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Chatter avoidance method for milling process based on sinusoidal spindle speed variation method: simulation and experimental results

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Abstract
This paper investigates the effectiveness of Sinusoidal Spindle Speed Variation (SSSV) technique as a chatter suppression method in milling process. On this purpose, a two-fold study was carried out: on the one hand, a simulation analysis, and on the other, experimental machining. First, a time domain model of the cutting process was modified to include simulation capabilities concerning spindle speed variation. The results obtained by SSSV techniques mainly depend on the relationship between the chatter frequency and the tooth passing frequency. The SSSV-based strategy for chatter avoidance was embedded in a Computer Numerical Control (CNC) to run experimental tests. They were carried out to show the SSSV technique performance, focused on both high and low spindle speeds. To summarise, this technique lifts the asymptotic stability limits mainly at low spindle speeds.

1 INTRODUCTION
The productivity of milling operation is often constrained by the regenerative chatter. This occurs when relative vibrations between the cutting tool and the workpiece modulate the cutting force, leading to self-excited vibrations. Depending on cutting conditions and dynamic properties, the self-excited vibration can maintain constant (stable cut) or grow resulting in chatter (unstable cut). This affects the dimensional quality of the surface finish, along with excessive tool wear or tool breakage. Thereby the material removal rate is limited.

In order to increase the material removal rate a chatter suppression method based on continuous spindle speed variation (SSV) is analysed. This technique consists on a continuous variation of the tooth assign frequency, yielding a continuous variation of the phase between the tool-workpiece relative displacement and the tooth passing cycle.

Stoferle and Grab [1] introduced the idea of the spindle speed variation method in 1972. Later, Inamura and Sata [2] developed a simplified function for the study of the stability of turning process with variable spindle speed. Takemura et al. [3] studied the SSV with different forcing signal shapes (triangular, sinusoidal and rectangular) by means of an energy balance. Later, Sexton and Stone, [4] argued previous works showing that the results obtained with the SSV were not as good as predicted before. De Canniere et al. [5] showed that the speed modulation was mostly equivalent to the modulation of the time lag. Altintas and Chan [6], Radulescu et al. [7], Bediaga et al. [8, 9] modified time domain models in order to test the SSV. Tsao et al. [10] used angle based models to include the SSV. Afterwards, Jayaram et al. [11] developed a Fourier expansion of the turning process equations. That was a similar approach to the sophisticated multi-frequency solution for constant speed. This development was extended by Sastry et al. [12] for the face milling process. Al-Regib et al. [13] and Namabachchivaya and Bedini [14] have also investigated the benefits of the SSV. Recently, Insperger et al. [15] and Long and Balachandran [16] adapted the semidiscretization method to investigate the effect of variable speed machining.

In this paper an industrial implementation and a methodology for the spindle speed variation technique application is discussed. Time domain model simulations and experimental tests are carried out to verify the effectiveness of spindle speed variation technique. The arrangement of this paper is as follows. In section 2, the modelling of the chatter is summarised. In section 3 an explanation of the spindle speed
variation method is included. In section 4 the restrictions of the spindle speed variation method and its implementation are explained. Afterwards in section 5, time domain simulations and experimental tests are detailed to demonstrate the utility of the SSV in milling.

2 MODELLING OF CHATTER IN MILLING
First researches on chatter were carried out in the 40's [17]. Tobias and Fishwick, [18], Tlusty and Polacek [19] stated that the dynamic regeneration of the chip thickness and the vibration mode coupling effect are responsible for chatter. Merrit [20] designed a closed-loop scheme, which made chatter easier to understand and predict. Sridhar al. [21] and Opitz and Bernardi [22] accomplished the first milling modelling attempts.

Minis and Yanishevsky [23] used Floquet’s theory and Fourier series on a two-degree-of-freedom cutting model for the formulation of the milling stability. Altintas and Budak [24] developed a stability method, which led to an analytical determination of stability limits. This technique was based on a two-dimensional single-frequency analysis (ZOA), making possible to calculate milling lobes diagram faster than by time domain models [25, 26].

Most of the previous analytical modelling of chatter is usually based on a number of assumptions, such as average direction of the cutting force. It is known that chatter is an unstable process that is bounded by nonlinear dynamics due to loss of contact between tool and workpiece. Tlusty and Ismail [27] used time domain modelling to simulate the dynamic behavior of milling. The simulation is run in sequential small time steps. At each time value, the cutter is rotated, the force on each tooth involved in the cut is computed, and the force vectors are summed and computed in all mode directions. The accelerations are integrated twice to produce displacements, which yield tool positions. Time domain simulation method has been used by many researchers to study the dynamic milling process [28-35].

In order to analyse the SSV in milling a time domain model has been developed [36]. The time domain modelling permits simulating very different kind of superimposed signals. On the other hand, being very time consuming constitutes its main drawback.

3 SPINDLE SPEED VARIATION METHOD
The spindle speed variation method consists in the superimposition of speed variations over the commanded constant spindle speed. As a result, the SSV method excites more frequencies than the constant machining, with less energy. This ensures that surface waves will be irregularly spaced. It prevents the regenerative mechanism of chatter from taking place.

The effectiveness of the spindle speed variation method depends on the forcing input signal, and on its parameters (amplitude and frequency).

3.1 Forcing input signal
In fact, if an operator dials the speed override knob back and forth, chatter sometimes vanishes. But not all kind of variations permit avoiding chatter. There are many possibilities of input forcing signals: sinusoidal, random, rectangular, etc.

**Sinusoidal Spindle Speed Variation (SSSV)**
This method consists in adding a sinusoidal component to the constant spindle speed according to (1). The time dependent function \( N(t) \) of the spindle speed is given by,

\[
N(t) = N_0 + A_{ssv} \cdot \sin(2\pi \cdot f_{ssv} \cdot t + \psi) \quad (1)
\]

where the spindle speed \( N \) varies around the nominal spindle speed \( N_0 \) with amplitude \( A_{ssv} \) (rpm), frequency \( f_{ssv} \) (Hz) and phase \( \psi \) (rad).

**Multi-level Random Spindle Speed Variation (MRSSV)**
The proposed MRSSV signal can mathematically be expressed as,

\[
N(t) = N_0 + A_{ssv} \cdot M(t; p) \quad (2)
\]

\( M(t; p) \) denotes uniform random process, as a function of \( p \), the fixed time step size.

Several investigations [8, 9, 15] state that sinusoidal shape variation seems to be the best forcing input.

3.2 Superimposed signal parameter selection
The amplitude and frequency parameter selection of the superimposed signal is one of the pending tasks. There are some investigations in this field [13], although, there is not an exhaustive work on validating experimentally their claims. However, it has been found that the ratio \( k \) between chatter and tooth passing frequency is of primary importance. For high
spindle speeds – low order ratio $k (k<1)$ - the sinusoidal amplitude must be extremely high, rarely achievable by the spindle dynamics. On the other hand, for high order ratio $k (k>1)$, the required sinusoidal amplitude is lower, and attainable by the spindle.

The SSSV frequency is not as critical as the amplitude [7, 13]. However, special attention must be paid on the effectiveness of SSSV, which requires a frequency higher than certain value.

### 4 INTEGRATION OF SSSV IN AN INDUSTRIAL MILLING MACHINE

The industrial implementation of the sinusoidal spindle speed variation method in a SORALUCE milling machine is presented and its restrictions discussed herein.

#### 4.1 Implementation restrictions

The industrial use of the spindle speed variation method reaches in the spindle drive a mechanical restriction. Due to maximum jerk limitations and the dynamic bandwidth the spindle drive cannot track the sinusoidal forcing signal accurately. So the system does not respond in a sinusoidal way.

Another kind of limitation appears if the feed rate $f_z$ (mm/min) is kept constant during variable machining. The feed per tooth $f_{z,\text{insert}}$ (mm/tooth) will vary between a maximum and minimum value (see Figure 1). Thus, if the forcing sinusoidal lowers the minimum feed per tooth value $f_{z,\text{insert}}$ the inserts will warm up and will suffer from premature wear. On the other hand, if the forcing sinusoidal surpasses the maximum feed per tooth value $f_{z,\text{insert}}$, the inserts will overload and damage faster.

In order to protect the inserts of the tool some restrictions must be established to the spindle speed variation algorithm. Therefore, according to (3) and (4), the amplitude $A_{ssv}$ of the forcing sinusoidal is limited according to the feed rate per tooth given by the tool manufacturer.

$$N_{\text{max}} = N_0 + A_{ssv} \quad N_{\text{min}} = N_0 - A_{ssv} \implies A_{ssv} = \min \{ N_{\text{max}} - N_0, N_0 - N_{\text{min}} \} \quad (3)$$

where $N_{\text{max}}$ and $N_{\text{min}}$ are the maximum and minimum available spindle speeds:

$$N_{\text{max}} (t) \rightarrow \min (f_{z,\text{insert}}) < f_{z,\text{insert}} \quad (4)$$

$$N_{\text{min}} (t) \rightarrow \max (f_{z,\text{insert}}) > f_{z,\text{insert}} \quad (4)$$

The minimum feed per tooth in the machining $\min (f_z)$ must be higher than the minimum feed per tooth that the inserts permit $f_{z,\text{insert}}$. In the same way, the maximum feed per tooth in the machining $\max (f_z)$ must be lower than the maximum feed per tooth that the inserts permit $f_{z,\text{insert}}$. Inequation (4) can be expressed as,

$$f_z \leq \frac{1}{N_{\text{max}} \cdot z} \quad (5)$$

$$f_z \geq \frac{1}{N_{\text{min}} \cdot z} \quad (5)$$

Equations (3), (4) and (5) yield the max and min amplitude of the sinusoidal spindle speed,

$$A_{ssv} \leq \frac{f_z}{f_{z,\text{insert}}} \cdot \frac{1}{z} - N_0 \quad (6)$$

$$A_{ssv} \leq N_0 - \frac{f_z}{f_{z,\text{insert}}} \cdot \frac{1}{z} \quad (6)$$

Consequently, the restriction can be expressed as,

$$A_{ssv} = \min \left\{ N_0 - \frac{f_z}{f_{z,\text{insert}}} \cdot \frac{1}{z} - N_0 \right\} \quad (7)$$

#### 4.2 Integration in open architecture CNC

The industrial implementation of the sinusoidal spindle speed variation method has been successfully developed inside the kernel of the Sinumerik 840D CNC of a SORALUCE milling machine (Figure 2). The open system architecture of the NC kernel provides the possibility of accessing internal data using compiled-cycles. These compiled-cycles are developed on SUN workstations using SOLARIS running under UNIX OS. The compiled-cycle is the most powerful method that permits acting on the spindle speed every millisecond. On the other
hand, G-code functions SSVON() and SSVOFF() are used to interface with user.

Figure 2: SSV integration on milling machine.

5 APPLICATION OF SSSV IN MILLING

In this section the utility of the sinusoidal SSV to suppress chatter in face milling roughing operation is evaluated. Initially the experimental set-up is described and the machining cutting coefficients are presented. They are used to run time domain simulations, validated by means of experimental tests. They demonstrate the capability of SSV in regenerative chatter mechanism distortion.

5.1 Experimental set up for model validation

Experiments for this work were carried out on a five-axis SORALUCE SV6000 milling machine [37]. The workpiece was mounted on a test bed in order to accomplish a dominant mode and thus facilitate the experiments [38, 39]. The test bed –see Figure 3- has been designed with finite elements program. It has been built with 150 kg weight steel block placed on a couple of HBE100 beams. The natural frequency of this test bed is nearly constant for the working area.

Figure 3: Test-bed architecture.

Table 1 shows the modal parameter of the test bed for experimental tests.

<table>
<thead>
<tr>
<th>Direction</th>
<th>f (Hz)</th>
<th>ζ</th>
<th>K (N/m)</th>
<th>M (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>95.6</td>
<td>6.04·10^{-3}</td>
<td>49.1·10^6</td>
<td>136</td>
</tr>
</tbody>
</table>

Table 1: Test bed modal data.

5.2 Cutting process characterization

The cutting coefficients were obtained in order to determine correct cutting forces. Steel face milling tests were carried out using inserted cutting tools. To identify the cutting constants a mechanistic identification method has been used [40, 41]. This method is based on average cutting forces.

In this work, the cutting coefficients shown in the Table 2 were obtained with a SANDVIK - Coromill R245-12SQ40-12M tool and R245-12T3M-PM 4020 inserts machining F1140 (C45) steel.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Ktc</th>
<th>Krc</th>
<th>Kac</th>
<th>Kte</th>
<th>Kre</th>
<th>Kae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute</td>
<td>1889</td>
<td>775.6</td>
<td>364.3</td>
<td>63.1</td>
<td>78.2</td>
<td>82.6</td>
</tr>
<tr>
<td>Relative</td>
<td>0.41</td>
<td>0.193</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Cutting coefficients for the defined cutting tool and F1140 steel workpiece.

These cutting constants depend on the workpiece material and on the features of the cutting tool insert. Hence, these coefficients can be used to simulate the cutting forces for many tools with different diameters and number of inserts.

5.3 Model simulations and experimental results

Several authors [15, 6] state that the SSSV method is more efficient in high order lobes (k>>1). Therefore, simulated and experimental results of the SSSV working on low and high order lobes for face milling roughing operations are analysed. In both cases, initially unstable machining condition is selected and it is tried to become stable by using the SSSV.

Simulations at low order stability lobes (k<1)

Firstly, the stability lobe diagram is obtained though time and frequency domain models. Therefore, the flexibility of the test-bed, the cutting coefficient and the machining conditions are considered. The diameter of the cutting tool is 80 mm with 6 inserts. The selected radial immersion was 40 mm in down milling (50% of radial immersion) with a feed per tooth of 0.15 mm/z. Highlighted crosses and circles in Figure 4 indicate experimental tests, which validate simulated stability lobes.

A 2mm axial depth of cut at 1100 rpm is chosen as an unstable machining condition (dotted circle in Figure 4). Considering the restriction imposed by the cutting inserts –feed per tooth
must be within 0.11 to 0.28 mm/z - maximum affordable amplitude of 350 rpm (32% of amplitude variation) is obtained (see equation 7).

Figure 4: Time and frequency domain simulated lobes compared to experimental tests.

Then, several time domain simulations are carried out with different parameters of amplitude and frequency of SSSV (see Figure 5). The severity of the vibration (measurement of vibration velocity) is measured instead of the amplitude of the chatter peak in the spectrum. The reason is that the measurement of chatter peak could lead to a mistaken conclusion, since the SSSV excites more frequencies than the normal machining but with less energy. Experience has shown that the overall RMS value of vibration velocity measured over a fixed range (i.e. 2 to 500 Hz) gives the best indication of a vibration's severity. A probable explanation is that a given velocity level corresponds to a given energy level so that vibration at low and high frequencies are equally weighted from a vibration energy point of view.

A contour plot of the severity reduction ratio between constant and variable speed machining of either simulated (white background text boxes) and experimentally obtained severity (black background text boxes) are displayed in Figure 5. In addition, experimental severity is also marked in italics inside a black star.

Figure 5: Simulated and experimental severity contour plot.

The impossibility of tracking accurately the forcing input signal is the most probable reason for the discrepancy between simulated and experimental severity at high amplitude variation areas (delimited by dashed line in Figure 5).

As conclusion, the simulations show that very high variations are needed in order to reduce chatter. Although, vibration reduction can be obtained, the chatter continues being very severe (dominant). Concluding, that it has been almost impossible to suppress completely chatter vibration at low order stability lobe.

**Experimental results at low order lobes**

While machining at constant speed a dominant chatter peak appears at 97.5 Hz with amplitude of 156.2 mm/s in the velocity RMS spectrum (see figure 6). The severity of the vibration measured from 2 to 500 Hz shows very strong chatter 154 mm/s.

Figure 6: Experimental acceleration signal and its RMS vibration velocity spectra.

Then, the SSSV with optimal parameters (dotted circle in Figure 5) is applied, but a chatter peak appears at 96.56 Hz with amplitude reduced to 46.76 mm/s. The severity of the vibration has also been reduced to 70.3 mm/s, which indicates a reduction of 55% in the severity. Even though, very severe chatter continues appearing.

It is remarkable, that the unique case where chatter was completely eliminated concerned flip or period doubling instability lenses appeared in highly interrupted high-speed end-milling operations [36]. The application of the SSSV inside the lens made the instability disappear completely [42]. This effect occurred when amplitude of SSSV was high enough to go in and out the lens.
As conclusion, it is not recommendable to use SSV when machining at the low order lobes ($k=0$), no significant improvement is obtained. Consequently, the application of other techniques must be considered, i.e. stable spindle speed selection technique [43].

*Simulations at high order stability lobes*

The stability lobe diagram is obtained though time and frequency domain models. In order to work at higher order lobes ($k>1$) regarding cutting speed rage, the number of inserts is lowered to 3.

Figure 7: Time and frequency domain simulated lobes compared to experimental tests.

A 4mm axial depth of cut at 525 rpm is selected as an unstable machining condition (dotted circle in Figure 7). Considering the restriction imposed by the cutting inserts, the maximum available amplitude for the superimposed sinusoidal is 191 rpm (see equation 7). On the other hand, spindle drive also imposes a mechanical constraint. Experimentally has verified that forcing input signal tracking limit was near 30% amplitude variations at 3 Hz of frequency.

Figure 8: Simulated and experimental severity contour plot.

Then, several time domain simulations are carried out with different parameters of amplitude and frequency of SSSV. A contour plot of the severity reduction ratio between constant and variable speed machining of either simulated severity (white background text boxes) and experimentally obtained severity (black background text boxes) are displayed in Figure 8.

Although, some divergences exist among simulated and experimental tests, a good approximation to variable speed machining is denoted. Therefore, an amplitude variation of 15% around the nominal spindle speed at a frequency of 3 Hz is determined to be the best option to suppress chatter.

The comparison between the simulated displacement of the tool before and after applying SSSV is shown in figure 9.

Figure 9: Vibration velocity and corresponding RMS spectra plots.

It can be observed that when machining at constant speed a strongly dominant chatter peak appears at 97.79 Hz with amplitude of 520.7 mm/s in the velocity RMS spectrum. Then, the SSSV was applied obtaining a very important vibration amplitude reduction. The RMS spectrum of the velocity shows that the chatter peak appears now at 101.5 Hz with amplitude of 5.8 mm/s, very slight chatter.

**Experimental results at high order stability lobes**

As can be appreciated in figure 10, while machining at constant speed a dominant chatter peak is displayed at 97.5 Hz (a deviation of a 0.29 Hz respect to the simulation) with amplitude of 81.6 mm/s in the velocity RMS spectrum. Then, the SSSV is applied obtaining a very important vibration amplitude reduction. The RMS spectrum of the velocity shows also very strong chatter 101 mm/s. Then, the SSSV is applied, and a chatter peak at 101.9 Hz (a deviation of a 0.3 Hz respect to the simulation) with amplitude reduced to 10.03 mm/s -very slight chatter- is shown. The severity of the vibration is also reduced to 13.3 mm/s,
which denote a reduction of 87% in the severity. Even though, slight chatter marks continue appearing.

Figure 10: Experimental acceleration signal and its RMS vibration velocity spectra

6 CONCLUSIONS
In this work, industrial implementation and a methodology for the spindle speed variation technique application has been discussed.

A three dimensional time domain model has been used to simulate variable spindle speed machining. And experimental tests were carried out to discuss the effectiveness of SSSV technique. The simulations agreed with experimental results, although always indicated better results than those obtained experimentally.

It is shown that SSSV is not an appropriate method to suppress chatter at low order stability lobes ($k=0$ or $1$). Therefore it is not an appropriate method for neither high speed machining of light alloys nor common face milling of hard materials. Even though it can be very useful when machining at higher order lobes ($k >> 1$), i.e. roughing operations of low machinability materials (titanium, stainless steel, etc.) or when chatter is produced by a flexible clamping device.

On the other hand, SSV technique is especially appropriate to suppress chatter in turning process, where machining lobe is very high ($k > 10$).

Finally mention that, in this work has not been studied the effects of the SSV on the spindle drive life cycle. Certainly, an increment in the power consumption has been observed.

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7 REFERENCES


efecto del chatter utilizando actuadores inerciales, XV Congreso de M-H y Tecnol. de Fabricación, 817-826.


