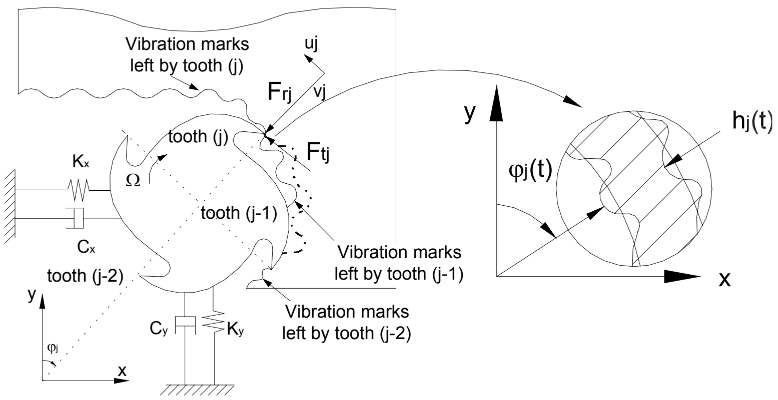

Figure 1 – Schematic of milling operation

The cutter is assumed to have N flutes with a zero helix angle. It rotates at a constant angular speed Ω and it has a constant pitch angle $\varphi_p = 2\pi/N$. The tooth passing frequency and period are defined as $f_t = N\Omega$ and $\tau = 1/f_t$, respectively and the feed rate is f_0. The angle between each cutter flute and the vertical axis is φ_j. They vary in time as the expression below:

$$\varphi_j = 2\pi/N + j\varphi_p \tag{1}$$

The cutting forces excite the structure in the feed (X) and normal (Y) directions, causing dynamic displacements x and y respectively. The instantaneous chip thickness variation, $h(\varphi_j)$, is calculated by:

$$h(\varphi_j) = [\Delta x \cdot \sin\varphi_j + \Delta y \cdot \cos\varphi_j] \cdot g(\varphi_j) \tag{2}$$

where

$$\begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = \begin{pmatrix} x(t-\tau) - x(t) \\ y(t-\tau) - y(t) \end{pmatrix} \tag{3}$$

and

$$g(\varphi_j) = \begin{cases} 0, \varphi_j < \varphi_{st}, \varphi_j > \varphi_{ex} \\ 1, \varphi_{st} \le \varphi_j \le \varphi_{ex} \end{cases} \tag{4}$$

The unit step function $g(\varphi_j)$ determines whether the tooth is in or out of cut. The chip thickness is nonzero when φ_j is between the entry angle φ_{st} and the exit angle φ_{ex}.

The tangential F_{tj} and radial F_{rj} cutting forces acting on the tooth j is proportional to the axial depth of cut a_p and chip thickness $h(\varphi_j)$.

$$F_{tj} = K_t \cdot a_p \cdot h(\varphi_j) \tag{5}$$

$$F_{rj} = K_r \cdot F_{tj} \tag{6}$$

where cutting coefficients K_t and K_r are constant. Resolving the cutting forces in the x and y directions and summing over all the flutes, the total dynamic milling forces acting on the cutter are found as,

$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \sum_{j=1}^{N} \begin{pmatrix} \cos\varphi_j & \sin\varphi_j \\ -\sin\varphi_j & \cos\varphi_j \end{pmatrix} \cdot \begin{pmatrix} F_{tj} \\ F_{rj} \end{pmatrix} \tag{7}$$

In the method proposed by Altintas and Budak, the time independent terms are expanded in a Fourier series and only the constant term is retained. This result in the following time independent expression for the force in terms of the tool displacements.

$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \frac{1}{2\varphi_p} a_p \cdot K_t \begin{pmatrix} \alpha_{xx} & \alpha_{xy} \\ \alpha_{yx} & \alpha_{yy} \end{pmatrix} \cdot \begin{pmatrix} \Delta x(t-\tau) \\ \Delta y(t-\tau) \end{pmatrix} \tag{8}$$

where the components of the matrix are defined by,

$$\alpha_{xx} = \frac{1}{2}\left[\cos 2\varphi - 2K_r\varphi + K_r \sin 2\varphi\right]_{\varphi_{st}}^{\varphi_{ex}}$$

$$\alpha_{xy} = \frac{1}{2}\left[-\sin 2\varphi - 2\varphi + K_r \cos 2\varphi\right]_{\varphi_{st}}^{\varphi_{ex}}$$

$$\alpha_{yx} = \frac{1}{2}\left[-\sin 2\varphi + 2\varphi + K_r \cos 2\varphi\right]_{\varphi_{st}}^{\varphi_{ex}}$$

$$\alpha_{xx} = \frac{1}{2}\left[-\cos 2\varphi - 2K_r\varphi - K_r \sin 2\varphi\right]_{\varphi_{st}}^{\varphi_{ex}} \tag{9}$$

In the Laplace domain, the structural response of the system at the tool tip can be represented by a transfer function matrix as follows:

$$\begin{Bmatrix} x(s) \\ y(s) \end{Bmatrix} = \begin{Bmatrix} G_{xx}(s) & G_{xy}(s) \\ G_{yx}(s) & G_{yy}(s) \end{Bmatrix} \begin{Bmatrix} F_x(s) \\ F_y(s) \end{Bmatrix} \tag{10}$$

Taking the Laplace transform of Eq. (8) and combining it with Eq. (10) results in:

$$\left\{ I - a_p \cdot K_t\left(1 - e^{-s\tau}\right) \cdot G(s) \cdot A_0 \right\} \begin{pmatrix} x(s) \\ y(s) \end{pmatrix} = 0 \tag{11}$$

where $A_0 = \left(1/2\varphi_p\right) \cdot \alpha$ and I is a 2 x 2 identity matrix. Equation (11) has a non-trivial solution if its determinant is zero.

$$\left| I - a_p \cdot K_t (1 - e^{-s\tau}) \cdot G(s) \cdot A_0 \right| = 0 \tag{12}$$

The signs of the real parts of the roots of Equation (12) determine the stability of the system. Putting $s = i \cdot \omega_c$, borderline stability condition, into Eq. (9), the values of a_p and τ for which the system becomes unstable can be obtained.

According to Davies et al. (1998), the assumptions that the contact time between each flute and the workpiece is unaffected by the cutter dynamics and that the periodic terms due to intermittent engagement of the tool and workpiece can be ignored, are generally true for slotting operations. In this case, the flutes enter and exit gradually. However, these assumptions are not necessarily valid for partial immersion cuts, where it may be necessary to consider process non-linearities in determining stability.

4. Results and Discussion

Four and six flutes, 16 mm diameter, 75.2 mm length endmills were used in the cutting tests. The tools were clamped by a shrink fit chuck. Figure 2 shows the transfer function at the tool tip for these tools. The natural frequency was nearly 1.485 Hz.

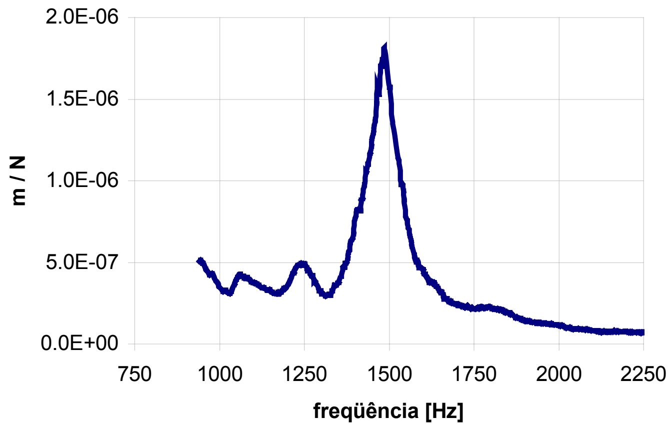

Figure 2. Transfer function of the endmill, L/D= 4.7.

Full immersion (slotting) operations were performed on aluminum workpieces. The feed rate was 0.1 mm/tooth.

The graph of figure 3 shows the surface roughness at the bottom of the slots in function of the spindle rotation for a four flute endmill. The axial depth of cut (a_p) was 1.0 mm.

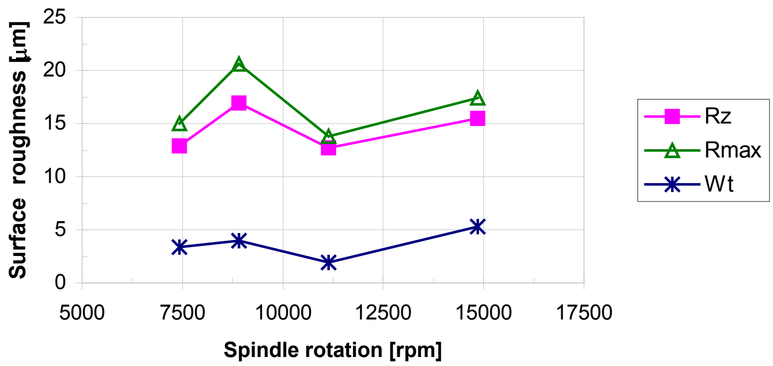

Figure 3. Surface roughness in function of the spindle rotation for a 4 flute endmill.

The curves have similar behavior for all the surface roughness parameters. There are peaks characterizing considerably high values of surface roughness at some spindle rotations. These results were caused by relative vibrations between workpiece and tool, which arisen during the operation. In these cases, the depth of cut used in the cutting tests was higher than the critical one for a stable cut. Figure 4 shows the chatter marks on machined surface for the unstable cuts.

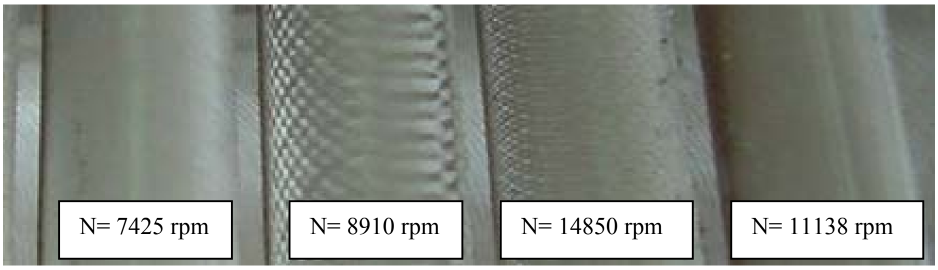

Figure 4. Machined surfaces for stable and unstable cuts

The graph of fig. 5 shows the surface roughness in function of the spindle rotation for a six flute endmill, for the same conditions.

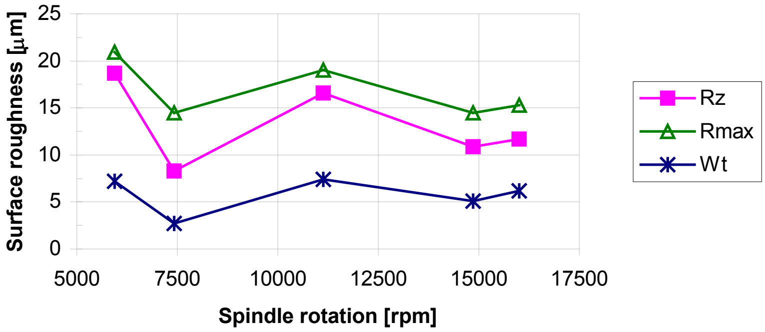

Figure 5. Surface roughness in function of the spindle rotation for a 6 flute endmill.

Comparing the graphs of fig. 3 and 5, a great difference can be noticed in the results. For the six-fluted endmill, lower surface roughness values were found at spindle rotation n = 14.850 rpm. At this spindle rotation, the tooth passing frequency was equal to the natural frequency of the system, characterizing a resonance condition. The forced vibrations were at their highest, but they were not a problem. For the four-fluted endmill, the use of the same spindle rotation resulted in a poor surface finish due to the vibrations arisen during the process. Better results were achieved for this tool by using the spindle rotation n = 11.338 rpm. In this case the tooth passing frequency was half of the natural frequency of the system. At the spindle rotation n = 7.425 rpm, the surface finish was satisfactory for both tools. For this value, the tooth passing frequency was 1/2 and 1/3 of the natural frequency of the system.

The graph of fig. 6 shows the surface roughness parameters and the depth of wave measure on the bottom of the slots in function of the depth of cut for a spindle rotation of 13.922 rpm. There is no significant change for the values until the depth of cut 1,75 mm. For higher depth of cut, the values grow abruptly, indicating that the stability limit was surpassed and the process became unstable, with the vibration amplitude achieving unacceptable levels. Therefore, the depth of cut considered critical for this case was 1,75 mm.

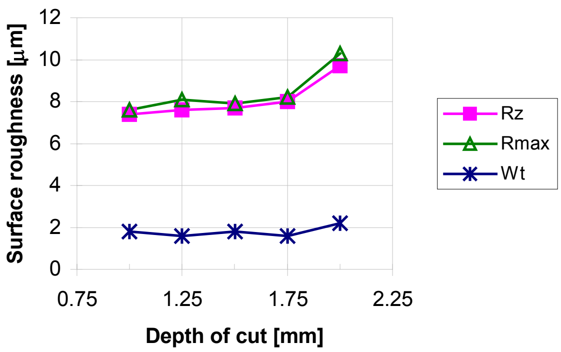

Figure 6. Surface roughness in function of the depth of cut for a spindle rotation n = 13.922 rpm

Similar graphs were found for other values of spindle rotation. Adopting the same procedure to establish the critical depths of cut, it was possible to build the stability lobe diagram of fig. 7. The vertical coordinate is the depth of cut and the horizontal one is the spindle rotation. To interpret the diagram, the curves are considered to be borders between stable (below the curves) and unstable (above) regions.

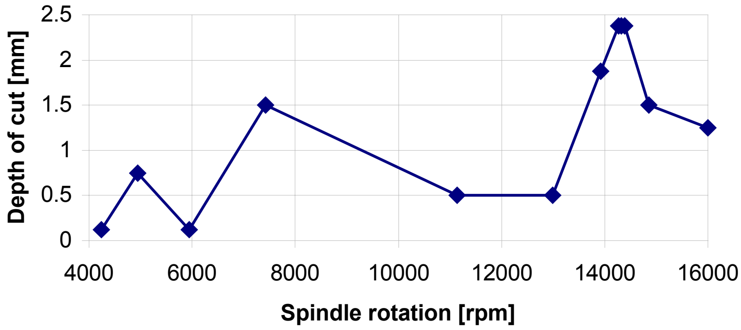

Figure 7. Stability lobe diagram

The stability lobe diagram shows that the spindle speeds, which have the higher, stable depth of cut are those whose tooth passing frequency approach to the natural frequency of the system. The highest stable depth of cut was found for the spindle rotation n =14.338 rpm. For this value the tooth passing frequency correspond to 96,69 % of the natural frequency of the system. According to Smith and Tlusty (1990), the higher stability is due to the fact that exactly one wave is reproduced between teeth. Although vibration is assumed, the waves produced by two subsequent teeth are in phase and no chip thickness variation results, thus there is no force variation either and the vibrations are not reexcited and disappear. This is the case shown in the left side of fig. 8.

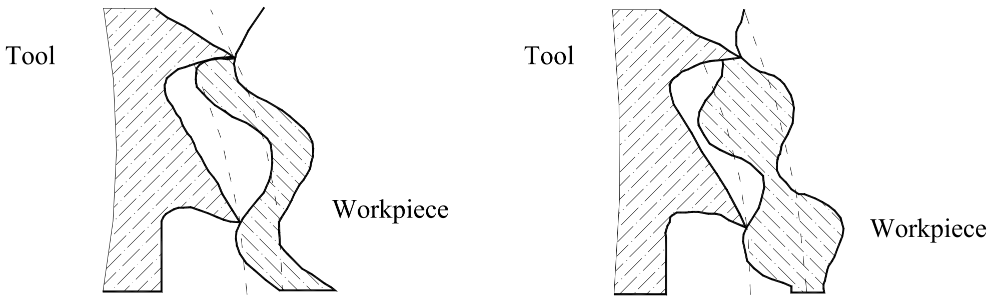

Figure 8 – Chip thickness variation for stable (left) and unstable (right) conditions

Other spindle rotation values, which have high stable depth of cut, correspond to values whose tooth passing frequency is half and one third of the natural frequency of the system (fig. 9). In these cases two and three waves are reproduced between teeth, respectively. The higher the number of waves, the lower is the attenuation effect over the regenerative vibrations.

The most unfavorable conditions were those whose tooth passing frequency were in opposition of phase. In fig. 8 (right), with one and a half waves between teeth, for the same vibration amplitude, a variation in chip thickness with twice the vibration amplitude occurs, resulting in a large force vibration that excites further vibration. The worst case phase is about 1,75 waves between teeth. The lowest stable depth of cut found was $a_p = 0{,}125$ mm.

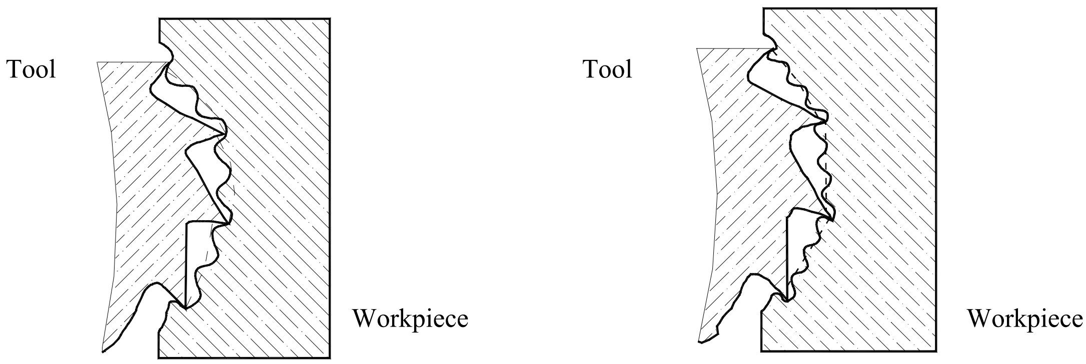

Figure 9 – Waves between teeth, left (2 waves) and right (3 waves)

Figure 10 shows the stability lobe diagram resulted from simulations based on the linear stability theory described in section 3. The experimental data for the transfer functions were obtained from impact test at tool tip. The cross-transfer functions were assumed to be zero. The cutting force coefficients K_t e K_r (600 MPa and 0,3 respectively) were obtained from tables (Kalpajkian, 1991). The blue points are resulted from the simulations and the red ones were obtained experimentally.

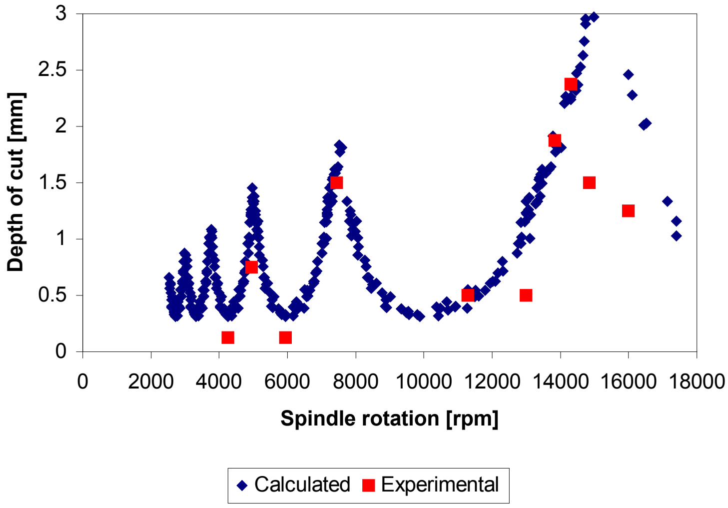

Figure 10. Simulated stability lobe diagram

The simulated stability lobe diagram has higher critical depth of cut than the experimental ones, and its region of great stability is shifted to higher spindle speed. These differences can be attributed to the non-linearities, which are not considered in the linear analysis. According to Tlusty and Ismail (1981) the basic non-linearity in machining chatter is due to the fact that with increased vibration the tool starts to move outside of the cut for a part of the cycle. During this time the force is not anymore proportional to chip thickness but it is simply zero. Another non-linearities are related to multiple regeneration and the variations of the cutting coefficients. Besides, as pointed out by Jensen and Shin (1999), the accurate modeling of a system's structural dynamics under operating conditions plays a important role in determining the vibration which will occur during actual machining. There are differences in stiffness, damping and natural frequency when the system dynamics are measured under two conditions: free movement and the cutter in contact with the workpiece.

5. Conclusions

The spindle rotation has great influence on the stability of the high speed milling process. The results showed that the spindle rotation, which permit the use of high axial depth of cuts without chatter are those whose tooth passing frequency are close but not equal to the natural frequency of the system. In this case the forced vibrations are near their highest, but the regenerative ones, which are more critical, are at their lowest. The differences between the simulated and experimental results can be attributed to the assumptions made in the linear stability analysis and the fact that the system dynamics measurement was made considering free movement of the cutter. The right choice of the spindle rotation is one way to minimize chatter problems and increase material removal rate.

6. Acknowledgement

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