An Efficient Simulation Tool for Predicting Chatter during Cutting Operations

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ABSTRACT: The trends in chatter prediction are to compute stability lobes showing the maximal depth of cut versus spindle speed, following the work of Tlusty, Tobias and, more recently, Altintas. For mass production such as the production of automotive parts, this kind of approach is not suitable because the goal is to find cutting conditions stable *and* independent of perturbations inherent to machining (clamping, rough part dimensions …). Still, in this method, the greatest allowable depth of cut to avoid chatter at any spindle speed is considered. The model is based on Tlusty's theory and the local stiffness of the machined surface is computed through a static finite element analysis. The result is a chatter map of the machined surface showing the maximal depth of cut at each node.

Key words: Machining, Simulation, Chatter

1 INTRODUCTION

Chatter is a dynamical phenomenon that occurs when the system composed of the tool, the machine and the workpiece is self-excited. For J. Tlusty, it occurs when chip width is too great versus dynamic stiffness [1].

This phenomenon leads to bad surface aspect, high noise level and reduced tool life. Doi and Koto proposed one of the very first scientific articles dealing with chatter in 1953, then have Tlusty and his assistant, Polacek in 1957, one year before Tobias and Fishwick who published in 1958 [2,3,4].

Tlusty and Polacek have proposed a limit stiffness coefficient; Tobias and Fishwick have first developed stability diagrams showing the limiting depth of cut versus spindle speed.

More recently have Altintas and Budak proposed a method to compute Tobias' stability diagram based on transfer functions of the system [5].

As this method is not designed for any kind of case encountered in automotive industry, we developed another method, which provides the depth of cut that prevents from chatter at any spindle speed. This depth of cut is the lowest value provided by Altintas and Budak's method.

2 COMPUTATION METHOD

For the chatter cases studied, the phenomenon is generally due to important workpiece flexibility. The method presented makes the assumption that the tool is more rigid than the workpiece. This leads us to work on workpiece stiffness in order to find a criterion that put emphasis on chatter zone of machined surface.

The study of Single Degree Of Freedom (SDOF) systems following the work of J. Tlusty [1], results in a critical depth of cut that prevent chatter for any spindle speed. This solves the problem for turning operations. Our work mainly consists in adapting it to chatter prediction during milling operations.

2.1 *Tlusty's theory for SDOF systems*

The chip thickness is:

$$h(t) = h_0 - [y(t) - y(t - T)] \tag{1}$$

Where T is the time-delay between two pass and h_0 is the feed per tooth.

$h(t)$ expression in the Laplace domain is:

$$\tilde{h}(s) = h_0 + \left(e^{-sT} - 1\right)\tilde{y}(s) \tag{2}$$

Using a linear cutting force model, the expression of the cutting force is:

$$\tilde{F}_f(s) = K_f b \tilde{h}(s) \tag{3}$$

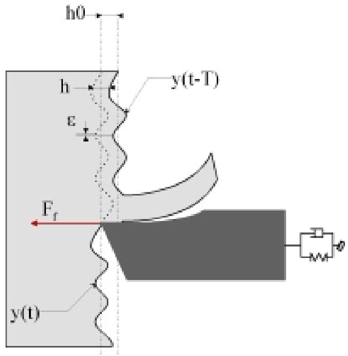

Fig. 1 Tlusty's model for SDOF

Where K_f is a pressure and b is the chip width.
And using the transfer function $\Psi(s)$:

$$\Psi(s) = \tilde{y}(s) \big/ \tilde{F}_f(s) \tag{4}$$

Leads to:

$$\tilde{y}(s) = K_f b \tilde{h}(s) \Psi(s) \tag{5}$$

Replacing $\tilde{y}(s)$ by its value in $\tilde{h}(s)$:

$$\tilde{h}(s) = h_0 + \left(e^{-sT} - 1\right) K_f b \tilde{h}(s) \Psi(s) \tag{6}$$

Which leads to:

$$\frac{\tilde{h}(s)}{h_0} = \frac{1}{1 + \left(1 - e^{-sT}\right) K_f b \Psi(s)} \tag{7}$$

The stability of this last transfer function depends on its complex poles, s_c.
At the threshold of stability, we have :

$$\begin{aligned} s_c &= i\omega_c \\ b &= b_{\lim} \end{aligned} \tag{8}$$

Where ω_c is the chatter pulsation and $b_{\lim}$ is the limiting depth of cut that prevents from chatter. Plotting $b_{\lim}$ gives the stability lobes. As s_c is a pole of expression (7), it has the following property:

$$1 + \left(1 - e^{-i\omega_c T}\right) K_f b_{\lim} \Psi(i\omega_c) = 0 \tag{9}$$

Considering real and imaginary parts of this equation leads to:

$$\tan(\varphi) = \frac{\mathrm{Im}(\Psi(i\omega_c))}{\mathrm{Re}(\Psi(i\omega_c))} = \frac{\sin(\omega_c T)}{\cos(\omega_c T) - 1} = \tan\left((\omega_c T/2) - 3\pi/2\right) \tag{10}$$

Using this last expression, ε is defined as:

$$\omega_c T = 3\pi + 2\varphi = \varepsilon \tag{11}$$

and ε corresponds to the phase shift between the inner and the outer modulation of the chip.
On the other hand another definition of ε is:

$$2\pi\omega_c = 2k\pi + \varepsilon \tag{12}$$

Where k is an integer.
The corresponding spindle speed can be computed:

$$\begin{aligned} N &= \frac{60}{T} \\ T &= \frac{2k\pi + \varepsilon}{2\pi f_c} \end{aligned} \tag{13}$$

The expression of $b_{\lim}$ can be obtained from the real part of the characteristic equation (9):

$$b_{\lim} = \frac{-1}{2K_f \,\mathrm{Re}\left(\Psi(i\omega_c)\right)} \tag{14}$$

Those two last expressions (13) and (14) are leading to the stability lobes diagram. Since only the critical chip width, namely b_{crit}, that prevent from chatter at any spindle speed is wanted, the low part of equation (14) has to be minimized. The transfer function theory gives:

$$\mathrm{Re}\left(\Psi(i\omega_c)\right)_{\min} = \frac{1}{4K\zeta(\zeta+1)} \tag{15}$$

Where ζ is the damping ratio and K is the static stiffness.
Projecting this on the cutting direction, a coefficient u appears and b_{crit} becomes:

$$b_{crit} = \frac{2K\zeta(\zeta+1)}{K_f u} \tag{16}$$

This criterion is easy to apply with finite element-based chatter predictions turning operations. Only K has to be computed for each node of the machined surface in order to provide a chatter map showing the critical depth of cut for those nodes.
This work mainly focuses on adapting this to milling operations.

2.2 Modelling milling operations

The previously explained criterion is to be used on milling operations, this implies providing a stiffness K and a cutting coefficient K_f on the cutting direction.
F.E.M. is used to compute K following the philosophy of the article [6].
For a meshed workpiece, the stiffness matrix ***K*** can be condensed on the machined surface's nodes. This results in the matrix $\boldsymbol{K_c}$. After applying the boundary conditions corresponding to the clamping system, this matrix can be inverted into a flexibility matrix ***S***.
Since solid elements are used, the matrix ***S*** is composed of 3x3 sub-matrixes that are representing the flexibility of each machined surface's nodes with each other. Making the assumption that one tooth is immerged, only diagonal terms $\boldsymbol{S_{ii}}$ have to be kept.

The highest flexibility, namely S_3 and its relative direction is then computed through the research of eigenvalues on each $\boldsymbol{S_{ii}}$ sub-matrix.
The cutting force model used is the model of Kienzle. Cutting forces are computed for each position of the immerged tooth. The ratio between this value and the uncut chip area gives a cutting pressure k_d. The cutting force is projected from the cutting direction on the maximal flexibility direction previously computed during the eigenvalues research. This projection is resulting in the coefficient u.
Doing so, the critical chip width expression can be adapted from SDOF to milling case:

$$b_{crit} = \frac{2\zeta(\zeta+1)}{S_3 k_d u} \quad (17)$$

The depth of cut a is more commonly used. The critical depth of cut is:

$$a_{crit} = \frac{2\zeta(\zeta+1)}{S_3 k_d u}\sin(\kappa_R) \quad (18)$$

Where κ_R is the tool cutting edge angle.

2.3 Limitations of the model

As already seen, this model does not take the case of multiple immerged teeth into account.
The assumption on the fact that the tool is more rigid than the workpiece is true for thin walls milling in automotive industry. In this case, the geometry of the workpiece implies that most of the time, there is only one immerged tooth. Nevertheless, some variations in the trajectory could lead to multiple immerged teeth as shown in fig. 2.

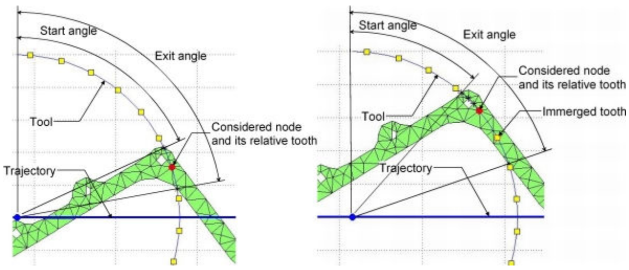

Fig. 2. Multiple immerged teeth due to trajectory

2.4 Comparison with stability lobes computation method

As seen in the introduction, a chatter prediction method is already existing. This method, proposed by Y. Altintas and E. Budak focuses on plotting Tobias' stability diagram that is based on computation of stability lobes.
This diagram presents the evolution of the depth of cut that prevents from chatter versus spindle speed. It takes the form of an intersection of a series of lobes. The advantage of this representation is that it shows optimal spindle speeds that allow to cut the most quantity of material in the shortest delay.

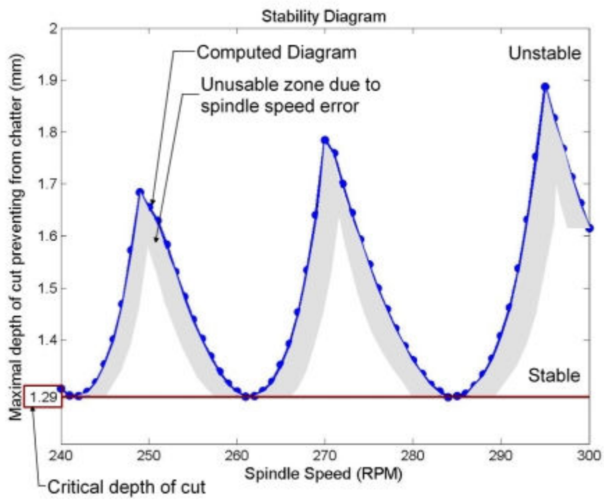

Fig. 3 Stability diagram obtained by lobes computation method on a workpiece

This kind of result is typically meant for chatter case due to a flexible tool because it implicitly makes the assumption that all simultaneously cut nodes have the same dynamic behaviour. This allows considering more than one immerged tooth but it is only true when the workpiece is huge or far more rigid than the tool.
In the case of one immerged tooth, the workpiece behaviour can be considered and stability diagram for each cut node can be plotted through an adaptation of the original method but the result is difficult to analyse and needs to be presented under the form of spindle speed-dependant chatter maps.
Finally, in this case and for the spindle speed used, stability lobes proved to be very close to each other as shown on figure 3. In addition, considering an error on the spindle speed can lower of the maximal values of the stability diagram.

3 CASES STUDY

The method proposed is based on the computation of the highest flexibility S_3 and its relative direction for each node of the meshed machined surface. So the use of both value and direction allows the critical depth of cut computation. This leads to a critical depth of cut for each node that can be shown as a chatter map presenting the surface coloured accordingly to the critical depth of cut.
This section shows several cases study and relative chatter maps.

3.1 *Cylinder block distribution face*

This case of chatter occurs while milling a cylinder block lateral face that presents a typical thin wall design, which is very likely to present chatter vibrations.

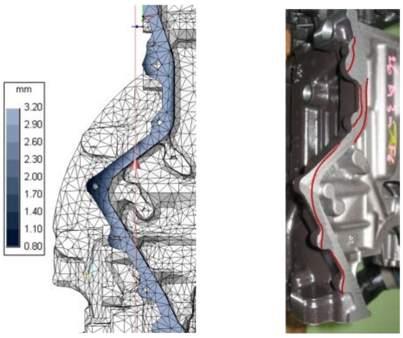

Fig. 4 Left : Computed Chatter Map considering a 200mm cutter with 32 teeth and a 45° lead angle - Right : test part, depth of cut = 3 mm

Figure 4 shows the critical depth of cut on the left and the result of a milling test on a real part for a 3 mm depth of cut on the right. A good correlation between the predicted chatter zones and reality is obtained.

This case has been solved through a heavy modification of the part geometry around this zone and a clamping system modification.

3.2 *Cylinder block fire face*

This case occurs while milling the fire face of another cylinder block. This face presents a thin wall-designed oil canalisation on which chatter takes place.

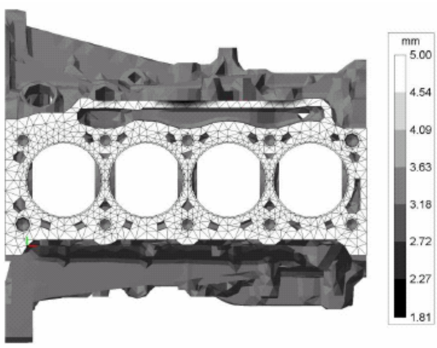

Fig. 5 Computed Chatter Map considering a 400mm cutter with 64 teeth and a 45° lead angle

The computed chatter map is presented in figure 5. Since only one tooth is immerged in the thin wall, our results are reliable. Furthermore, they are confirmed by tests parts.

On the basis of the computed prediction, this case has been solved by testing a patented two-step mill in the machine.

4 CONCLUSIONS

A summary of comparison between the developed chatter maps method and the stability lobes computation method is presented in table 1. The case corresponding to automotive industry is highlighted.

Table 1. Both methods comparison summary.

		One immerged tooth	
Flexible Tool	Lobes Computation	efficient	
	Chatter Maps	inapropriate	
Flexible Workpiece	Lobes Computation	not efficient	Automotive industry
	Chatter Maps	efficient	
		Multiple immerged teeth	
Flexible Tool	Lobes Computation	efficient	
	Chatter Maps	inapropriate	
Flexible Workpiece	Lobes Computation	to be adapted	
	Chatter Maps	to be adapted	

As shown through this comparison and cases study, the chatter maps computation method proves to be very well adapted to chatter prediction in automotive industry.

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