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Analysis of Chatter in Orthogonal Machining: Dynamic Stability Mapping

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Abstract

The phenomenon of chatter vibration in which self-regenerated during milling operations is considered as an issue of dynamic instability which is very harmful to the system composed by spare part-machine-tool. To study this phenomenon, we began by outlining the reasons for its appearance and methods to avoid it. Through this study, we described the various studies published in this field. Then based on Thevenot modeling, we plotted the graphs of various real and imaginary parts of the transfer function and commented their evolution opposite to the system stability. In the same context the dynamic stability map is drawn to select the rotational speed of the spindle and to increase the cut depth while remaining in the stable domain. Finally, we showed results from different experiments conducted in a numerical control milling machine using a new instantaneous detection device of chatter, which is the analysis of the machine noise using a microphone and appropriate processing software of the noise signal.

Keywords: *Parametric Excitation, Chatter, Boring Process, Stability; Milling, Instability Rare.*

1. INTRODUCTION

Vibration Machine (chatter), of the system toolbody degrades the quality of the machined surface and accelerates tool wear. An important chatter reduces productivity and sometimes makes it impossible to machining. There is no regenerative chatter and regenerative chatter. The non-regenerative chatter originates in the phenomenon of shear cutting which produces a background noise. It is ranked among the forced vibration and self-excited vibrations. Regenerative chatter is a more complex and more common in metal cutting. Its main causes are:

- The variation of the friction force of the chip sliding under the tool
- The inappropriate choice of the rotation speed of the spindle.
- The variation of cutting forces for the case of milling.

This is extremely detrimental to cut, mainly because it leads to:

- a very bad surface finish,
- a decrease in the lifetime of the tool,
- an unpleasant noise during machining,
- a premature wear of the components of the spindle (Bearings).

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This has been the subject of several researches: Arnold in 1946, Tlusty in 1963 and Tobias in 1965 [1]. The goal is to understand this phenomenon and to develop prediction methods. Among these methods are cited theory of stability lobes, which was explained by Tlusty [2] and Merrit [3]. This theory allows for a speed of rotation to choose a fixed axial depth of cut to avoid instability. The development of this method is well suited to the case of the shooting because the cutting forces are constant over time. Its application to the case of milling becomes much more complicated, because the chip thickness varies with time, which indicates that the cutting forces are too. Regenerative chatter is present in all milling operations. Even if the machine is stable during the first turns, it can become unstable after because of the variation of chip thickness. Figure1 illustrates this phenomenon for the case of orthogonal milling.

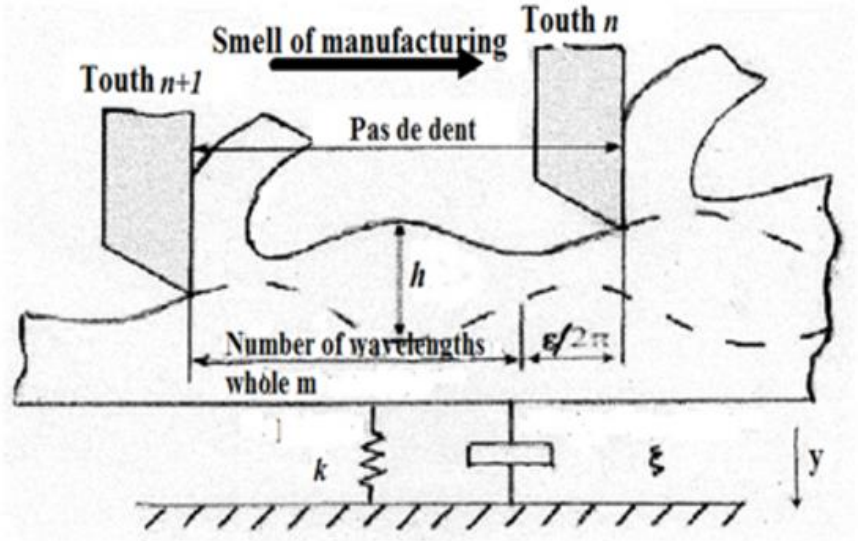

Figure 1: Cut pattern with regenerative vibration with one degree of freedom [4]

During the machining operation, there is a variation of the thickness of the chip. The parameter ε represents the phase shift of the tool relative to the traces of the previous pass. For milling we have:

$$\frac{j+\varepsilon}{2\pi} = \frac{f_c}{nZ} \qquad (1)$$

With Z the number of cutter teeth, j the number of whole waves between each tooth pass, N the rotational speed of the spindle and the critical frequency. So if $\varepsilon = 0$ the chip thickness is constant and there is no regenerative chatter, otherwise, the degree of chatter is by value of .

2. PREDICTION METHODS OF REGENERATIVE VIBRATIONS

Regenerative vibrations involve several concepts that:

- The cutting forces that are the source of excitation between the tool and work piece.
- The phase shift between the different surfaces machined.

3. ANALYTICAL METHODS

The analytical methods used to linearize the system tool-room around an equilibrium position and to seek the limits of system stability. These methods are used to make simplifications and reduce the complexity of solving equations. This type of analysis gives the stability diagram also appointed Stability lobes, depending on cutting parameters such as speed of rotation of the spindle, the advance of the table, the depth of cut etc...

The analytical model of Budak and Altintas [5,6] considers the system work piece rigid-flexible tool with two degrees of freedom and infinitely rigid along the axis of rotation of the cutter. Maps stabilities are plotted against the speed of spindle rotation N (rpm) and the axial involvement in the case of profile milling and commitment to the case of radial milling.

The method of the semi-discretization is based on discretization of lagged terms in the equation of dynamics. It is introduced by Insperger Stepam and [7] in the case of orthogonal cutting. It is applied to milling by Hartung [8]. The main idea of this method is to discretize the term delay of the equation (t-T), where T is the period of machining. The aim is to transform the system of differential equations non-autonomous delayed in a serie of autonomous differential equations whose solutions are known.

4. REPRESENTATION OF STABILITY LOBES FOR THE CASE OF MILLING THIN WALLS

Drawing on the analytical modeling Seguy and Design [4] and based on assumptions Thevenot [9], we address the analytical method for the case rigid tool and work piece deformation is controlled and represents the corresponding stability lobes the system chosen.

The milling of thin walls is widely used in aeronautics, including the blades for jet engines and parts cooled air through the fins. Seguy took a model made of aluminum alloy (Figure 2). Seguy's assumptions are:

- The tool is rigid relative to the work piece.
- The work piece is considered flexible but rigid along the cutting area.
- All movements of the piece are assimilated a single degree of freedom perpendicular to the axis of movement of the cutter.

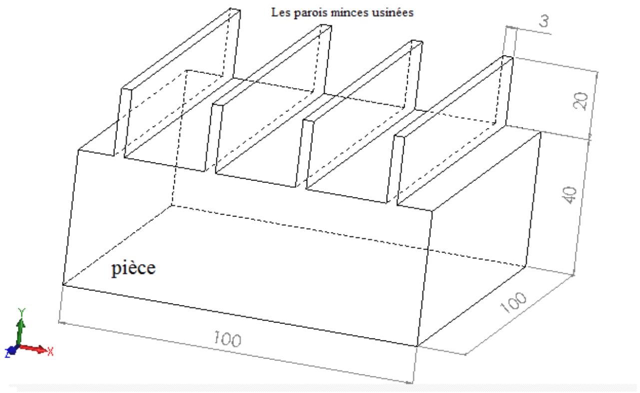

Figure 2: Study work piece with thin walls [4]

The transfer function of the system work piece-tool is:

$$G_x(i\omega_c) = \frac{\omega_0^2}{k(\omega_0^2-\omega_c^2+2\xi\omega_0\omega_c i)} \qquad (2)$$

Where $i^2 = 1$, k stiffness, ξ damping, ω_0 natural frequency of the system, ω_c the chatter's frequency. The stability lobes are plotted as:

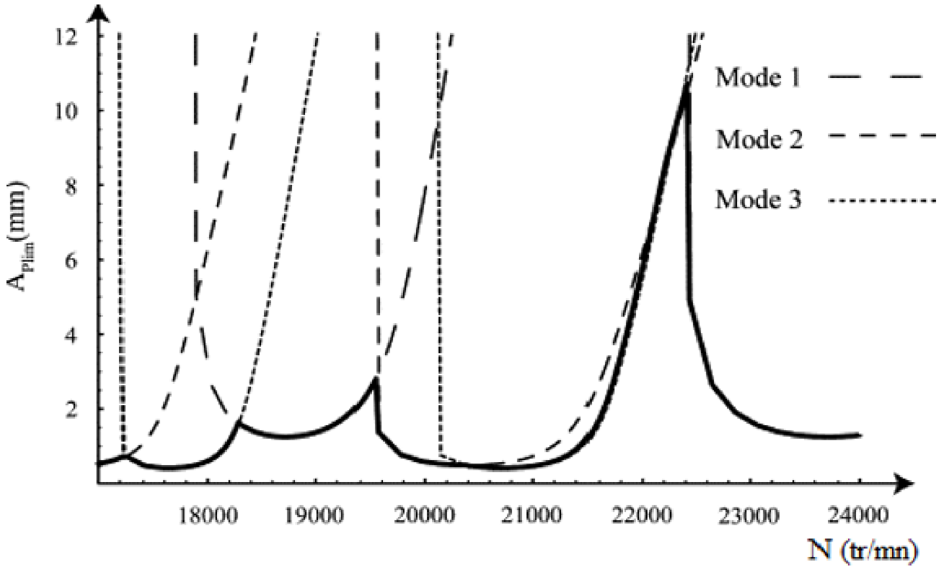

Figure 3: Stability lobes of Seguy[6]

4.1 Development of the method of the theory of stability lobes

Self-excited vibrations in milling are frequently obtained when using long tools, small diameter milling thin-walled profile milling or contouring. This phenomenon creates a very poor surface finish. The foundations of this theory date back to 50 with Tobias [10], who studied this phenomenon for the case of orthogonal cutting. This theory helps to know the conditions of stability of cut (depths of cut, speed of spindle rotation, number of teeth...) during the machining operation.

4.2 Formulation of the transfer function of the System work piece- tool

Based on the assumptions of Thevenot [9], after development and calculations we obtain the transfer function of a machining system with a single degree of freedom y

$$\left|\phi_y(i\omega_c)\right| = \left|\frac{Y}{F_0}\right| = \frac{1}{k}\frac{1}{\sqrt{(1-d^2)^2+(2\xi d)^2}} \qquad (3)$$

It can be separated into real and imaginary components:

$$G_y(\omega_c) \text{ and } H_y(\omega_c)$$

$$\phi_y(i\omega_c) = G_y(\omega_c) + jH_y(\omega_c) \qquad (4)$$

$$\Re(\phi_y(i\omega_c)) = G_y(\omega_c) = \frac{1}{k}\left[\frac{1-d^2}{(1-d^2)^2+4\xi^2 d^2}\right] \qquad (5)$$

$$\Im(\phi_y(i\omega_c)) = H_y(\omega_c) = \frac{1}{k}\left[\frac{-2\xi d}{(1-d^2)^2+4\xi^2 d^2}\right] \qquad (6)$$

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4. 3 Plot Graphs of the Transfer Function

The resonance of the system is obtained when the cutting frequency is equal to the natural frequency of system work piece- tool, $\omega_c = \omega_n$, $d = \frac{\omega_C}{\omega_n} = 1$. We use the experimental data published by Thevenot [9] for the case of milling thin walls: steel part S235 Strawberry and 8mm, with$K_t = 2400MPa$, $k = 45.10^9 N/m$, $\omega_0 = 592\ Hz$, $z = 4$, $K_r = 0.9$, $\xi = 0.333$.

We draw graphs showing the evolution of the components of the transfer function according to the ratio of frequencies which are itself a function of the critical pulse ω_c.

It is found that when passing through the critical pulse, the real part of the transfer function vanishes it is the case of resonance, while the imaginary part goes through its extremum.

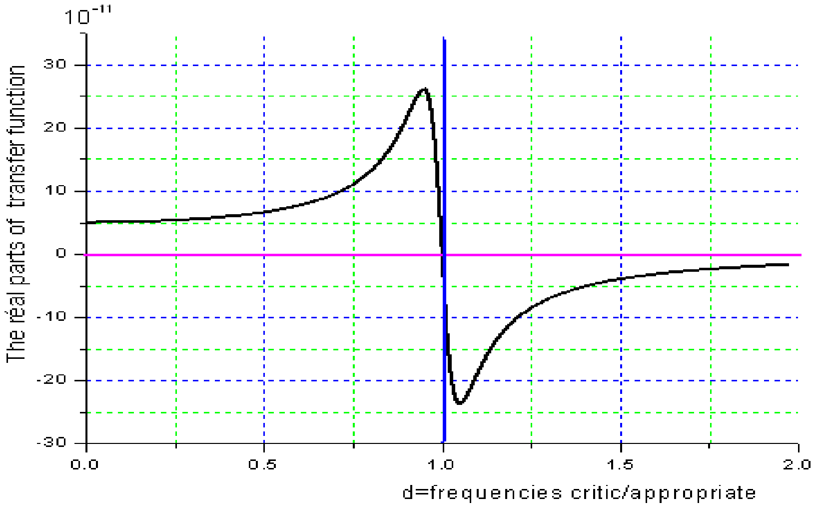

Figure 4: Real part of the transfer function

4.4 Axial depth of cut limit

The expression of the axial depth of cut is [3].

$$A_{plim} = \left[\left[\frac{z}{2\pi}\right]\beta_{yy} k_t G_y(\omega_c)\right]^{-1} \tag{7}$$

4.5 Speed of the spindle

It gives expression to the rotation speed of the spindle according to the pulsation critical $N =$

$$\frac{30\omega_c}{z.\left[m\pi + \pi - \arctan\left[\frac{d^2-1}{2\xi d}\right]\right]} \tag{8}$$

It gives the curve of axial depth limit depending on the speed of rotation of the spindle. From equations (7) and (8), we obtain $A_{plim} = f(\omega_c)$ and $N = f(\omega_c)$.

Failing to find $A_{plim} = f(N)$, we plotted the stability of the lobes parametrically, using the parameters given by Thevenot [11]for milling thin walls with a single degree of freedom :

- Work piece (S235),$k_r = 0.9$, $\xi = 0.033$

$k_t = 45 \times 10^9 N/m$, $\omega_n = 592Hz$.

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It is seen in this graph that for speeds below 500tr/mn we can increase the axial depth of cut, staying in the stable domain. At this point, we are losing productivity because of the low feed rate which is directly connected to the spindle speed. The risk of triggering the forced vibration due to shock increases dramatically.

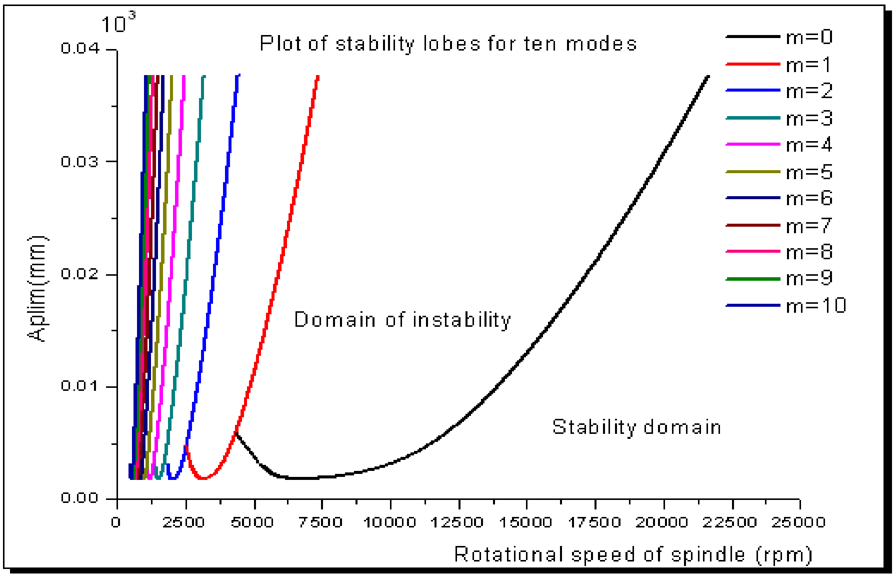

Figure 4.4: Plot of stability lobes in the case of milling thin walled

5. EXPERIMENTAL ANALYSIS OF THE INFLUENCE OF THE CHATTER

We consider two cases widely used in mechanical manufacturing: Rigid work piece and rigid tool and work piece whose direction of flexibility is controlled and the tool is rigid.

The parts used for the study are of mild steel, unalloyed A40.The objective of the experimental study is to understand the phenomena involved during machining. The chosen pieces have predetermined sizes and shapes that do not require installation of special machining. The tests are performed on a CNC milling machine, MOCA-MC600. The used machine is new in order to minimize the likelihood of association with other types of vibrations as free and forced vibrations. We limit ourselves to the study of noise emission during machining and analysis of roughness (profilometer type Mituyoto).

5.1 Rigid work piece and rigid tool

The machining tool is a cutter piece HSS two sizes 20mm diameter. The distance traveled by the tool is 50mm. The variables considered are speed of rotation of the spindle N the feed rate, f cutting depth a_p and thickness of the remaining part e Output parameters are the sound frequencies of vibration and criteria of the machined surface roughness.

It is found that when the pin exceeds the speed of rotation of 1500tr/mn, the values of roughness Ra decreases significantly. The vibration noise of the machine is stabilized on a very acceptable frequency. Sound recording is done for the worst case, where the speed is equal to 1263tr/mn.

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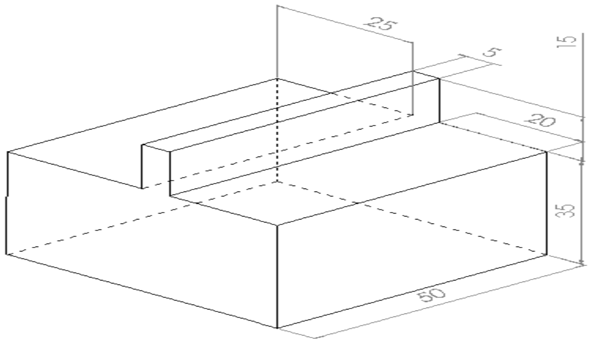


Figure 5: First piece of experiment

First test series: Study of the evolution of the roughness and frequency of chatter with variable speed of rotation of pin N. Selected parameters and results for roughness are summarized in Figure 6 ($f = 0.15mm/tr$ et $a_p = 1mm$).

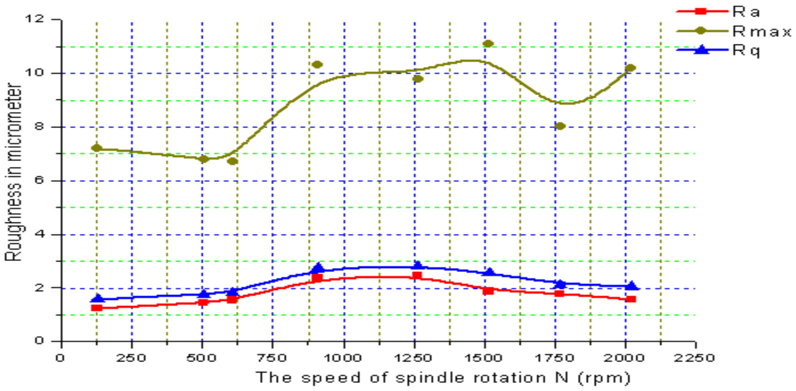
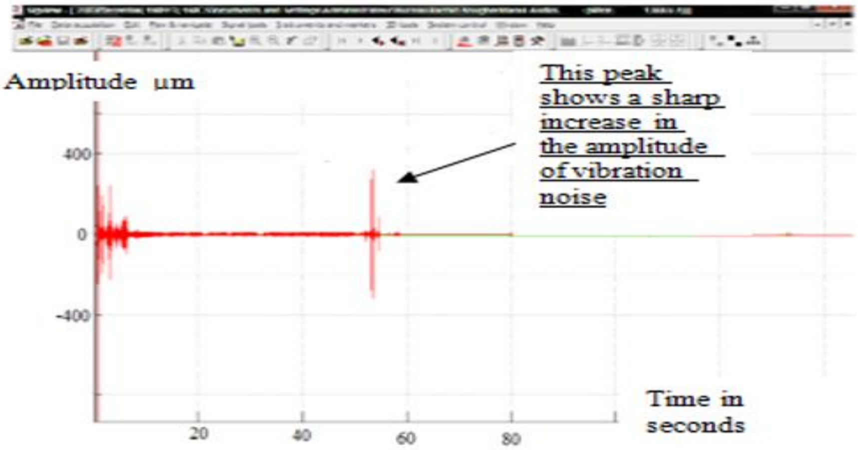


Fig. 6: Evolution of the roughness function



This peak shows a sharp increase in the amplitude of vibration noise

Figure 7: FFT of the audio signal

By analyzing the FFT of this signal, we note that at the start of machining, vibration noise emerged, but after a few seconds the machine is stabilized on a constant noise, and then comes a very loud noise for a short time indicates that as machining passes through the chatter. Knowing that the recording of the sound spectrum of this operation is disturbed by other noises apart from those of chatter, to find the fluctuation noise spectrum shows that the noise produced by the chatter, we plot the differential and the FFT of this signal. It is found after 55^{eme} seconds of machining, the first peak of chatter that appears with an amplitude exceeding$350\mu m$. These results concern the sound vibrations always collected during the first milling operation, that indicate the emergence of the phenomenon.

Case of the deformable piece and the rigid tool

These series of tests concerns the machining finish: work piece deformable A40, cutter with 4 tooth speed steel, 20mm in diameter, for a milling operation in profile, the distance traveled by the tool is 50mm.

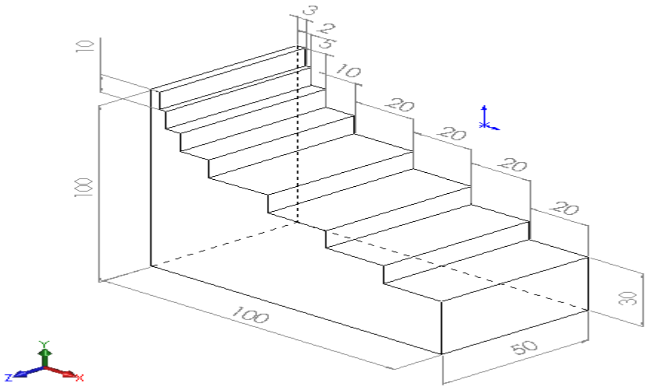


Figure 8: The second piece of experiment

The machining parameters are: the speed of spindle rotation N, the feed rate f, the depth of cut $a_p = 1mm$ set for all operations and e the remaining thickness of the piece varies. Output parameters are the sound frequencies of vibration and criteria of the machined surface roughness.

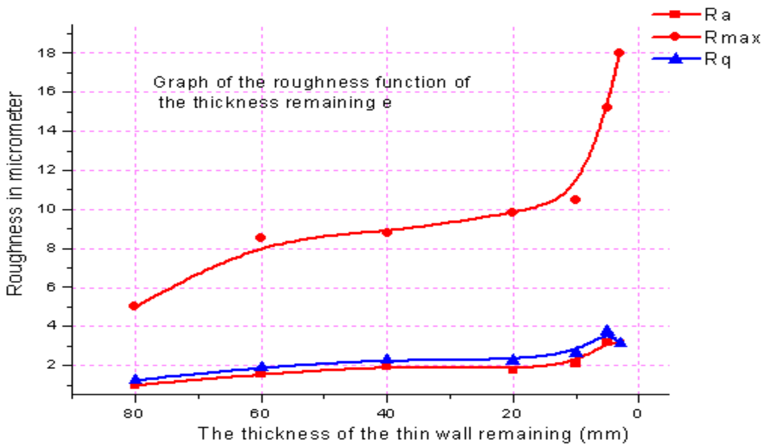


Figure 9: Evolution of the roughness depending on the remaining thickness e (mm)

Test series: We give the roughness for N=250tr/mn f=0.25mm/tr and we vary the thickness of the remaining work piece Figure9 We find that with the progressive thinning of the walls, it is more likely to be on the case of chatter. For example, for e=3mm and e=5mm, the roughness is at its maximum and the frequency sound passes by a high peak. For values of the thickness between 80mm and 20mm, the machined face is considered as rigid, this is a very stable case with a normal roughness.

6. CONCLUSION

In the experimental study, we note that to ensure the stability of machining, we encounter the cases:

- Rigid work piece and rigid tool: for finishing operations we have rarely the type of asked vibration, if we increase the depth of cut there will be other types of vibration.
- Thin-walled piece and rigid tool: this case was investigated experimentally and analytically. We define the limits of stability (the stability lobes) and the machining conditions: the rotational speeds of the spindle and the table's advances, and the axial depth of cut.

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