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THE USE OF RESPONSE SURFACE OPTIMIZATION METHOD TO MINIMIZE THE VIBRATIONS IN THE MILLING PROCESS

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ABSTRACT

In nowadays the increasing productivity in the shortest possible time and with high quality is undoubtedly one of the biggest challenges for the industry. Recently, the industry has turned to CNC machines very often, since they work automatically and are able to achieve high precision with a high performance. In this sense, the vibration has been presented during the last decades as one of the main limiting factors for the improvement of productivity specially in machining operations. This work contributes to the reduction of vibrations, proposing the use of optimization methods to minimize vibrations using milling parameters (cutting speed, feed speed, axial penetration and radial penetration) related to the section area. This study presents a theoretical analysis on the materials and tools used throughout the experimental tests, as well as the methods and programs used. During this study Response Surfaces method was used.

Keywords: machining, milling, vibration, optimization

INTRODUCTION

Technologies involving chip removal operations, also known as machining processes, have suffered tremendous advances in the last decades. The machining of new materials has demanding the development of new tools and machines as well as the optimization of the machining parameters (Grzesik, 2008). To obtain good results in machining processes it must be guarantee a low surface roughness, high removal rate and long tool life (Ribeiro, 2017). These goals are reached it is necessary that the structure of machine-tools have high static rigidity in bending and twisting, appropriate dynamic characteristics, dimensional stability, as well as low coefficient of thermal expansion. Beside these characteristics is very important to choose the optimal machining parameters and minimizing the vibrations effects.

The vibrations generated during the machining process can compromise surface finish and dimensional tolerances of the workpiece as well as wear and fracture of the cutting tools (Miguélez, 2010). Machining can result in three different types of vibrations that can increase with the low dynamic stiffness of one or more elements of the structure, such as the spindle, the tool chuck or even the cutting tool. These three types of vibration can be described by free, forced and self-excited vibrations (Tobias, 1965). Free vibrations occur when a mechanical system is transferred from its equilibrium condition and its vibration arises freely without external excitation. Forced vibrations appear due to external sources, which may originate from the entry of the cutting edges of a top milling cutter on the material to be removed from the part or even due to the lack of balancing of the spindle of the machine. While the self-excited vibrations, usually named chatter, have the property of withdrawing energy from the system upon initiation and then increasing the energy level employed due to the interactions of the tool with the part during the machining process (Altintas, 2008). This type of vibration makes the process unstable and therefore is the most undesirable and difficult to control. Predicting the appearance of vibrations during the machining process is essential to ensure the best application of the cutting parameters and consequently maximize the productivity of a given machine-tool-clamping system. The stability prediction of the machining, which generally produces a diagram that relates the spindle rotation to the limiting machining depth, known as the stability lobule diagram is a widely used method to avoid the appearance of vibrations. However, it is necessary to obtain information about the characteristics of the material to be machined, the cut geometry and the dynamics of the system (Santos, 2014). Several studies have been carried out over the last few years in order to increase the stability limits of the machining process, which can be done basically in two ways: either passively or actively. Passive methods have usually altered the dynamic characteristics of the machine-tool-clamping system, increasing its dynamic range-that is, its ability to resist or absorb vibrations, improving stability limits in the machining process in general (Wang, 2004). In contrast, in active methods vibrations are monitored during the machining process and the dynamic characteristics of the machine-tool-clamping system can be changed as required. Another way of reducing or eliminating vibrations in the machining process is by interrupting the regeneration or self-excitation mechanism rather than changing the dynamic characteristics of the machine-tool-clamping system. For this, it is necessary to act on parameters of the machining process such as cutting speed, feed rate and machining depth. This method can be used actively or passively. As the change of the machining parameters, it can influence the dimensional and geometric tolerances of the part, which presupposes the greatest care with the amplitude of the variations of such parameters. It has the advantage of not requiring the addition of actuation mechanisms capable of changing the dynamic system, which in general makes it a solution that requires less financial investment and less application complexity, since no structural changes are necessary in the machine tool. The approach adopted to carry out this work was based on this method, that is, a set of systematic alterations of some machining parameters was implemented and the level of vibrations in the machine quill, as well as the degree of quality of the surface finish of the machined part. However, to minimize the number of experimental tests was implemented an optimization method.

For few decades many optimization algorithms have been developed and applied in machining processes (Aggarwal, 2005) they not only optimize the processes but also reduced the need for time-consuming and expensive tests. However, the most used are the fuzzy logic (Palanikumar, 2005), genetic algorithms (Wang and Jawahi, 2004), Taguchi technique (Gopalsamy, 2009), grey relational analysis (Tzeng, 2009) and response surface (Makadia, 2013).

The aim of this work is develop a method that is able to optimize the machining parameters to improve the surface quality and minimize the vibrations effects. For that, was used the optimization method of Response Surface to minimize the vibrations during the machining process. The level of vibrations has a direct relation in the surface quality and the tool life.

EXPERIMENTAL PROCEDURE

Before the implementation of experimental work was need to use an efficient process for the design of experiments. For this, an optimization method for design of experiments was implemented, the response surface method. In this optimization method, the response surface method was elaborated and implemented through Matlab R2015a, and the modelling function was defined by the variables z and x. The variable z has five components that represent:

- z1 - cutting speed;
- z2 - cutting federate;
- z3 - axial depth;
- z4 - radial depth;
- z5 - vibrations (RMS - Root Mean Square).

To model the problem, two distinct problems were defined. The first one has main objective to identifying the best model, i.e. to identify the function that best fit the data. The second problem is to determine the optimal values of the variables z1, z2, z3 and z4 that provide the minimum vibration.

For first problem, the variable x has between five and twenty-five components, whose minimum depends on the function, which represents the fit of the function to the given data.

Initially, several functions were tested to model the vibration of the tool. Thus, the following functions were tested:

- $f_1(x,z) = \sum_{i=1}^{4} x_i z_i + x_5$;
- $f_2(x,z) = \sum_{i=1}^{4} x_i z_i^2 + \sum_{i=1}^{4} x_{i+4} z_i + x_9 \times z_1 \times z_2 + x_{10} \times z_1 \times z_3 + x_{11} \times z_1 * z_4 + x_{12} \times z_2 \times z_3 + x_{13} \times z_2 \times z_4 + x_{14} \times z_3 \times z_4 + x_{15}$;
- $f_3(x,z) = \sum_{i=1}^{4} x_i z_i^2 + \sum_{i=1}^{4} x_{i+4} z_i + x_9$;
- $f_4(x,z) = \sum_{i=1}^{4} x_i z_i^3 + \sum_{i=1}^{4} x_{i+4} z_i^2 + \sum_{i=1}^{4} x_{i+8} z_i + x_{13} \times z_1 \times z_2 + x_{14} \times z_1 \times z_3 + x_{15} \times z_1 \times z_4 + x_{16} \times z_2 \times z_3 + x_{17} \times z_2 \times z_4 + x_{18} \times z_3 \times z_4 + x_{19}$;
- $f_4(x,z) = \sum_{i=1}^{4} x_i z_i^3 + \sum_{i=1}^{4} x_{i+4} z_i^2 + \sum_{i=1}^{4} x_{i+8} z_i + x_{13} \times z_1 \times z_2 + x_{14} \times z_1 \times z_3 + x_{15} \times z_1 \times z_4 + x_{16} \times z_2 \times z_3 + x_{17} \times z_2 \times z_4 + x_{18} \times z_3 \times z_4 + x_{19}$;
- $f_6(x,z) = \sum_{i=1}^{4} x_i z_i^3 + \sum_{i=1}^{4} x_{i+4} z_i^2 + \sum_{i=1}^{4} x_{i+8} z_i + x_{13} \times {z_1}^2 * z_2 + x_{14} \times {z_1}^2 \times z_3 + x_{15} \times {z_1}^2 \times z_4 + x_{16} \times {z_2}^2 \times z_3 + x_{17} \times {z_2}^2 \times z_4 + x_{18} \times {z_3}^2 \times z_4 + x_{19}$;
- $f_7(x,z) = \sum_{i=1}^{4} x_i z_i^3 + \sum_{i=1}^{4} x_{i+4} z_i^2 + \sum_{i=1}^{4} x_{i+8} z_i + x_{13}$;
- $f_8(x,z) = \sum_{i=1}^{4} x_i z_i^3 + \sum_{i=1}^{4} x_{i+4} z_i + x_9$.

For the choice of the best model, n trials were considered in order to solve the problem of optimization of equation (1):

$$min_x \sum_{i=1}^{n} (f(x,z) - z_5)^2 \qquad (1)$$

To solve the problem of optimization of equation (1) we will use the Nelder-Mead method implemented in the toolbox Optimization of Matlab software.

Initially 10 (n = 10) trials were used to select the best model and 6 new assays were used to validate the functions studied.

Analyzing Table 1, it was found that the functions $f_1(x,z)$, $f_3(x,z)$ and $f_7(x,z)$ were the ones that had the minimum error, that is, they are the best models.

Subsequently, 16 (n = 16) trials were used to select which of the three functions would be the best. The values of Table 2 were obtained from the model validation.

Table 1 - Results for 10 of 16 tests.

Function	**Minimum found**	**N. iterations**	**Functions evaluations**
f_1	5.22×10^1	140	262
f_2	$6.81*10^7$	2187	3000
f_3	4.18×10^2	881	1380
f_4	$4.85*10^{12}$	2776	3800
f_5	$5.71*10^{14}$	3888	5000
f_6	$5.92*10^{14}$	2877	3800
f_7	$5.40*10^3$	1604	2451
f_8	$2.02*10^7$	719	1280

Table 2 - Results for 16 of 16 tests.

Function	**Minimum found**	**N. iterations**	**Functions evaluations**
f_1	9.46×10^1	151	264
f_3	$1.43\text{x}10^3$	744	1206
f_7	$1.86\text{x}10^5$	1672	2554

Observing Table 2, we see that the function $f_1(x,z)$ is the one with the least error, so this will be the best model. Since $f_1(x,z)$ is the best function it is going to be used throughout the optimization for the problem (2).

$$min_z|f_1(x,z)| \tag{2}$$

By means of the response surface method, we determine the optimal coefficients of variable x solving the problem 1. After the determination of the optimal parameters obtained in problem 1, for which the vibrations are smaller, we will solve the problem 2 to identify the optimal parameters for the variable z. The Genetic Algorithm it was used to solve the problem 2.

The absolute value is presented (in problem 2), since represents the minimum value of the vibrations and this parameter cannot have negative values and needed to be closest to zero.

The experimental tests were carried out in the Laboratory of Mechanical Technology (LTM) of the Higher School of Technology and Management (ESTIG) of the Polytechnic Institute of Bragança (IPB) and the aim was to optimize the vibration values when machining with a CNC of cylindrical steel.

To evaluate the frequency of the system itself the tool impact hammer tests were carried out. After the tool was mounted to the machine quill, a uniaxial accelerometer was attached to the tool. The structure was excited and the frequency determined after an excitation made by the impact hammer as shown in Figure 1.

For the measurement of vibrations during machining a triaxial accelerometer connected to an acquisition plate was used. Treatment of the response was performed with the LabView software. The data were processed in order to obtain mean values at the desired operating / machining intervals. The cylindrical steel block (1.2738) that had initially the dimensions of 219 mm in diameter and 40 mm in height, composed of a very hard steel (45 Rockwell C of hardness). The tool inserts have the reference model of WNHU04T310 manufactured by Palbit®.

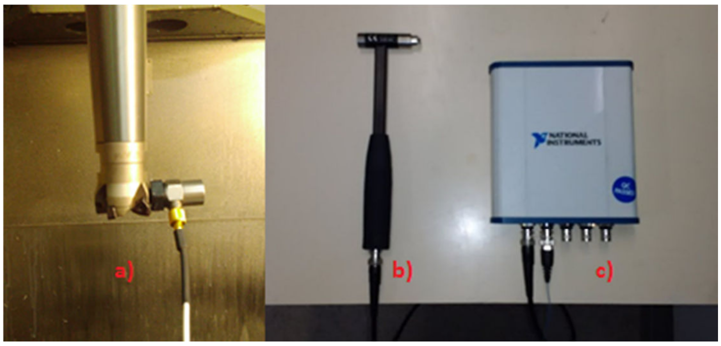

Fig. 1 - Instrumentation for measuring own frequencies (a) Accelerometer (b) PCB 86C03 and (c) NI 4431 USB.

To measure the vibrations produced during the milling process, a triaxial accelerometer (PCB Piezotronics, model 356B18), placed in the center of the machine axis, was used as close as possible to the cutting tool (Figure 2). The resulting accelerometer signal was obtained using an NI-4431 USB vibration signal acquisition board which was then processed through LabView. The values observed were the amplitude of vibration and the RMS in the measurement period.

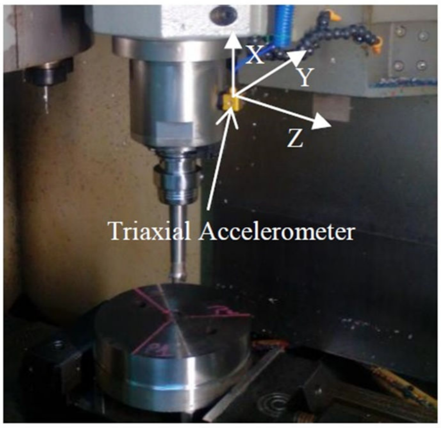

Fig. 2 - Positioning of the triaxial accelerometer to measure the vibrations during the tests.

RESULTS

In order to evaluate the natural machining tool, the impact was exerted with the hammer and the accelerometer was used to obtain natural tool frequency. The measurement detected natural frequencies at 99.97, 200, 297.33, 399.33 and 467.33 Hz. Knowing that during the tests the machine only operated in three different rotations, 2546, 2644 and 3820 rpm, that is, 42.41, 44.04 and 63.63 Hz, respectively. Analyzing Table 3 it is verified that there is no resonance because all values of the ratio are less than 1, so as already expected the machine tool set has a good rigidity.

In the Table 4 is represented the Root Mean Square (RMS) in two orthogonal directions, RMSY and RMSZ, the M value represents the Euclidian norm of vector (RMSY, RMSZ), determined by:

$$M = \left\|(RMS_Y, RMS_{Z)}\right\| = \sqrt{(RMS_Y)^2 + (RMS_Z)^2}.$$

Table 3 - Measured frequencies

Mode	Frequency [Hz]	Ratio		
		42.41	**44.04**	**63.63**
1	99.97	0.42	0.44	0.64
2	200.00	0.21	0.22	0.32
3	297.33	0.14	0.15	0.21
4	399.33	0.11	0.11	0.16
5	467.33	0.09	0.09	0.14

Table 4 - The RMS in two orthogonal directions and respectively Euclidian norm

Test	Average		M
	RMS_Y	RMS_Z	
1	3.698	8.810	9.555
2	5.043	10.922	12.030
3	3.902	9.839	10.584
4	4.301	10.075	10.955
5	4.154	9.059	9.965
6	5.419	12.769	13.871
7	4.815	9.678	10.810
8	10.146	16.709	19.548
9	10.432	17.057	19.994
10	2.777	8.812	9.239
11	2.301	7.631	7.970
12	1.949	5.883	6.197
13	2.686	8.227	8.655
14	2.849	8.784	9.235
15	3.090	8.395	8.945
16	2.620	7.329	7.783

In order to identify the optimum value for z1, z2, z3 and z4, that is, values of cutting speed (z1), cutting federate (z2), axial depth (z3) and radial depth (z4), where was used the function f1(x,z) and thirteen tests.

To execute the program through the matlab software, the function f1(x,z) was used in problem 1 and using thirteen (1,2,3,4,5,6,7,9,11,13,14,15,16) of the sixteen tests (these were randomly selected). In the verification tests (EV1, EV2) in Problem 1, it was solved by the Nelder-Mead method and in Problem 2 it was solved by the Genetic Algorithm method. A third verification test (EV3) was also performed, however, it was verified that the values obtained were very similar to those already in existence, and would therefore present similar vibration values to the tests already performed.

From the implementation of these problems resulted the input values and the vibrations presented in Table 5.

From the Table 5, is possible verify that for the verification tests EV1 and EV2 the values of RMS are very similar, 8.9 m/s2 and 8.5 m/s2, respectively and these values are very low compared with the random tests. So, for the present study, the response surface method using the Nelder-Mead and the Genetic Algorithm techniques proved to be a good optimization method for minimizing the vibration in milling process.

Table 5 - Vibrations obtained through verification tests and respective input parameters

Tests	z_1	z_2	z_3	z_4	z_5
1	2546	1018.4	0.1	2.0	9.6
2	2546	1018.4	0.1	4.0	12.0
3	2546	1018.4	0.4	2.0	10.6
4	2546	1018.4	0.4	4.0	11.0
5	2546	4584.0	0.1	2.0	10.0
6	2546	4584.0	0.1	4.0	13.9
7	2546	4584.0	0.4	2.0	10.8
9	3820	1018.4	0.1	2.0	20.0
11	3820	1018.4	0.4	2.0	8.0
13	3820	4584.0	0.1	2.0	8.7
14	3820	4584.0	0.1	4.0	9.2
15	3820	4584.0	0.4	2.0	8.9
16	3820	4584.0	0.4	4.0	7.8
EV1	2546	4440.7	0.1	2.0	8.9
EV2	2644	4272.5	0.3	2.0	8.5

CONCLUSION

The response surface method is an optimization method that could be used to optimize the milling parameters which minimize the vibrations during the machining process.

This method converges very quickly for optimal parameters which is an interesting optimization method because with less experimental tests it is possible to obtain good results.

With the Response Surfaces method, good vibration results were verified in the first two tests (EV1 and EV2) and the optimization process was stopped due to the values obtained being similar.

The values of RMS for EV1 and EV2 vibration tests are 8.9 m/s2 and 8.5 m/s2, respectively.

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