p-ISSN : 2335-1357 e-ISSN : 2437-1122

Mediterranean Journal of Modeling and Simulation

Med. J. Model. Simul. 06 (2016) 045-058

The prediction of the surface quality based on the stability lobes and the optimization of the cutting parameters in the vibration restraining

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ARTICLE INFO

Article history :
Received April 2016
Accepted August 2016

Keywords :
Machining ;
Turning process ;
Cutting parameters ;
Vibrations ;
Stability lobes.

ABSTRACT

The turning process is one of the best used processes in the mechanical industry. Therefore, the choice of the cutting parameters is very important in order to obtain a good machined surface quality. During the machining operation, the occurrence of vibrations cannot be avoided since these vibrations represent usually the periodic movements of the elastic system around its equilibrium position. The present article proposes to study the chatter vibration during a turning process by using new cutting conditions and using the stability lobes to optimize the surface quality. The main objective is to determine the best solution in the stability area during a turning process where the chatter is nonexistent, because the quality of a final product depends on the stability of the system piece / tool / machine. The proposed work shows its advantages by using a simulation and an experiment work. For the dynamic modeling of our work ; analytical, experimental and numerical methods were used.

1 Introduction

Chatter vibration is the most important problems during machining since it is a kind of self excited vibration common. It is also a vibration of the tool exited by cutting parameters. It originates from the coupling between cutting force and vibration of the work piece-cutting tool-machine system. It also causes a short life of the cutting tool and a poor quality surface.

Chatter vibration is divided in two parts : forced chatter vibration and self excited chatter vibration. The first one is caused by large cutting resistance and the second one is caused by regenerative effect. [1]. [2]. [3]. [4].

Historically, the system vibrations have been known since a long time. Many studies

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have been made by different scholars. Taylor was the first who identified the chatter vibration. Tobias and Tlusty were able to explain the causes of these self-sustained vibrations in the case of an orthogonal cutting applied to turning process[5]. [6]. [7].

Thereafter, Merrit and Altintas developed the feedback loop to represent the delay effect that is currently used unanimously by the community. [8]. [9].These results are the basis of the theory of stability lobes. This theory permits for a selected a rotation speed fixed to choose an axial depth of cut in order to avoid the instability. The development of this method was well adapted to the case of the turning process since the cutting efforts are constant depending on time. In practice, Thevenot showed that the machining causes a gradual removal of the materiel with a rapid change of its dynamic characteristics. Also, the work piece materialhas several modesof vibration[10].

Different methods were proposed in order to analyze and control the work piece-cutting tool-machine system. Therefore, and since the choice of the cutting parameters is strongly related to the process of fabrication, it becomes necessary to optimize the machining parameters by using a numerical modeling of machining. To obtain the best conditions of machining, we have to take in consideration three important parameters : the machine tool, the cutting tool and the work piece.

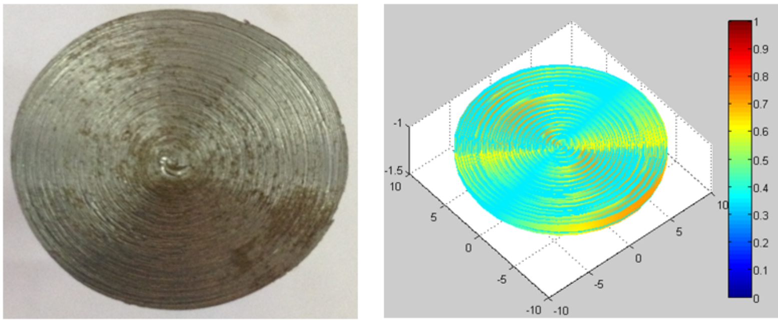


Fig. 1 – Real image and simulated image of a workpiece.

The dynamic parameters of the turning machine tool, affected by its structure and all the components taking part during the cutting process, play an important role to obtain a perfect machined surface quality. In case of an instable cutting process due to the vibration, the cutting process leads for example to the premature failure of the cutting edge by tool chipping. The machines tool vibration is generated by the interaction of the elastically machining system and the machining process associated to the functioning of the machine tool. This interaction and the machining process constitute the dynamic system of the machining system. Also, this vibration cannot be avoided. It represents periodical movements of the elastic system about its equilibrium position and the value of the displacements depends on the characteristics of all elements of the dynamic system as the intensity of the interaction between these elements. The characteristic parameters of the couple cutting tool-wok piece material can be identified whatever the cutting tool geometry.

While applying numerical methods, we use two different approaches : the periodical or analytical and the temporally approach. Several mathematical models have been developed in order to produce the geometric structure of the machined surfaces such as[11].These models are established based on a geometric description of the machined surface, the various geometric parameters and the cutting kinematic parameters.

Our literature search allowed us to identify several sets of the existing models in the various machining with metal removal process. [12].[13].[14].

These models once developed, allow the study of the machined surface quality and the surface state of the machining parts. In our case, it may be noted that the model does not introduce any interaction between the calculated efforts and the construction of the surface. It means that we should not take into account the bending of the tool due to the cutting efforts. However, this bending tool is a significantly parameter which affects the final texture of the final machined surface quality. The bending tool should easily be considered integrated while we developed our approach.

2 Experimental approach

During machining, the stability of the machine tool has an important role. Therefore, we should use the perfect parameters in order to obtain this stability. Among these parameters, we have the rotation speed of the work piece, the displacement of the cutting tool, the exceeded depth, the selected power, the accuracy and the state surface of the work piece.

Our system is modeled by a set composed of mass/spring and where the characteristics of the dynamic system are the mass (m), the amortization (c) and the stiffness (k). In the proposed experience, we used a Heckert parallel turning machine (DZFG 200 with a power of 5.5 KW). The work cylindrical piece material was made by steel XC 48. Its dimensions were 30x100mm.

Our work is based entirely on tests for a cutting tool and a work piece. The goal is to establish a correlation between the cutting parameters and the tool geometry with modeled values (cutting efforts, wear, quality of the surface of the machining part,).

The analytical approach will be detailed in this paragraph for the case of the orthogonal turning process. The system is supposed to admit only one degree of freedom. This approach was addressed and detailed by many scholars.[15]. Others, like Shamoto, presented novel strategies to optimize cutting tool path/posture and to avoid chatter vibration in various machining operations. [16].

The model is represented in figure 2.

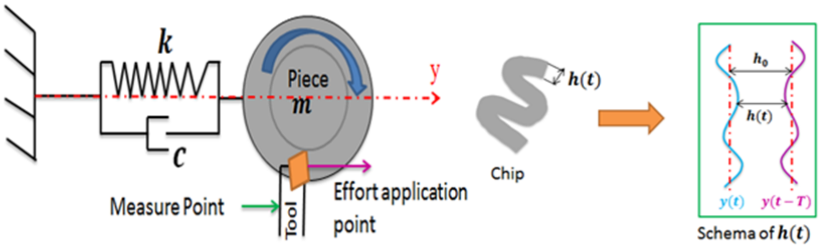


Fig. 2 – Schematic figure of the turning process.

The dynamic modeling was studied according to the works of Ehmann [17].

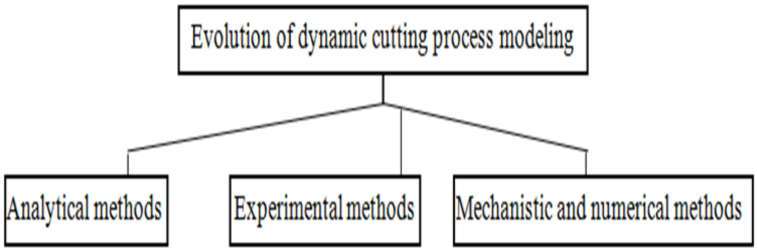


Fig. 3 – Dynamic model.

The transfer function is obtained by the simplified properties of the block diagrams and by a direct calculation. Different methods using the Nyquist criterion are applied to calculate the stability of the system. For this, we will first consider the case where the cutting tool is sufficiently flexible and the work piece considered sufficiently rigid.

If $F_f(t)$ = feed effort,
K_f = specifically coefficient of cutting,
b = width of chip
$h(t)$ = the instantaneous thickness of chip,
The dynamic equation becomes :

$$F_f\left(t\right) = m\ddot{y}\left(t\right) + c\dot{y}\left(t\right) + ky\left(t\right) \tag{1}$$

$$F_f\left(t\right) = \ K_f bh\left(t\right) \tag{2}$$

The expression of instantaneous thickness of chip $h(t)$ is given by :

$$h\left(t\right) = h_0 + \left[y\left(t - T\right) - y\left(t\right)\right] \tag{3}$$

Where :
h_0 = nominal thickness of chip,
T = revolution period of the work piece during the turning process,
$[y(t - T) - y(t)]$ = variation thickness of chip.
Therefore :

$$m\ddot{y}\left(t\right) + c\dot{y}\left(t\right) + ky\left(t\right) = K_f b\left(h_0 + \left[y\left(t - T\right) - y\left(t\right)\right]\right) \tag{4}$$

Applying Laplace-Carson transform :

$$ms^2 y\left(s\right) + csy\left(s\right) + ky\left(s\right) = k_f b\left[h_0 + \left(e^{-sT} - 1\right)y\left(s\right)\right] y\left(s\right)\left[ms^2 + cs + k\right] = F_f\left(s\right) \tag{5}$$

Such as :
$F_f(s) = K_f b h(s)$

$$\frac{y\,(s)}{F_f\,(s)} = \frac{1}{[ms^2 + cs + k]} = \Psi\,(s) \tag{6}$$

$\Leftrightarrow y\,(s) = F_f\,(s)\,.\,\Psi\,(s)$
The transfer function of the system of one degree of freedom $\Psi\,(s)$ is therefore :

$$\Psi\,(s) = \frac{1/k}{\left[\frac{1}{{\omega_n}^2}s^2 + \frac{2\xi}{\omega_n}s + 1\right]} \tag{7}$$

ξ : Damping ratio
ω_n : Natural frequency

3 The study of the stability system

The study of the stability system is done by searching the ratio between the non deformed thickness of the chip h0 and the average thickness of the chip $h(s)$.
For the case where the work piece is considered rigid and the cutting tool is considered flexible, we will calculate the transfer function and the stability by an analytical method. Our method is only used for the case of an orthogonal cut. Then, we will develop the stability criteria's and simulate afterwards.
The determination of $\frac{h(s)}{h_0}$:

$$h\,(s) = h_0 + \left(e^{-sT} - 1\right) y\,(s) \tag{8}$$

With :
$y(s) = F_f(s).\Psi(s)$
and $F_f(s) = K_f b h(s)$

$$\Leftrightarrow \frac{h\,(s)}{h_0} = \frac{1}{[1 + (1 - e^{-sT})]\,.K_f b\Psi\,(s)} \tag{9}$$

This equation allows us to model the dynamic behavior of the turning process as a diagram shown in figure 4.

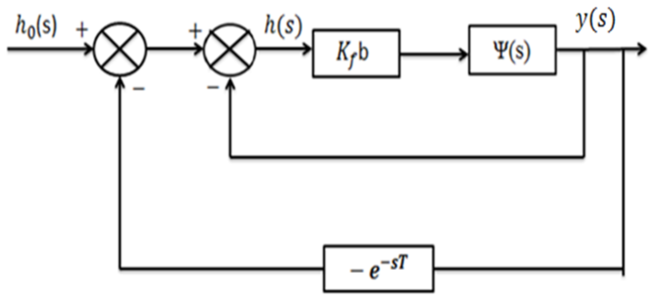


Fig. 4 – Dynamic model of one degree of freedom for a turning process.

The stability of the transfer function depends on its poles $s = \sigma + j\omega_c$.
During the critical regime, $s = j\omega_c$ and $b = b_{lim}$.

$$\left[1 + \left(1 - e^{-j\omega T}\right)\right] .K_f b\Psi\left(j\omega_c\right) = 0 \quad (10)$$

$$\text{If } \Psi\left(j\omega\right) = G + jH \quad (11)$$

$$1 + k_f b_l im[G(1 - cos\omega_c T) - H(sin\omega_c T)] + j(k_f b_l im[Gsin\omega_c T - H[1 - cos\omega_c T]) = 0 \quad (12)$$

The rotation speed is expressed as a -function of the chatter pulsation and the phase shift φ :

$$N\left(\omega_c\right) = \frac{60\omega_c}{3\pi + 2\varphi\left(\omega_c\right) + 2k\pi} \quad (13)$$

The equation 13 is used in order to let the associations of the critical pulsation with the different rotation speeds. From this, we can have a form of a lobe which can be repeated depending on the variation K $(K = (1, 2, 3, \ldots\ldots.., n))$.

The expression of the depth of the pass limit (b_{lim}) is derived from the real part of the characteristic equation :

$$b_{lim} = \frac{-1}{2K_f G\left(\omega_c\right)} \quad (14)$$

With :
$G\left(\omega_c\right) = Re(\Psi\left(j\omega_c\right))$
ω_c : Pulse chatters (vibration pulsation of the system)
These equations constitute a parameterized system of equations. It is then possible to draw the stability lobes for each vibration mode of the machined face.

Finally, these equations can define the stability limits of our case that is a compliant cutting tool and work piece behavior during machining. Dynamic characteristics of both parameters (cutting tool and work piece) should be identified and substituted in these equations. Afterwards, the stability charts of our process and the optimum cutting conditions can be defined.

4 Results

The compliance between the cutting tool and the work piece in a case of a turning process was studied trough a system supposed to admit only one degree of freedom. Chatter experiments were conducted in order to verify the proposed stability model. The transfer function is obtained by the simplified properties of the block diagrams and by a direct calculation. Also, the transfer function of the tool and the work piece were measured by the modal test setup. Different experiments were done. The dynamic properties and cutting conditions can be found in Table1.

Table 1 – Dynamic properties.

Mass (m) Kg	0.55
Dynamical stiffness (k) N/m	$23.82.10^{6}$
Dynamic snubbing (c) N.s/m	$1.36.10^{3}$
Damping ratio (ξ)	0.05
Cutting coefficient (K_f) MPa	2 400

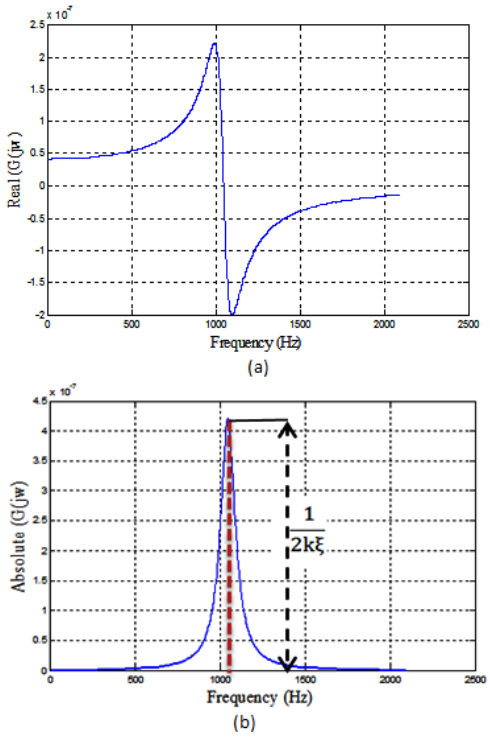


Fig. 5 – Frequency response functionof the cutting : a) real part ; b) magnitude.

Determining the dynamic stiffness was conducted by modeling the work piece in the form of a clamped beam in order to determine analytically its stiffness.

Figure 5 represents the real part of the response function depending on the cutting tool frequency. It is possible to note that the analyzed natural frequency fn is close to 1050 Hz.

fn is calculated by :

$$\omega_n = \sqrt{\frac{k}{m}} \tag{15}$$

$$\omega_n = 2\pi .\ f_n$$
$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

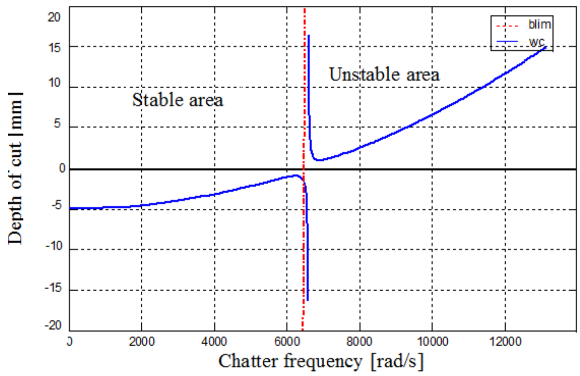


Fig. 6 – b_{lim} evolution in function of ω_c.

The evolution of b_{lim} (blimite) depending on ω_c gives some negative values which cannot then be conserved.

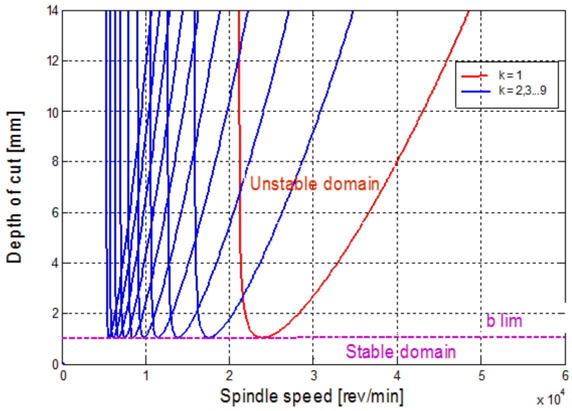


Fig. 7 – Stability lobes curves.

Figure 7shows a good agreement in predicting the unconditionally stable cutting depth at the bottom of each lobe. Stability limits of both models were also in good agreement at low spindle speed. The width of the lobes increases in parallel with the spindle speeds and this is one of the principal criteria of the stability theory. The curves show the evolution of the influence of the different parameters used such as the mass (m), the dynamic stiffness (k) and the snubbing (c) on the stability of the piece-tool-machine system.

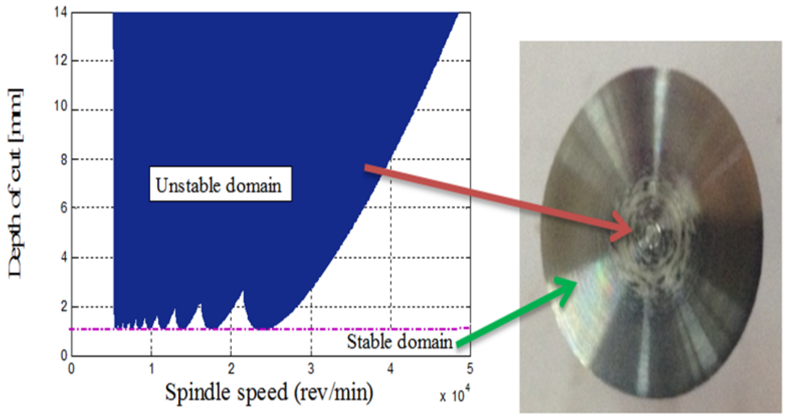


Fig. 8 – The stable and unstable areas.

Figure 8 shows the stable and unstable areas of the cutting in function of the spindle speed and the depth of cut. At the beginning of our work, we considered that the work piece is considered flexible and the cutting tool is considered rigid. But sometimes, it happens that this assumption cannot be verified, and both of the work piece and the cutting tool are mobile. In this case, the coupling phenomenon can occur if both proper modes of the work piece and the cutting tool are close. We should then vary the spindle speed during machining in order to ensure complete stability of the system. Therefore, the theory of stability that we used before, will not be valid, and we should use one more time the equation 1 but with the new configuration. Indeed, the change of one of the dynamic parameters of the equation 1 requires repeating the whole calculation explained above.

Then, and as a solution, a diagram of the lobes of stability was adopted. Its aspect is shown in the different figures for the proper mode of the cutting tool. Under some conditions of machining, the facing operation is stable. Conversely, beyond certain values, the machining becomes unstable. Under no circumstances, this method predicts the vibration in terms of amplitudes or frequency.

5 Illustrative example and result

The stability limits for both cases were determinate after. We did not find a big error for both results. The two examples used for comparison are shown on the system stability lobe diagram in Figure 9 and 10, where example 1 is expected to be unstable, and example 2 is expected to be stable.

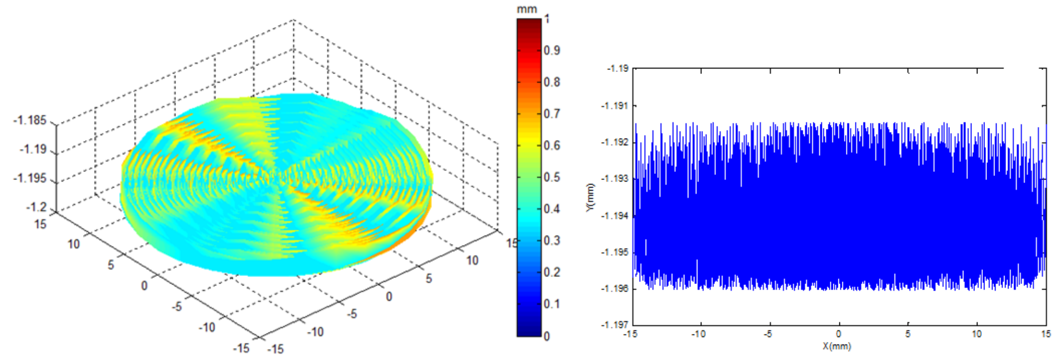


Fig. 9 – Simulated and measured surface topographies for face cutting of the work piece under the cutting conditions : N = 6000 rev/min , depth of $cut(a)$ = 2 mm, f = 0.2 mm/rev , re = 1.2 mm (presence of chutter vibration).

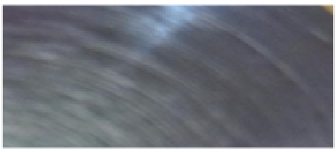
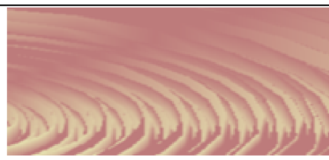
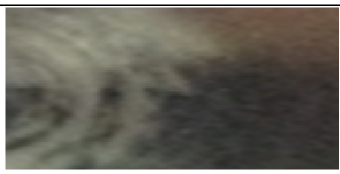
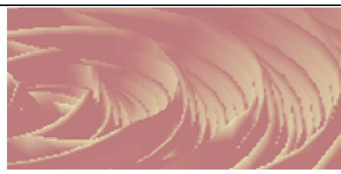
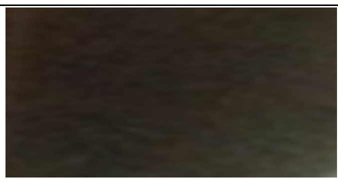
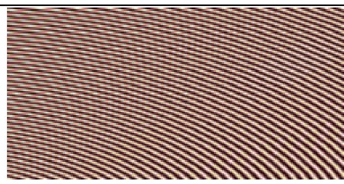
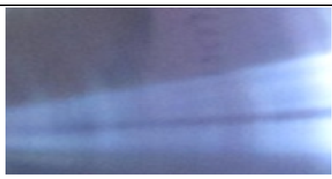
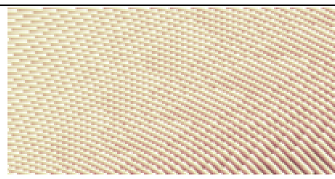
Selected points	Cutting conditions		Surface topography of work piece (surface finish)	Virtual image	Results
	N (rev/min)	b (mm)			
a	4000	1.5			Chatter
b	6000	2			Chatter
c	6000	1			Stable
d	20000	0.5			Stable

Fig. 10 – Verification results of cutting conditions : a,b,c and d.

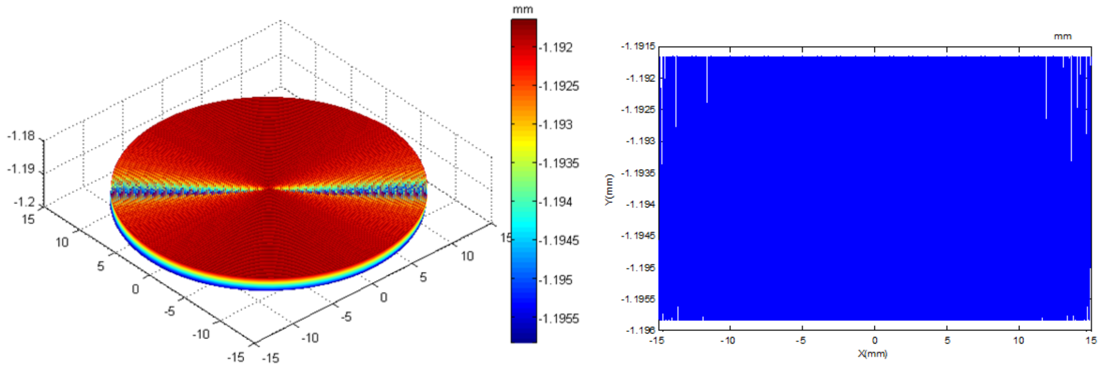


Fig. 11 – Simulated and measured surface topographies for face cutting of the work piece under the cutting conditions : $N = 20000$ rev/min , depth of $cut(a) = 0.5$ mm,$f = 0.05$ mm/rev, $re = 1.2$ mm (absence of vibration).

We notice that the cutting parameters during machining affect in a major way on the surface condition. However, proper use of cutting parameters can improve the surface finish, a bad choice of a cutting parameter leads to obtaining a poor surface finish.

We present the use of the intelligent programming with particle swarm Optimization (PSO) , in order to obtain the appropriate machining parameters, so we can minimize the surface roughness.

Several researches have been done about this method, the goal is to take a mathematical approach and solve the machining cutting parameters.

The most important criterion for the assessment of the surface quality is roughness, Ra, calculated according to :

$$R_a = kV_c^{x_1} * f^{x_2} * a_p{}^{x_3}$$

Where x_1, x_2, x_3 and k are the constants relevant to aspecific tool-workpiece combination.

In our case, we will apply the experience design method,

This method is one of mathematical methods to obtain maximum information by minimizing the number of experiments to be performed. We are only interested to minimize cutting conditions to find the optimal roughness from the stability lobes plot.

In general form it can be expressed as follows :

$$R_a = function\,(V_c, a_p, f)$$

To implement our optimization objective and choose the optimum cutting conditions, we measured the surface roughness $Ra(\mu m)$ using a type TR100 Surface Roughness Tester.

The average values of roughness Ra measured for each part corresponding to each cutting procedure are presented in the following table :

Table 2 – values of roughness Ra.

Pieces	Cutting speed V_c [m/min]	Depth of cut a_p [mm]	Feed rate f [mm/rev]	Roughness Ra [μm]
1	150	0.3	0.05	2.85
2	150	0.8	0.2	3.18
3	1000	0.3	0.2	1.48
4	150	0.8	0.05	3.01
5	1000	0.8	0.2	1.39
6	1000	0.8	0.05	1.25
7	1000	0.3	0.05	1.05
8	150	0.3	0.2	2.37

Limiting the cutting tool is very important to the safety of machining;the cutting parameters are limited with the bottom and top allowable limit.

Allowable range of cutting conditions is :

$$150 \leq V_c \leq 1000 m/min\,;\, 0.05 \leq f \leq 0.2 mm/rev\,;\, 0.3 \leq a\_p \leq 0.8 mm$$

With the data processing, our equation is :

$$\begin{cases} \text{minimize } Ra \\ Ra = 3.45259 - (2.72395e^{-003}V_c) - (0.23804.\text{a}_p) - (7.53412.f) \\ +(8.31373e^{-004}\text{e} - 004.V_c.\text{a}_p) + (0.011561.V_c.f) + (10.87843.\text{a}_p.f) - (0.014745.V_c.a_p.f) \\ \text{with} \\ 0.05 \leq f \leq 0.2 \\ 0.3 \leq a_p \leq 0.8 \\ 150 \leq V_c \leq 1000 \end{cases}$$

The best result is : $f = 0.1$ mm/tr, $ap = 0.3t$mm , $V_c = 1000$ m/min , $Ra = 1$ μm

6 Conclusion

In this study, dynamic characteristics of the cutting tool and the work piece were taken into account in order to obtain the best approach of the physical phenomena during vibration. We were interested in the prediction of the lobes of stability with regard to the vibration instability through a dynamic model. For the dynamic modeling of our work; analytical, experimental and numerical methods were used.

Our model provides an approach to the dynamic system by solving the stability limit. The effect of the process parameters on the stability is demonstrated. This process is verified by a simulation method and overall, the results are the same. Several trails were carried out for the verification of our method. The obtained results show a perfect agreement with the theory of the lobe of stability since the width of the lobes increases according to the rotation speeds. Also, the measurement of surface roughness allowed us to qualify the quality of machining, for that you optimize cutting conditions to avoid appearances of vibrations and surface defects.

The reliability of the proposed mathematical model has been tested by the optimization (PSO) method. The results showed that the model is highly significant and good fit with the stability lobe path and also with the experimental results.

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