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COMPARATIVE ANALYSIS OF SPINDLE SPEED VARIATION TECHNIQUES IN MILLING

Bediaga, I.; Hernández, J.; Muñoa, J. & Uribe-Etxebarria, R.

Abstract: Self-excited vibrations in milling process are probably one of the most important obstacles to increase the material removal rate (MRR). In order to avoid chatter, some authors have proposed the use of strategies aimed at disturbing the excitation caused by the periodic strike of the teeth on the workpiece. One of these techniques, spindle speed variation (SSV), would be presented in this article. After a brief revision of the state-of-the-art in application of SSV techniques, a numerical cutting model is developed and modified to include the capability to simulate the SSV. Finally, a comparative analysis of spindle speed variation techniques is presented based on computer simulations.

Key words: Modelling; Chatter; Simulation; Variable Spindle Speed

1. INTRODUCTION

One of the most significant factors affecting the performance of machine tools is chatter, the self-excited vibration between the workpiece and the cutting tool. This type of vibrations do not only restrict the productivity of the cutting process, but also affect the dimensional precision and quality of the machined surface. Moreover, chatter could decrease the life of the tool, or even the machine tool life itself.

Research has been done in order to reduce or suppress chatter. A possibility to avoid it consists on using the stability lobes diagram to select the spindle speed assuring the maximum depth of cut (SSSS-*Stable Spindle Speed Selection*). Therefore, mathematical models are needed to simulate the stability lobes diagram. Another way to eliminate chatter is to disturb the excitation caused by the periodic strike of the teeth on the workpiece. Jayaram (Jayaram et al., 2000) and Namachchivaya (Namachchivaya & Beddini, 2003) propose the continuous modulation of the spindle speed as one of the most attractive techniques due to its simplicity and efficiency. There are different methods to vary the spindle speed. The most studied in the literature is the sinusoidal variation method (SSSV-*Sinusoidal Spindle Speed Variation*), consisting on a sinusoidal variation of the spindle speed around the mean speed value. There have been many research efforts on this strategy for turning process (Al-Regib et al., 2003; Yang et al., 2003). In milling, Sastry (Sastry et al., 2002) developed an analytical method that allowed the analysis of the stability with variable spindle speed. Another alternative of variation is to vary the spindle speed randomly (MRSSV-*Multi-level Random Spindle Speed Variation*), Yilmaz (Yilmaz et al., 2002) presents the effectiveness of this method in turning by simulations and experimental tests.

In this article, a software development is presented which allows the simulation of milling cutting process under continuous variation of spindle speed, in order to analyse and compare sinusoidal and random variation techniques for chatter suppression. The software is based on a bidimensional-cutting model in time domain allowing spindle speed variation, which will be first presented.

2. TIME DOMAIN BIDIMENSIONAL CHATTER MODEL WITH SPINDLE SPEED VARIATION

Modification of a time domain chatter model to include the capability to simulate the SSV technology is performed.

2.1 Sinusoidal Spindle Speed Variation (SSSV)

This method consists on the addition of a sinusoidal component (“forcing signal”) to the constant spindle speed. As a result, the teeth do not strike the workpiece at a constant frequency, and the regeneration mechanism of chatter is disturbed. The spindle speed time varying function is given by (1):

$$w(t) = w_o + A \sin(2\pi ft) \quad (1)$$

$$w(t) = w_o (1 + RVA \sin(2\pi RVF \cdot t \cdot w_o / 60))$$

Where:

w_o is the mean spindle speed (rpm).

RVA is the normalised sinusoidal amplitude.

RVF denotes the normalised sinusoidal frequency.

For an ideal spindle the system can track any additional component in the right way. Nevertheless, it is known that the spindle drive system imposes dynamic constraints to the input signal. In order to take them into account, experimental tests were carried out for the SV-6000 SORALUCE’s milling. The bandwidth of the spindle drive system was found out to be of $w_{bw}=20\pi$ rad/s, or $f_{bw}=10$ Hz. For this reason, the spindle is modelled as a low pass filter applied to time varying forcing signal. In case of High Spindle Machining (HSM), SSSV technique requires a greater amplitude and frequency, which could be constrained by the spindle drive system. That is the reason because lower spindle speed simulations have been carried out.

The effectiveness of the spindle speed variation techniques to suppress or reduce chatter severity is tested through the simulation for an initially unstable cut with constant spindle speed. A cutting tool of 16mm diameter and 3 straight teeth has been used. Experimentally measured cutting tool modal parameters are shown in the Table 1.

	w_n (Hz)	k (N/m)	ξ
X	892,06	3,5186e+6	1,7143e-2
Y	916,12	4,3074e+6	1,9320e-2

Table 1. Measured modal parameters.

If it is tested in down-milling operation with an 1800rpm constant speed (Figure 1, left side), 6mm radial and 1.5mm axial depth of cut, the spectrum of the cutting forces shows big amplitude peaks and chatter at 973Hz frequency. Sinusoidal spindle speed variation technique with $RVA=0.3$ and $RVF=0.3$ parameters has been applied (Figure 1, right side) and, although the spindle system tries to track the input forcing signal, the filter effect forces a delayed response with a smaller amplitude. Despite this effect, an important reduction of the simulated

force amplitude is obtained. So, the spectrum of the force signal also shows lower chatter amplitude.

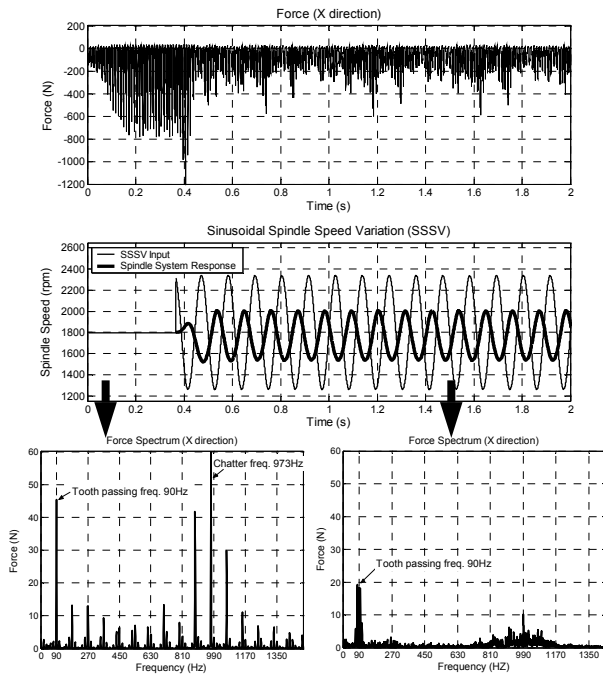


Fig. 1. SSSV technique application (RVA=0.3; RVF=0.3) with filtered input signal.

The SSSV technique excites more frequencies than the normal machining, with less energy, to avoid feeding the regenerative mechanism of chatter. Consequently, if proper forcing signal parameters are selected, an increase in the stability of the machine is obtained.

So, the ability of SSSV to suppress chatter depends on the selected parameters (frequency and amplitude), and a wrong choice could lower the process stability limits. There is no systematic way to select the proper values of the sinusoidal forcing signal. So, several simulations must be carried out to find the optimal values.

2.2 Multi-level Random Spindle Speed Variation (MRSSV)

In this method, the spindle speed is varied randomly around a defined set point. The amplitude signal is discretised for uniform time steps. The maximum normalised amplitude ratio (RVA) corresponds to the amplitude ratio allowed by the spindle drive system, and the uniform time step size (z) is constrained by the spindle system bandwidth. The proposed MRSSV signal can mathematically be expressed as shown in equation (2).

$$w(t) = w_o + A \cdot M(t; z) = w_o (1 + RVA \cdot M(t; z)) \quad (2)$$

Where:

$M(t; z)$ denotes uniform random process, as a function of z , the uniform time step size in seconds.

RVA is the normalised amplitude ratio.

The low pass filter response of the spindle system constitutes a restrictive condition for applying SSSV and it is even more critical when considering MRSSV. A random variation of the input forcing signal causes abrupt amplitude changes on the signal, so the spindle system response cannot track the set trajectory properly. Consequently, the response signal differs from the initially set.

The simulation for an initially unstable cut with constant spindle speed as proposed for SSSV technique is performed. The application of MRSSV technique (Figure 2, right side), with $RVA=0.3$ and $z=0.2$ s parameters, causes the reduction of the simulated force amplitude. The spectrum of the force signal also shows lower chatter amplitude. However, for chosen

parameter values, the reduction of chatter with MRSSV method is not as significant as it is with the SSSV technique.

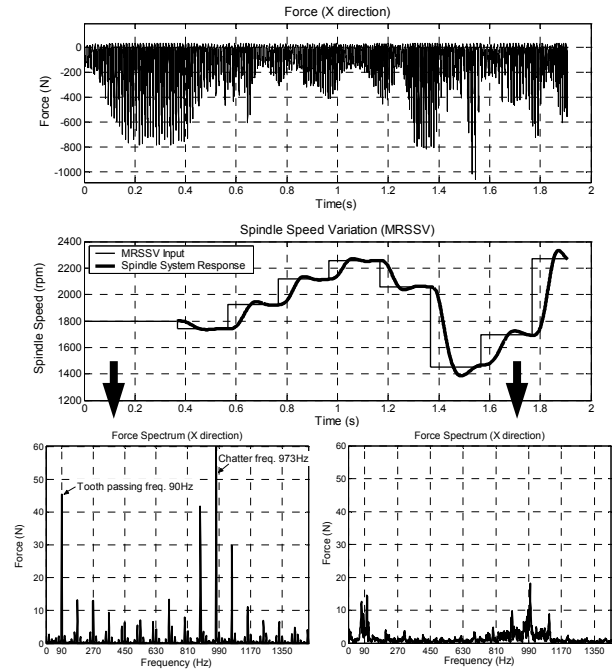


Fig. 2. MRSSV technique application (RVA=0.3; $z=0.2$) with filtered input signal.

CONCLUSIONS

A bidimensional time domain model for chatter detection in milling has been developed and modified to include the capability to simulate SSSV and MRSSV techniques. Their effectiveness to reduce/suppress chatter vibrations has been demonstrated. However, the results depend on the selected parameters. In general, the numerical results suggests that the stability improvement by SSSV is better than the obtained by MRSSV. On the other hand, in case of high spindle speed, SSV techniques require a great amplitude and frequency, which could be constrained by the spindle drive system.

Considering the result of this research, the verification of the simulated SSV techniques (SSSV & MRSSV) with experimental tests will be carried out as future work.

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