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Computer Model for Simulating and Optimizing Milling Process

Iñigo Bediaga, Jokin Muñoa, and Igor Egaña, Member, IEEE

Abstract — A model for optimizing milling process is presented. It is based on time and frequency domain simulations by means of Matlab SimulinkTM, that constitutes an accurate approach to cutting conditions –forces, vibration phenomena, stability, etc.-. The main feature of this software compared to others is the use of advanced strategies to plan chatter avoidance –variable pitch cutter and variable spindle speed-including complex modelling (3D).

Keywords — Computer simulation, milling, variable pitch cutter, variable spindle speed.

I. INTRODUCTION

In the last years, the development of accurate and reliable machining process models has received considerable attention from both academic researchers and industry practitioners. This trend has been driven to a large extent by the need for analytical/numerical tools capable of predicting the machining process performance to enable simultaneous engineering of products and machining process. Traditionally, the techniques used in industry are based on past experience, extensive experimentation, and trial-and-error. Such approach is time consuming, expensive, and lacks a rigorous scientific basis.

Stability lobes charts relate the spindle speed to the chatter free maximum depth of cut. The regenerative chatter is a common type of self-excited vibration in machine tool. It is a well-known phenomenon among milling machine tool users, becoming one of the most important restrictions of the milling process and a trade-off laying between productivity and surface quality. Regenerative chatter consists in a destabilization of the process due to cutting force oscillations. The relative vibration between workpiece and tool causes a wavy machined surface. When a milling flute starts cutting on a modulated surface, dynamic excitation of the machine takes place. It causes a vibration that yields a variation in chip thickness, depending on the phase lag angle between different waves. If the depth of cut exceeds a variable limit, the vibration becomes unstable.

The first milling process time domain modelling attempts were carried out in the 70’s [1], [2]. Opitz and Bernardi [2] applied turning stability theory to milling process stability. They replaced the time variable cutting coefficient by a constant term, that is the average value term over the real cutting period of each cutter. Searching for an analytical solution, Minis and Yanusheskyvsky [3] used Floquet’s theorem and Fourier series on a two-degree-of freedom cutting model for the formulation of the milling stability. Altintas and Budak [4] developed a stability method, which led to an analytical determination of stability limits. Later, Jensen and Shin [5] used a similar methodology to Altintas and Budak [4] in order to present a model that allowed simulating a three-dimensional system. It included the axial component of the cutting force and an additional cutting edge lead angle to locate the direction of the chip regeneration in the third axis [6].

On the other hand, changing the cutting conditions is likely the easiest way to avoid chatter. This involves reducing the depth of cut and compensating the loss of productivity by increasing the feed rate, or either changing the geometry of the tool. However, this method implies a lower productivity rate. Another way to reduce chatter consists in using the stability lobes diagram obtained by means of milling modelling, to select the spindle speed assuring the maximum depth of cut (SSSS – Stable Spindle Speed Selection). Therefore, accurate mathematical models are needed to simulate the stability lobes charts. SSSS method is useful in high speed machining, where stability lobes are usually accurately defined [7].

Another way to eliminate chatter is withstood by the use of variable pitch cutters, so that the phase difference between the outer and inner modulations on the chip thickness is disturbed [6], [7]. These methods are constrained under specific cutting conditions and geometry of workpiece. With the same objective of disturbing the excitation caused by the periodic strike of the teeth on the workpiece, Jayaram et al. [8] and Namachchivaya and Beddini [9] propose the continuous modulation of the spindle speed as one of the most attractive techniques due to its simplicity and efficiency.

In addition, 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), entailing a sinusoidal variation of the spindle speed. Another choice is the random variation of the spindle speed (MRSSV–Multi-level Random Spindle Speed Variation). Yilmaz et al. [10] present the effectiveness of this method in turning.
The work described in this paper offers a more comprehensive method, which provides a useful software tool for milling process design and analysis. The usefulness of such a tool to industry practitioners is manifold. It will make possible establishing optimal cutting conditions, designing efficient tooling, fixtures, cutting tool selection, and simulation of several chatter suppression methods.

The arrangement of this paper is as follows. In Section 2, the algorithms for milling process simulation are described. In Section 3 an explanation on the chatter suppression techniques supported by the simulation tool is included, and in Section 4 conclusions are stated to emphasize the contributions of this work.

II. MILLING PROCESS SIMULATION ALGORITHMS

Consider two kinds of nonlinearities. On the one hand, multiple cutting edges are cutting at the same time—some entering, some coming out from the workpiece—, and on the other, cutting coefficients are highly nonlinear. These facts make milling process simulation more complex than other machining processes’. In addition, the cutting forces $F_{TT}$ vary in magnitude and direction, showing an effect on the vibration $v_j$, and hence on the chip thickness $h_s$. Machine tool chatter vibrations arise as a result of a self-excited system in the generation of the chip thickness during machining operations. The closed-loop model of machining dynamics is governed principally by the dynamics of the machine tool or the cutting process. This is shown in Fig. 1, where $h$ is the intended chip thickness and $K$ represents the set of cutting coefficients, which is explained later. $\Phi(s)$ is the FRF of the machine, and $T$ is the time delay of the outer modulation, due to the tooth passing frequency.

![Fig. 1. Regenerative chatter vibrations in orthogonal cutting.](image1)

The resultant machining force $F_{TT}$ is modelled to be proportional to the depth of cut $b$ and to the uncut chip thickness $h_s$, which is modulated about its nominal value $h$ by the current and delayed tool displacements $v(t)$ and $v(t-T)$ respectively, where $T$ is the spindle speed period,

$$h_s(\phi, \gamma) = h + \left(v_{j,0} - v_j\right) \cdot g(\phi)$$

$$h = f_i \cdot \sin(\phi) \cdot \sin(\gamma)$$

where $f_i$ is the feed rate per tooth, $\phi$ is the instantaneous angular immersion of tooth $j$ measured from Y axis, the cutting edge lead angle is $\gamma$ and $j$ is the tooth number.

Denoting the components of $v_j$ as x, y and z—Fig. 2—, the dynamic displacement of the system obeys,

$$v_j = [x \cdot \sin(\phi) + y \cdot \cos(\phi), \sin(\gamma) - z \cdot \cos(\gamma) \cdot \phi]$$

The constant of proportionality $K$ is often called the cutting constant, which is decoupled for radial, tangential and axial forces. Hence, the three dimensional components $F_i$, $F_s$ and $F_o$ of the cutting force $F_{TT}$ of the cutter can be determined from [11] using the following equations,

$$F_i = K_m \cdot h_s \cdot b + K_{rel}$$

$$F_s = K_r \cdot h_s \cdot b + K_{rel}$$

$$F_o = K_a \cdot h_s \cdot b + K_{rel}$$

where, $K_m$, $K_r$, $K_a$, $mt$, $mr$, $ma$, are coefficients that determine the shear forces, $K_r$, $K_a$, $K_m$, are the friction coefficients, and $l$ is the length of the flute, which is roughly the width of cut.

![Fig. 2. Dynamic representation of the cutting tool insert motion (figure based on [5]).](image2)

The total force $F_{TT}$ can be written on a reference system fixed to the tool tip,

$$\begin{pmatrix}
F_{TT} \\
F_t
\end{pmatrix} = \begin{pmatrix}
\sin(\gamma) \cdot \sin(\phi) & -\cos(\phi) & -\cos(\gamma) \cdot \sin(\phi) \\
\cos(\phi) & \cos(\gamma) & \cos(\gamma) \cdot \cos(\phi)
\end{pmatrix} \begin{pmatrix}
F_i \\
F_s \\
F_o
\end{pmatrix} \times \begin{pmatrix}
daF_t \\
daF_s \\
daF_o
\end{pmatrix}$$

Once the regenerative chatter mechanism is known, two cutting stability prediction methods are presented to obtain the chatter free maximum depth of cut for each spindle speed, one based on analytical simulations, and another one based on time domain.

A. Time Domain Stability Lobes Simulation

The time domain simulation is based on an iterative process, where force and displacement are calculated for each angular position of the tool. The displacement in the machine’s modes direction is obtained solving the equation of motion with a double numerical integration.

$$M \cdot \ddot{x}(t)+C \cdot \dot{x}(t)+K \cdot x(t)= F_{TT}(t)$$

Finally, when several number of revolutions have been simulated a chatter detection algorithm is applied to verify the existence of instability. The same simulation process is carried out for different depths of cut and spindle speeds.

One of the most important features of time domain simulations is the capability of introducing machine nonlinearities into the model, such as the loss-of-contact of the tool with the workpiece due to excessive vibrations. When the calculated chip thickness is less than zero $h_s < 0$, the tooth is not in contact with the surface being machined, so the force must be null.

On the other hand, time domain simulations are very useful in predicting machined surface finish, forces and vibrations. The developed model—Fig. 3—includes the possibility of selecting the geometry of the milling tool among straight teeth, helical end mill and ball end mill [11, 12].

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Fig. 3. Simulations of helical end mills (a) and ball end mills (b) with three flutes.

B. Frequency Domain Stability Lobes Simulation

The frequency domain simulations do not include the effect of process damping. Suppose that the force model of (3) is linearly proportional to the chip area \( b \cdot h_n \), so \( m_t, m_r, m_a \) parameters are considered as unit value. The dynamic system of the forces is reduced to,

\[
\Delta = \alpha \pi K b N F^4
\]

where, \( \Delta \) is the vibrating vector,

\[
\{ \Delta \} = \{ a \} \cdot [G(i \omega_c)] \cdot \{ F \}
\]

\([G(i \omega_c)]\) represents the frequency response function relative to the contact area of the tool-workpiece, \([a]\) is formed by the average directional coefficients, \( N \) is the teeth number, and \( \omega_c \) is the chatter frequency.

The system stability limit is determined by means of the characteristic equation (8), which is equivalent to computing the eigenvalues of \( \Phi \).

\[
\text{det}(I + \Lambda \cdot [\Phi]) = 0
\]

where \([\Phi] = [a] \cdot [G(i \omega_c)]\) and,

\[
\Lambda = \frac{N}{4\pi} \cdot b \cdot K \cdot (1 - e^{-\omega T})
\]

From this eigenvalue problem, and following [13], the analytical stability analysis is straightforward, and thus, no further details are included. Based on this, Fig. 4 shows the stability lobes diagram obtained with the simulation software.

Fig. 4. Milling process simulation software.

Milling process simulation algorithms covered in this section would give exactly the same stability lobes as time domain if the following conditions were fulfilled:

- The precise cutting force model is known, but not necessarily linear.
- The damping coefficient of the model is known.
- The milling machine is modelled perfectly with its vibrating modes.

III. SELF-EXCITED VIBRATIONS SUPPRESSION TECHNIQUES

A. Continuous Spindle Speed Variation Method

This method consists in the superposition of speed variations over 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.

1) Sinusoidal Spindle Speed Variation SSSV

This method consists in adding a sinusoidal component to the constant spindle speed [14]. It is shown in Fig. 5.

\[
\omega(t) = \omega_0 \cdot (1 + RVA \cdot \sin(2\pi \cdot RFV \cdot t \cdot \omega_0 / 60))
\]

\( \omega_0 \) is the mean spindle speed (rev/min), RVA is the normalised sinusoidal amplitude and RFV denotes the normalised sinusoidal frequency.

2) Multi-level Random Spindle Speed Variation MRSSV

The proposed MRSSV signal can mathematically be expressed as shown in the following equation,

\[
\omega(t) = \omega_0 + A \cdot M(t,p) = \omega_0 \cdot (1 + RVA \cdot M(t,p))
\]

\( M(t,p) \) denotes uniform random process, as a function of \( p \), the uniform time step size in seconds. Simulation results of the MRSSV technique are shown in Fig. 6.

To summarise, the SSV 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 (RVA, RFV), an increase in the stability of the machine is obtained.
A. Predictability of Chatter in Non-uniform Pitch Milling

The material removal rate at a specific cutting speed range can be increased significantly by selecting a cutter with non-uniform pitch angles. The constant regenerative time delay in uniform cutters is transformed into non-uniform multiple regenerative time delays for variable pitch cutters.

B. Milling Cutters with Nonconstant Pitch

The material removal rate at a specific cutting speed range can be increased significantly by selecting a cutter with non-uniform pitch angles. So, the constant regenerative time delay in uniform cutters is transformed into non-uniform multiple regenerative time delays for variable pitch cutters.

IV. Conclusion

A software package for analytic and time-domain milling process planning has been presented, which is useful for off-line milling process optimisation. It can be considered as an optimisation tool for process planners to increase production. Furthermore, the model includes new features over other simulation packages, like continuous spindle speed variation techniques (SSSV and MRSSV). All of this will be commercially available in the future.

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