25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-2071
TRIAXIAL ACCELEROMETER AND MACHINING PROCESS: A VIBRATION ANALYSIS USING DOEHLERT'S EXPERIMENTAL PLANNING

Rubens Soeiro Gonçalves
Thalyta Lopes Santos
Instituto Federal de Educação, Ciência e Tecnologia do Maranhão
soeiro@ifma.edu.br
thalyta.ls20@gmail.com

Matheus Santos Vieira
matheus.santos.vieira@gmail.com

Jhonatas Gutierrez Santos de Jesus
teslaguto@gmail.com

Antonio Santos Araujo Junior
asaraujojr@ifma.edu.br

Abstract. *The external cylindrical turning process is very widespread in the industrial environment but some vibrations inherent in the process can be harmful to the part. The vibration may cause damages such as the early wear of the cutting tool, problems with the roughness of final part, losses in dimensional reliability and reduce the lifespan of the equipment. Considering the above, it's clear to see that is necessary monitoring and studying this vibrations in order to allow optimal use of the equipment. For this purpose, it is proposed the analysis of the three-dimensional behavior of the vibrations acting using the Doehlert's Experimental Planning. The use of the experimental planning makes possible the reduction of the necessary tests, maintaining the reliability of the obtained data, as well as the simultaneous study of several variables, separating their effects. In this case, the objective is to study the effects of rotation speed and cutting depth on the machining process, based on the accelerations present in each axis. The Doehlert's matrix was defined with five levels for cutting depth and three levels for rotation speed, according to coded variables. Variance analysis and F-test were used to define the best model.*

Keywords: *Doehlert's Experimental Planning, vibration, three-axis accelerometer*

1. INTRODUCTION

The machinability can be considered as a property of the component that depends on parameters of machining process. However according to Wright and Trent (2000), as "the cost of machining the component or the quality of the finish in a critical surface". In general, this can be defined as a measurement of machining difficulty of a material Montgomery (2017). Some of the parameters used to evaluate machinability are cutting force, tool life, surface finish, wear rate and cutting temperature. Test conditions are a key factor in determining the mentioned property.

In the chip machining process, a cylindrical solid is transformed by withdrawing chips from its periphery in order to obtain a cylindrical object with defined and precise shapes. In this process the material rotates around the machine axis and the cutting tool is moved in the same plane as the referred axis. During the formation of the chips, most of the energy generated is converted into heat, producing high temperatures in the cutting region, which may cause thermal damage to the part and compromising its surface integrity, with the appearance of cracks, distortions, high residual stresses and dimensional nonconformities Kovacevic and Mohan (1995).

The Doehlert's Experimental Planning was presented Doehlert (1970) as a very useful and attractive alternative for second order experimental planning that is a essential tool in the development of new processes and in the improvement of processes in use. Adequate planning allows, in addition to process improvement, the reduction of the number of trials and the costs involved Button (2005). In what concerns the product design, it allows the evaluation and comparison of different configurations (projects), evaluation of the use of different materials, the choice of design parameters suitable for a wide range of product use and optimization of performance. The concepts of experimental planning can be summarized in three commonly used terms: quality, productivity and competitiveness. This methodology is widely applied in optimization situations and is usually accompanied by good results like recent works of Hollanda *et al.* (2019) and Ruschel *et al.* (2016) besides being useful to obtain the response surface, important methodology to analyze the behavior of some variables over to another ones as it's possible to observe in a work of Graça *et al.* (2017). It is proposed to apply the experimental design to verify the relation between the rotation speed, cutting depth and vibrations (in every dimension) in machining processes and obtain the response surface, promoting the optimal use of the tool used in the process.

2. METHODOLOGY

2.1 Doehlert Design

Experimental planning methods are important and efficient tools in the analysis of cause and effect **relationships** between the variables of a given process. Proper planning allows reducing the number of tests necessary without loss in the quality of identification. Concern about the number of tests is economically important in cases involving process design, since, for each experiment, the condition of the parts and tools used must be taken into account. Another advantage of the method is its ability to evaluate and compare different configurations and materials, to determine the best parameters for a given situation.

This paper aims to investigate the existence of correlation between the vibration present in the machining process and the rotational speed and depth of cut. Doehlert Design was chosen to analyzing two variables at five levels. The technique is based on conducting experiments according to the experimental matrix and subsequent analysis and interpretation of the effects of the investigated factors.

2.2 Prototype

In order to measure vibration in the tests, a compact tool with a high acquisition speed was required, as it was chosen for a wide range of frequencies to be analyzed. Taking these factors into account, the market price of the tools that meet these requirements proved to be too high to purchase. The solution came in the form of the development of an authorial device that fulfilled these requirements. The first hurdle was in the measurements of magnitude, since vibration alone is a variable with different prospects for analysis. Its value may appear in the form of displacement, velocity and acceleration and being in frequencies of regular or not. Given this and considering that there are no sensors that were able to measure the velocity and displacement of linear shapes and having a low cost, it was chosen devices that observe the other magnitude: the acceleration.

From the commercial parts available, the ADXL345 triaxial accelerometer, a low cost accelerometer (less than $5), high sampling rate (up to 3200Hz), high measuring range (up to 157m/s^2) and high sensitivity (0.039m/s^2) were chosen. The communication interface of the device is made by the I2C (Inter-Integrated Circuit) protocol, a serial protocol that has high compatibility with microcontrolled systems from different manufacturers and has a long use history, proving its stability and reliability. In order to have a better analysis of the data the use of computational tools was indispensable. Although there are commercial I2C to USB converters, it was decided to use a microcontroller, as it has a low cost and high programming flexibility, thus allowing future changes in their functions. For computer acquisition, Processing software was chosen because of its simplicity and wide range of features.

2.3 Experiments

The experiments were performed in a external cylindric turning Nardini ND325 and the Doehlert's matrix was defined with five levels in the first variable (cutting depth) and three levels in the second one (rotation speed), both coded. The Table 1 shows the Doehlert's matrix in which input variables are indicated in real values and coded values (parenthesis). After that, all the experiments were performed and the respective vibrations were measured by the prototype and a computer software, designed by the research group, registered the raw values.

Table 1. Doehlert Matrix

	Input		Output
Experiment	X_1	X_2	Y
1	0	0	-
2	1	0	-
3	0.5	0.866	-
4	-1	0	-
5	-0.5	-0.866	-
6	0.5	-0.866	-
7	-0.5	0.866	-

Models with and without interactions between the input variables and even a quadratic model were proposed, as shown in Tab. 2. These models were proposed because they encompass a preliminary analysis when it comes to metamodels with two input and one output variables. Adjusts were made using least squares method aiming to obtain the proposed parameters. The best model was determined by the following criteria: adjusted coefficient of determination, variance analysis and F test.The results shown were obtains through a computational code developed on Matlab, where a algorithm allow the simulation of all models proposed, from the planning input matrix, showing as output: the adjusted coefficients of the model's regressors, adjusted coefficient of determination, ANOVA table, surface response and contour graph. The Table 3 shows the experimental results.

It's necessary to reiterate that since the Doehlert's matrix uses an specific set of coded values and that the lathe used on the experiments also have a series of default rotation speeds, a agreement between the two sets was necessary. Since neither of them could change to adapt to the other, during the experiments were used the closest speed to coded values.

Table 2. Suggested equations

Model	Equation
1	$y = b_0 + b_1x_1 + b_2x_2$
2	$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1^2$
3	$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2$
4	$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 + b_5x_1x_2$

Table 3. Experimental results.

	Input		Output		
Experiment	Cutting Depth (mm)	Rotation Speed (rpm)	Vibration		
			X	Y	Z
1	$1.25(0)$	$315(0)$	-1.1782	0.0784	-0.0783
2	$2(1)$	$315(0)$	0.1492	1.2289	0.1042
3	$1.625(0.5)$	$630(0.866)$	0.1864	1.2111	-0.0645
4	$0.5(-1)$	$315(0)$	-1.1740	0.0816	-0.0786
5	$0.875(-0.5)$	$40(-0.866)$	-1.1825	0.0788	-0.0743
6	$1.625(0.5)$	$40(-0.866)$	-1.1793	0.0792	-0.0766
7	$0.875(-0.5)$	$630(0.866)$	-1.1768	0.0821	-0.0789

Table 4. Calculated coefficients for Axis X

Model	Equation
1	$y = -2.2836 + 0.8917x_1 + 0.0011x_2$
2	$y = -0.9885 - 1.5725x_1 + 0.0012x_2 + 0.9857x_1^2$
3	$y = -0.6153 - 2.0672x_1 - 1.7548 \cdot 10^-6x_2 + 1.1836x_1^2 + 1.7372 \cdot 10^-6x_2^2$
4	$y = 0.6184 - 3.0543x_1 - 0.0038x_2 + 1.1836x_1^2 + 1.7372 \cdot 10^-6x_2^2 + 0.0031x_1x_2$

Table 5. Calculated coefficients for Axis Y

Model	Equation
1	$y = -0.8555 + 0.7608x_1 + 0.0009x_2$
2	$y = 0.2828 - 1.4050x_1 + 0.0009x_2 + 0.8664x_1^2$
3	$y = 0.5826 - 1.8026x_1 + 2.6496 \cdot 10^{-}5x_2 + 1.0254x_1^2 + 1.3963 \cdot 10^{-}6x_2^2$
4	$y = 1.604 - 2.6200x_1 - 0.0031x_2 + 1.0254x_1^2 + 1.3963 \cdot 10^{-}6x_2^2 + 0.0025x_1x_2$

Table 6. Calculated coefficients for Axis Z

Model	Equation
1	$y = -0.1548 + 0.0840x_1 + 8.2302 \cdot 10^{-7}x_2$
2	$y = 0.0894 - 0.3808x_1 + 5.1064 \cdot 10^{-}6x_2 + 0.1859x_1^2$
3	$y = 0.0442 - 0.3209x_1 + 0.0001x_2 + 0.1619x_1^2 - 2.1015 \cdot 10^{-}7x_2^2$
4	$y = 0.0524 - 0.3274x_1 + 0.0001x_2 + 0.1619x_1^2 - 2.1015 \cdot 10^{-}7x_2^2 + 2.0188 \cdot 10^{-}5x_1x_2$

3. RESULTS

Table 7. ANOVA table for X axis

		SQ	nGL	MQ	MQR/MQE	f_inv
	Regression	1.8031	2	0.9016		
Model 1	Error	0.7858	4	0.1964	4.5892	2.4721
	TOTAL	2.5889	6	x		
	Regression	2.0994	3	0.6998		
Model 2	Error	0.4895	3	0.1632	4.2885	2.9359
	TOTAL	2.5889	6	x		
	Regression	2.1262	4	0.5315		
Model 3	Error	0.4627	2	0.2314	2.2974	4.2361
	TOTAL	2.5889	6	x		
	Regression	2.5885	5	0.5177		
Model 4	Error	0.0004	1	0.0004	1293.2	14.0084
	TOTAL	2.5889	6	x		

The statistical validation analysis of the proposed models, presented in Table 7 reveals that, with the exception of model 3, all the others are statistically valid in the confidence interval used, 0.8, or a significance of 0.2, given that the MQR/MQE ratio in this models is lower than the calculated finv, matching the statistics of the F test. It can be concluded that the model 4 is the best representation, since his MQR/MQE ratio is the higher, indicating a lower residual Error and higher adjusted variation coefficient.

Table 8. ANOVA table for Y axis

		SQ	nGL	MQ	MQR/MQE	f_inv
	Regression	1.2919	2	0.6459		
Model 1	Error	0.5647	4	0.1412	4.5759	2.4721
	TOTAL	1.8566	6	x		
	Regression	1.5208	3	0.5069		
Model 2	Error	0.3358	3	0.1801	4.5288	2.9359
	TOTAL	1.8566	6	x		
	Regression	1.5381	4	0.3845		
Model 3	Error	0.3184	2	0.1592	2.4147	4.2361
	TOTAL	1.8566	6	x		
	Regression	1.8551	5	0.3710		
Model 4	Error	0.0015	1	0.0015	250.7285	14.0084
	TOTAL	1.8566	6	x		

Using the same principles and, according to Table 8, the models 1,2 and 4 are statistically valid for Y axis, with the model 4 again presenting the lower residual Error, given its high MQR/MQE ratio, indicating also a higher adjusted variation coefficient.

Table 9. ANOVA table for Z axis

		SQ	nGL	MQ	MQR/MQE	f_inv
Model 1	Regression	0.0119	2	0.0060	1.5021	2.4721
	Error	0.0159	4	0.0040		
	TOTAL	0.0278	6	x		
Model 2	Regression	0.0225	3	0.0075	4.2196	2.9359
	Error	0.0053	3	0.0018		
	TOTAL	0.0278	6	x		
Model 3	Regression	0.0228	4	0.0057	2.3175	4.2361
	Error	0.0049	2	0.0025		
	TOTAL	0.0278	6	x		
Model 4	Regression	0.0229	5	0.0046	0.9316	14.0084
	Error	0.0049	1	0.0049		
	TOTAL	0.0278	6	x		

For the Z axis the situation is different, since, according Table 9 only the second model is statistically valid, and so, being the only one who can represent the experimental results. The Figures 1,2 e 3 show the surface response of the best models for the X,Y and Z axis respectively. For the X and Y axis this is model 4 in the Table 4 and 5 in this order. For the Z axis, the equation is the second one in the Table 6. Each of this models is capable of representing the estimated parameter of vibration considering the parameters of operation of the machines, this means that with this surface its possible to estimate the vibration when operating with a rotation speed between 0 and 700 RPM (presented in the Graphs of Figures 1,2 e 3 as "Rotation Speed") and with a cutting depth between 0.5 and 2 mm (presented in the Graphs of Figures 1,2 e 3 as "Cutting Depth").

With these Surface responses of models statistically validated its possible to make a better use of the equipment, since it'll permit a regulation between life cycle, efficiency and precision.

It's important to notice that there's always room for improvement, in this case it can be factored in each step of the process. First, since it uses a specially manufactured electronic tool, it would be an improvement to make a better mechanical structure of the tool itself, since with vibrations, for ideal measurement, there should be no dampening between the sensor and the lathe, and that could only be achieved with a powerful magnet, but, the magnet could cause an interference in the measurement, so only a elaborate casing could be used to do so. The data that comprises the packets of measurement do their job very well at the moment, only a few security protocols would really improve it. The calculation interface could be done in a open language which would make easier to distribute copies of the program.

The code and analysis could be associated with some optimization algorithms to dictate the best regimen of operation for the lathes. One detail to notice is that since its the Surface Responses are generated through a study on experimental data, it would be wise to redo it in regular intervals so that it could always represent the reality of the machine, and not an outdated portrayal. Following the same principle, it is necessary to do an experimental round in each individual machine, since even products of the same manufacturer will produce different results.

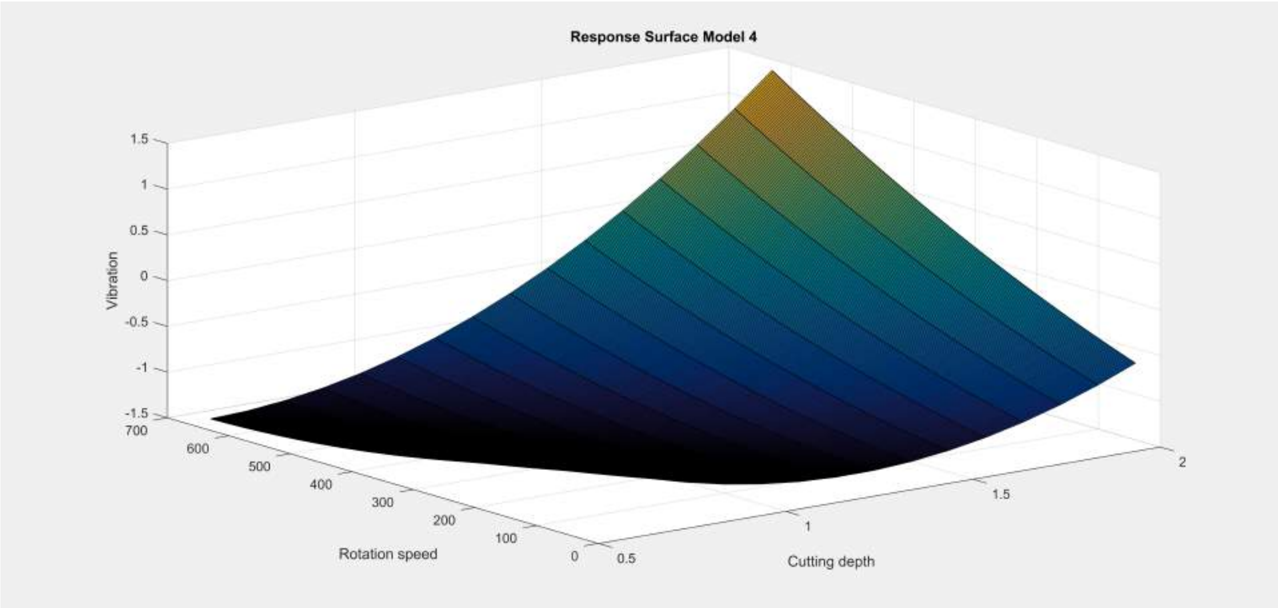

Figure 1. Surface response of Equation 4 from table 4, which best represented the experimental procedures on axis X

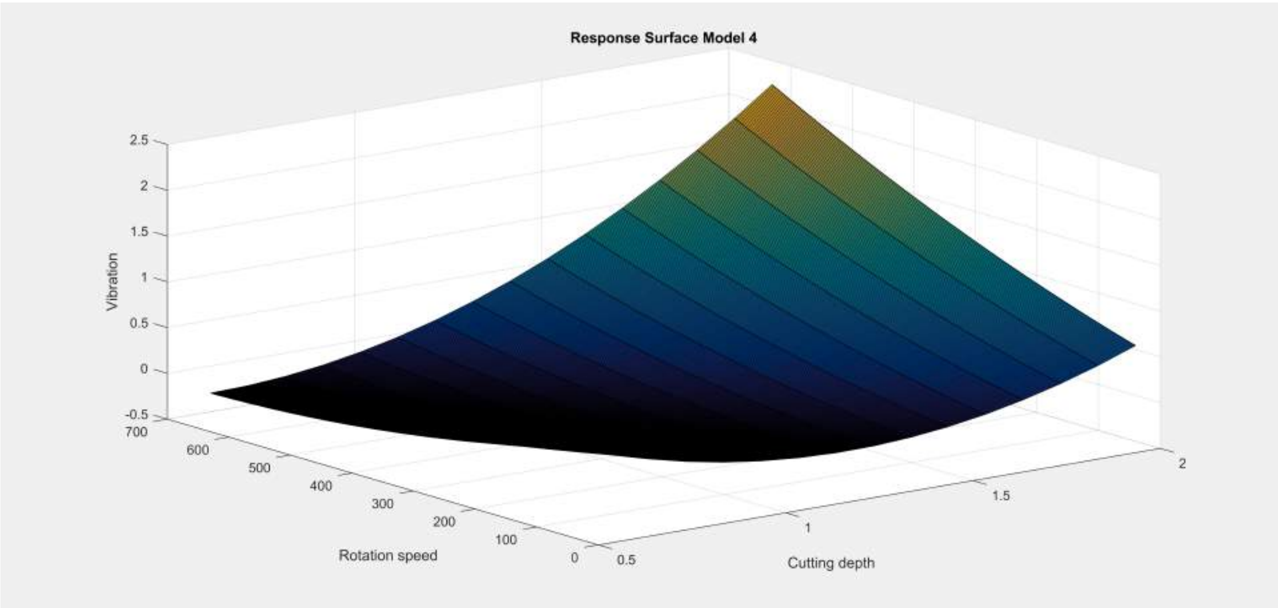

Figure 2. Surface response of Equation 4 from table 5, which best represented the experimental procedures on axis Y

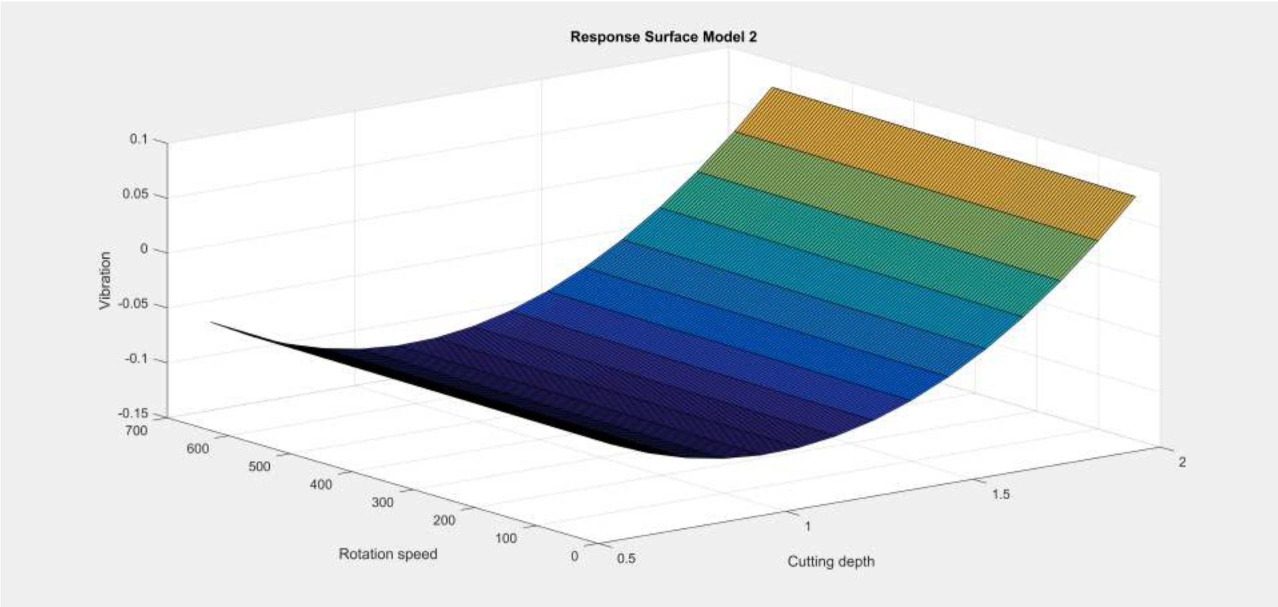

Figure 3. Surface response of Equation 2 from table 6, which best represented the experimental procedures on axis Z

4. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Federal Institute of Science and Technology of the State of Maranhão - IFMA for the fomentation and access to the necessary equipments.

5. REFERENCES

Button, S.T., 2005. *Metodologia Para Planejamento Experimental E Análise De Resultados*. Campinas - SP.

Doehlert, D.H., 1970. *Appl. Statist*.

Graça, C.A., de Velosa, A.C. and Teixeira, A.C.S., 2017. "Role of fe(iii)-carboxylates in amz photodegradation: A response surface study based on a doehlert experimental design". *Chemosphere*, Vol. 184, pp. 981 – 991.

Hollanda, L.R., Graça, C.A., Andrade, L.M., Mendes, M.A., Chiavone-Filho, O. and Teixeira, A.C., 2019. "Non-traditional atrazine degradation induced by zero-valent-copper: process optimization by the doehlert experimental design, intermediates detection and toxicity assessment". *Journal of Chemical Technology & Biotechnology*, Vol. 94, No. 4, pp. 1156–1164. doi:10.1002/jctb.5862.

Kovacevic, R. and Mohan, R., 1995. "Effect of high speed grinding fluid on surface grinding performance". *First International Machining and Grinding Conference*, , No. 1, pp. 919–931.

Montgomery, D.C., 2017. *Design and analysis of experiments*. John Wiley & Sons, New York, 9th edition.

Ruschel, C.F.C., Ferrão, M.F., Santos, F.P.D. and Samios, D., 2016. "OTIMIZAÇÃO DO PROCESSO DE TRANS-ESTERIFICAÇÃO EM DUAS ETAPAS PARA PRODUÇÃO DE BIODIESEL ATRAVÉS DO PLANEJAMENTO EXPERIMENTAL DOEHLERT". *Química Nova*, Vol. 39, pp. 267 – 272.

Wright, P.K. and Trent, E.M., 2000. *Metal Cutting*. Butterworth-Heinemann, 4th edition.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.