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Influence of material removal on dynamic behavior of thin walled structure in peripheral milling

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Abstract
The peripheral milling of thin walled structure generates vibrations of the workpiece, which affect the quality of the machined surface. A reduction of tool life and spindle life is also observed. The stability lobes theory allows us to determine cutting conditions for which the vibrations will not appear. These cutting conditions depend on dynamic properties of the workpiece. Machining is a working process by material removal, so, the dynamic properties will change during the machining. We show in this paper how to integrate in the stability lobes theory this variation of the dynamic properties. These computed results are compared with real experiments.

1 INTRODUCTION
During some machining operations, it can appear some vibrations between the tool and the workpiece. This vibrations affect the surface quality, the geometrical and dimensional accuracy and to a lesser extent, the tool and spindle life. Therefore, it is necessary to reduce these vibrations. In the 50’s, S. A. Tobias [1], J. Tlusty [2], and H. E. Merrit [3] studied the vibrations of the tool in the case of orthogonal cutting in turning, and developed the stability lobes theory. This theory makes it possible to predict cutting conditions from which the vibrations will appear. At the end of 1960, Sridhar [4] [5] developed the stability lobes theory for milling process, and in the middle of the 90’s, Altintas [6] presents the most comprehensive analytical method to determine the stability limits for the tool or the workpiece for general milling process. This theory is mainly used to reduce the tool vibrations, but can be used to study the vibrations of the workpiece [7]. But when a thin walled structure is machined, its dynamic characteristics change with time, and the stability lobes are not valid all along the machining. So we have to calculate the stability lobes, in order to obtain a 3D representation of the stability lobes, which allow us to determine stable cutting conditions at every moment of the machining.

2 STABILITY LOBES THEORY
This work is mainly based on the stability lobes theory developed by Y. Altintas and E. Budak [6] [8] [9] and is based on the regenerative chatter model with one degree of freedom. Our purpose is to show how to calculate the stability lobes all along the machining. So, we remind just the equations which permit to plot the lobes, and we use the simplest model possible.
2.1 Starting assumptions

- The workpiece is mobile compared to the tool, which is much more rigid than the workpiece.
- The workpiece can locally be considered as a rigid body in the machined zone.
- The workpiece moves along the direction y, like a rigid body in the machined zone, according to the following equation.

\[ \ddot{U} + 2\xi\omega_0\dot{U} + \omega_0^2 U = [(f_y)\omega_0^2]/k \]  \hspace{1cm} (1)

We use a linear cutting law of the type \( F = K_t A_p A_c \) and \( F = K_r A_p A_c \), where \( F_t \) and \( F_r \) are respectively the tangential and radial cutting force, \( K_t \) and \( K_r \) the tangential and radial milling force coefficients and \( A_p \) and \( A_e \) the axial and radial depth of cut.

2.2 Calculation of the stability lobes

We use an orthogonal cutting model although the lobes shape is not exactly the same with an oblique cutting model. But given the measurement inaccuracy for certain parameters, we prefer to use an orthogonal cutting model, which is easier to implement, and can be easily fitted with tests.

The stability lobes diagram represents the critical axial depth of cut \( A_{\text{plim}} \) according to the spindle speed \( N \). The lobes are plot from the parametric functions \( A_{\text{plim}} = f(\omega_c) \) and \( N = f(\omega_c) \), where the parameter \( \omega_c \) is the vibration pulsation of the workpiece, so called chatter pulsation.

The function \( A_{\text{plim}} = f(\omega_c) \) is given by:

\[ A_{\text{plim}} = \frac{1}{(2\pi)^2} \alpha_{yy} K_t \Re \left[ G_y(i\omega_c) \right] \]  \hspace{1cm} (2)

where \( z \) is the number of teeth on the cutter. \( \alpha_{yy} \) is the directional dynamic milling coefficient in y direction and is given by:

\[ \alpha_{yy} = \frac{1}{2} \left[ -\cos(2\theta) - 2K_r \theta - K_r \sin(2\theta) \right] \phi_{\text{ex}} \]  \hspace{1cm} (3)

where \( \theta \) is the engagement angle of the tool, \( \phi_{\text{ex}} \) the exit angle of the tool, and \( \phi_{\text{st}} \) the start angle of the tool (Figure 1).

\[ \Re[G_y(i\omega_c)] \] is the real part of the structural transfer function of a system with one degree of freedom:

\[ \Re[G_y(i\omega_c)] = \frac{1}{k} \left[ \frac{1 - d^2}{(1 - d^2)^2 + 4\xi^2 d^2} \right] \]  \hspace{1cm} (4)

where \( d = \omega_c/\omega_0 \), \( \omega_0 \) is the natural pulsation, \( k \) is the stiffness, and \( \xi \) is the damping ratio.

The function \( N = f(\omega_c) \) is given by:

\[ N = \frac{60\omega_c}{z \left[ 2\pi + \pi - 2 \arctan \left( \frac{d^2 - 1}{2\xi d} \right) \right]} \]  \hspace{1cm} (5)

So, we obtain, for one natural mode, the following diagram (Figure 2).

3 VARIATIONS OF THE DYNAMIC CHARACTERISTICS

3.1 Variation of apparent stiffness

When a thin walled structure is machined, we can see that the machined surface is not homogeneous in term of surface quality. So, the dynamic behaviour of the workpiece depends on the tool position, and the workpiece cannot be considered as a rigid body.
in the machined zone. The dynamic behaviour of a mode is very different if the exciting force is at a node or at a loop. We introduce thus a third dimension in the stability lobes diagram, which is the application point of the cutting force $M(t)$ (Figure 3).

The modal equation with a localized force (cutting force) at $M(t)$, normalized in displacement can be written as follow for mode $i$:

$$
\ddot{u}_i(M(t),t) + 2\xi_i\omega_i \dot{u}_i(M(t),t) + \omega_i^2 u_i(M(t),t) = \frac{\Phi_i^2(M(t),t)f_c(t)}{m_i}
$$

(6)

where $\xi_i$ is the modal damping ratio, $\omega_i$ the natural pulsation, $\Phi_i(M(t),t)$ the modal displacement at point $M(t)$, $f_c$ the cutting force, and $m_i$ the modal mass.

The expression (6) is similar to the starting equation (1), with:

$$
\xi = \xi_i
$$

(7)

$$
\omega_0 = \omega_i
$$

(8)

$$
k = \frac{k_i}{\Phi_i^2(M(t),t)}
$$

(9)

where $k_i$ is the modal stiffness. $k_i$, $m_i$ and $\Phi_i(M(t),t)$ are obtained here with finite elements calculus.

According to (9), the apparent stiffness $k$ is much higher when the tool is in a node that when the tool is in a loop. So, the critical axial depth of cut is higher in a node than in a loop (2) (4).

The variation of the apparent stiffness of the second mode of the workpiece is represented in Figure 4.

$\times 10^{12} (\text{MPa})$

![Figure 4: Variation of the apparent stiffness of the second mode of the test workpiece along the machining.](image)

The 3D lobes of the second mode of the test workpiece are represented in Figure 5 with the parameters in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$</td>
<td>12560 rad/s</td>
</tr>
<tr>
<td>$\xi$</td>
<td>0.00406</td>
</tr>
<tr>
<td>$K_t$</td>
<td>1414 MPa</td>
</tr>
<tr>
<td>$K_r$</td>
<td>0.8</td>
</tr>
<tr>
<td>$z$</td>
<td>4</td>
</tr>
<tr>
<td>$D$</td>
<td>12 mm</td>
</tr>
<tr>
<td>$A_p$</td>
<td>20 mm</td>
</tr>
<tr>
<td>$A_e$</td>
<td>1 mm</td>
</tr>
<tr>
<td>$X$</td>
<td>80 mm</td>
</tr>
</tbody>
</table>

Table 1: Parameters of the second mode of the test workpiece and of the test machining.
3.2 Variation of natural frequencies

By definition, machining is a forming process by material removal. So, when the material removal is significant, the dynamic properties of the workpiece change according to the tool position. Thus, we include in the third dimension of the stability lobes, on top of behaviour variation on the nodes and the loops, the variation of the dynamic parameters of the workpiece.

The material removal affects mainly the natural frequencies. So, the critical axial depth of cut and especially the optimal spindle speed will vary along the machining (2) (4) (5).

The 3D lobes of the second mode of the test workpiece with only the variation of the natural frequency are represented in Figure 7. The same parameters as Figure 5 are used, except \( \omega_0 \) which vary along the machining. The variation of natural frequency of the second mode is represented in Figure 6 and is obtained with \( A_p = 20 \text{ mm} \). Indeed, the variation of the natural frequency depends on \( A_p \) and there is a 3D lobes diagram for each value of \( A_p \).

When we take into account the variations of the natural frequencies and the variations of the apparent stiffnesses, we obtain the 3D lobes, for the second mode of the test workpiece, represented in Figure 8. The same parameters as Figure 5 are used.

In most cases, we have to take into account the two types of variation, especially the variation of the natural frequencies, because it shows that, in certain cases, it is not possible to find a constant optimal spindle speed.
3.3 Obtaining variation of dynamic parameters

To obtain the variation of the dynamic parameters of the workpiece we realize a parametric finite element calculus where the parameter is the position of the tool (Figure 9). For each step of the calculus, we determine the natural frequency, the modal stiffness and the modal displacement at the position of the tool for each mode. So, we can determine the variations of the natural frequencies and of the apparent stiffnesses all along the machining. We fit the stability lobes diagram with a measure of the real frequencies of the workpiece before machining.

4 VALIDATION TESTS

We consider the peripheral down-milling of an aluminium plate (Figure 3). Its thickness is 2 mm, two perpendicular sides are embedded. The programmed radial depth of cut is 1 mm, and the feed rate is 0.05 mm/tooth. We use a cylindrical mill, the diameter is 12 mm with 4 teeth, and the helix angle is 45°. The length of the machining is 80 mm, and the axial depth of cut is 20 mm. For this machining, the five first modes are important, so, we obtain the 3D stability lobes represented in Figure 10.

We can see that we cannot find a constant spindle speed for which the dynamic behaviour of the workpiece is stable all along the machining. We have to use different spindle speed. We realize a first machining (case 1) using the following spindle speed, according to the tool position (Table 2).

<table>
<thead>
<tr>
<th>X (mm)</th>
<th>N (tr/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 20</td>
<td>14000</td>
</tr>
<tr>
<td>20 - 35</td>
<td>16000</td>
</tr>
<tr>
<td>35 - 80</td>
<td>21000</td>
</tr>
</tbody>
</table>

Table 2: Variation of spindle speed according to the tool position.

We obtain the following machined surface (Figure 11).

We can see two marks at X = 20 mm and at X = 35 mm when the spindle changes speed. By safety, the CNC stops the linear axes when we apply a variation of the spindle speed.
These marks are not acceptable, but our purpose is to show the zones where the spindle speed is different.

We realize a second machining (case 2) where we don’t take into account the variations of the apparent stiffnesses and of the frequencies. So, the stability lobes are represented in Figure 12, and we set the spindle speed at 14000 rpm.

Figure 12: Standard representation of the lobes of the test workpiece

To compare with the first machining, we stop the linear axes at the same positions, and we obtain the following machined surface (Figure 13).

Figure 13: Resultant surface of a machining with constant spindle speed

For $X = 20 \text{ mm}$ to $X = 35 \text{ mm}$, we can see that the surfaces of the two machining are comparable in term of quality. But for $X = 35 \text{ mm}$ to $X = 80 \text{ mm}$, the surface quality of the first machining is better than the surface quality of the second machining. So, we have to take into account the variations of the dynamic parameters, the standard calculation of the stability lobes is not sufficient to choose the adequate cutting conditions all along the machining.

The regenerative model of vibration is valid in established mode. So, the time necessary for a significant variation of $k$ and $f$ must be much longer than the time necessary for the system to reach the established mode. The cutting tests show that the stability transition is very fast, compared to the variation of the dynamic parameters.

5 PROSPECTS

Initially, we have to be able to realize a continuous variation of the spindle speed to avoid the marks due to the stopping of the linear axes.

If we have to choose $A_p$ and $N$, our representation of the 3D lobes is not adequate, because a 3D lobes construction is calculated for a fixed value of $A_p$. So we have to develop another representation to efficiently choose the cutting conditions.

Finally, the flank milling of thin walled structure will be optimized with the choice of the spindle speed $N$ and the axial depth of cut $A_p$.

6 CONCLUSION

In this article, we show that the standard calculation of the stability lobes is not sufficient if we want to machine a thin walled structure. In this case, the dynamic properties of the workpiece vary along the machining. So we introduce a third dimension in the stability lobes diagram, which is the tool position. Firstly, the apparent stiffnesses change during machining, due to the passage of the tool in the nodes and the loops of the natural modes. So, the critical axial depth of cut is not constant, for each natural mode. Secondly, the natural frequencies of the workpiece change during machining, due to material removal. The optimal spindle speed is not constant, and we have to vary this speed during machining. The 3D lobes construction is validated by experimental machining. Thus, we can obtain the optimal cutting conditions all along the machining.

7 REFERENCES


