Forces, vibrations and roughness prediction in milling using dynamic simulation

POLYTECH.MONS

Edouard Rivière, Enrico Filippi, Pierre Dehombreux
Service de Génie Mécanique

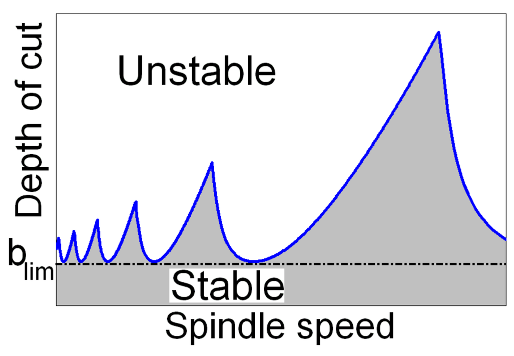
1. Introduction

Self-excited vibration « chatter » is one of the most common sources of instability in machining.
A basic method to predict this phenomenon is the stability lobes analysis based on a very simple model (plunge cutting, 1DOF, forces proportional to chip thickness and width of cut, no run-out,…).
The main Equation of the system is

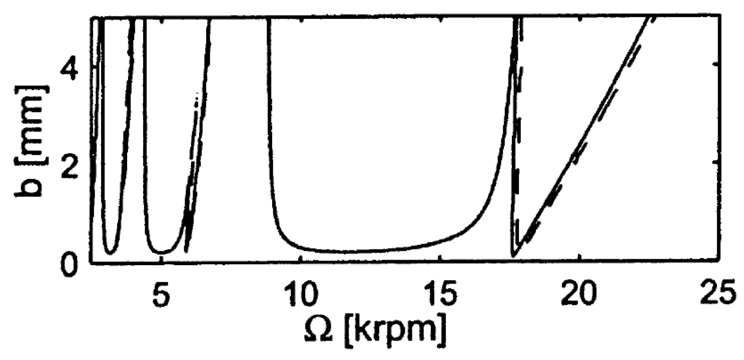
$$m \cdot \ddot{y}(t) + c \cdot \dot{y}(t) + k \cdot y(t) = F_{cut}(t) = K \cdot a \cdot h(t)$$

Where K is the specific pressure, a is the width of cut. In order to take regeneration into account, chip thickness is computed as follow:

$$h(t) = h_0 + y(t-T) - y(t)$$ (T is the time delay)



Classical stability lobes



New kind of stability lobes [1]

This method has been extended to simulate milling but many non-linearities are not taken into account (periodic variation of chip thickness, entries and exit of the tool…).
Insperger [1] showed that two kinds of lobes coexist in milling

- classical lobes linked to Hopf bifurcation
- second type of lobes linked to period doubling

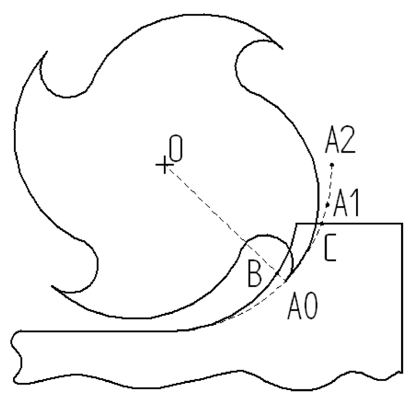
2. Dynamic simulation

Dynamic simulation can be used to predict stability of the milling process. The milling simulation is highly coupled procedure linking three aspects : surface modeling, cutting forces computation and dynamic model of the system. Efficient simulation of these three aspects is fundamental for accurate prediction.

We chose to discretize the problem in slices along axial direction in order to transform 3D problem into 2D.

a. Surface modeling

Surface is modeled using an 'eraser of matter' model given by Peigne [2].
Sector swept by cutting tool during Time interval Δt is removed from the surface



b. Cutting forces

Model given by Engin is used :

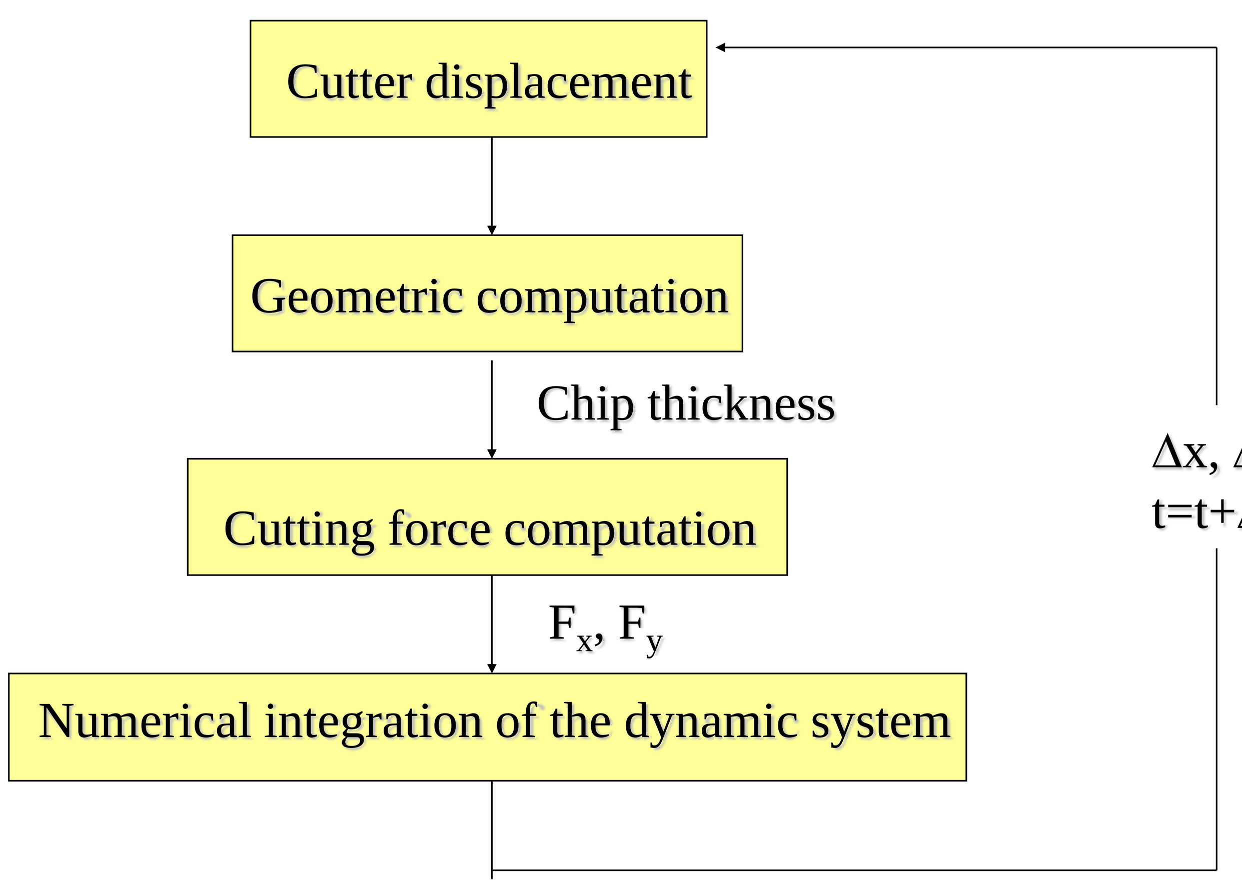
$$\begin{cases} dF_t = K_{te} \cdot dS + K_{tc} \cdot h \cdot db \\ dF_r = K_{re} \cdot dS + K_{rc} \cdot h \cdot db \\ dF_a = K_{ae} \cdot dS + K_{ac} \cdot h \cdot db \end{cases}$$

indices t,r and a stand for tangential, radial and axial directions. Coefficient K are constant for a given couple machined material/tool, h is the chip thickness, dS is the local edge length and db the projected length of cutting flute projected along cutting speed

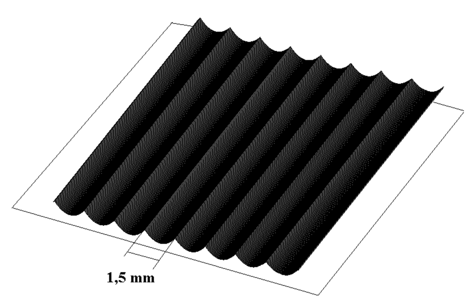
c. Dynamic system

Dynamic is currently modeled as a one degree of freedom system. Numerical integration is performed using Newmark's scheme.

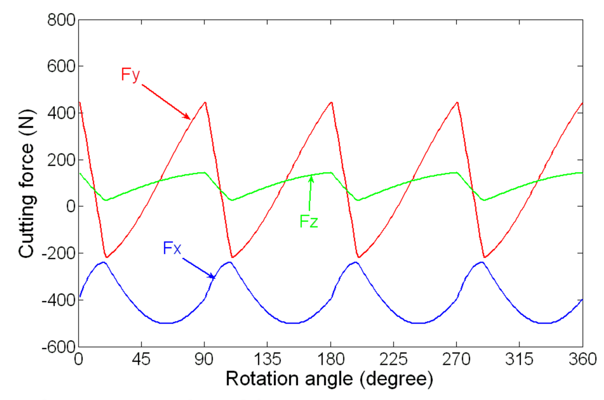
3. General algorithm



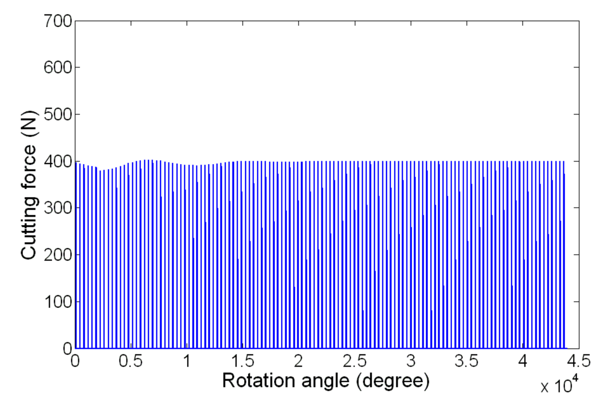
4. Typical results



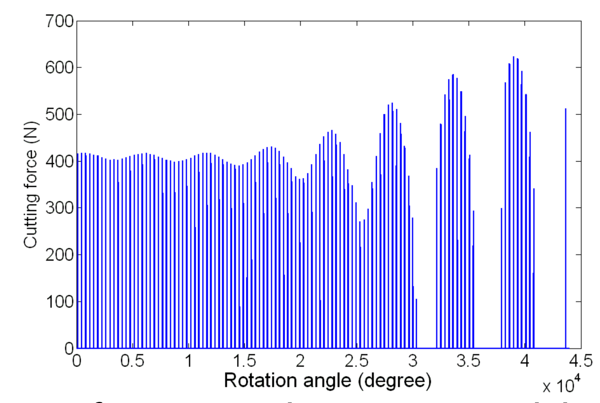
Machined surface



Cutting forces (half immersion upmilling with cylindrical mill 30° helix angle [3])



Total cutting force evolution, stable case [2]



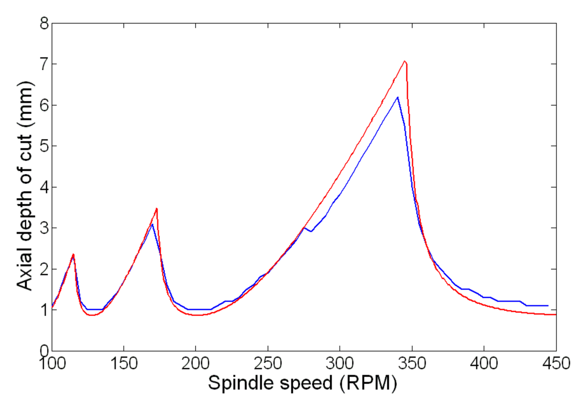
Total cutting force evolution, unstable case [2]

5. Lobes based on dynamic simulation

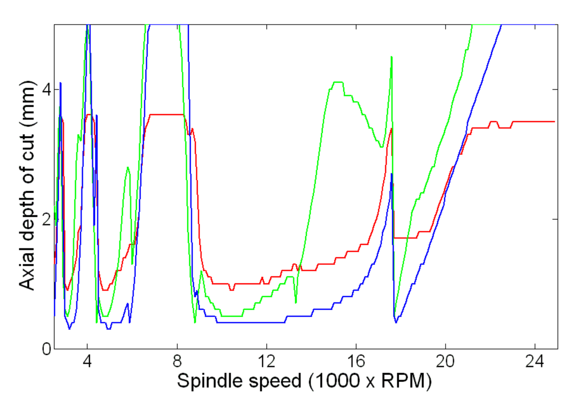
Dynamic simulation can be used to predict stability lobes. The plane spindle speed depth of cut is divided into simulation point. Stability is asserted using a criteria :

- Maximum chip thickness
- Maximum cutting force (tool wear)
- Maximum vibration amplitude
- Maximum roughness after machining

Results are in good agreement with classical lobes where cut is fairly continuous. Dynamic method is also able to predict both kind of lobes (Hopf and Flip).



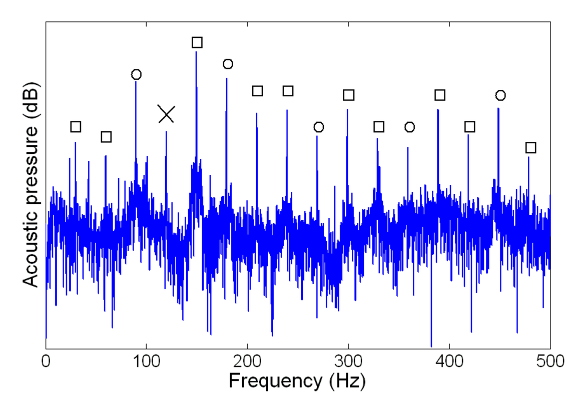
Comparison between analytical lobes (red) and lobes given by dynamic simulation (blue)



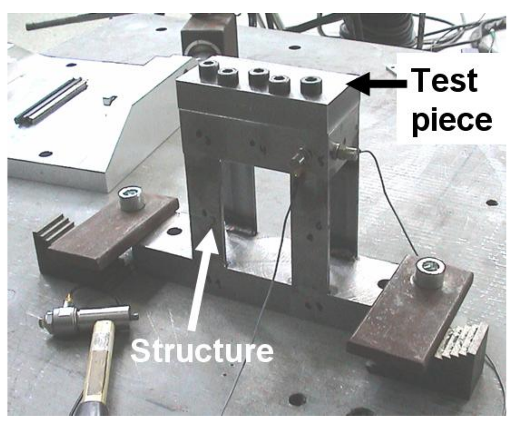
Lobes based on Force (red), displacement magnitude (green) and total roughness (blue)

6. Experimental validation - frequency content of the signal

Insperger [1] identified dominant frequencies of signal recorded during machining. Main peaks come from damped natural frequency of the workpiece/ the spindle, tooth passing frequency and its harmonics and specific frequencies linked to Hopf or Flip bifurcation depending on the instability reached.
We performed experimental validation of that theory using a simple test structure in order to master the natural frequency of the system.
There is a good agreement between measured signal and the theory.



Frequency content of measured signal (half immersion downmilling). Natural frequency (X), tooth passing (**O**) Hopf frequency (☐)



Test structure

7. Conclusion

A unified dynamic simulation tool for milling is presented. It is able to give time evolution of forces, displacement, speed and acceleration. Surface after machining can be reconstructed and roughness measured.
This software is able to link results given by various prediction methods. Additional results such as stability lobes on various stabilities criteria (maximum force, roughness after machining,…) are also accessible.

8. References

[1] T. Insperger and al, « *Stability of up- and downmilling, part I : Alternative analytical methods* », Int J. of Mach. Tools and Manuf., vol 43, pp 25-34, 2003
[2] G. Peigne and al, « *A model of milled surface generation for high speed cutting* », Proc. Instn Mech Engrs Part B : J. Engg Manuf., vol 217 Number 7 pp 919-930, July 2003
[3] S. Engin, Y. Altintas,, « *Mechanics and dynamics of general milling cutters, Part I : Helical end mills* », Int J. of Mach. Tools and Manuf., vol 41, pp 463-478, 2001