

# Investigation on influence of cutting parameters on spindle vibration of CNC wood milling machine

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**Abstract.** In machining operation, the cutting parameters greatly influences on the spindle vibration of a CNC wood milling machine. The paper presents the effect of the cutting parameters such as feed rate, cutting speed, and cutting depth on the vibration amplitude of the spindle when machined on CNC milling machine using Box-Hunter method of experimentation. The lowest natural frequency of this machine is 250 Hz. Experimental results have established a second-order regression equation that demonstrates the effect of three parameters such as feed rate, cutting speed, and cutting depth on the vibration amplitude of the spindle. From that base, determine the most reasonable cutting parameters when machining on CNC wood milling machines so that the spindle vibration amplitudes is minimal. In addition, The comparison results show that the spindle head vibration amplitude of the machine using the bolt joint is larger than the spindle head vibration amplitude of the machine using the weld joint.

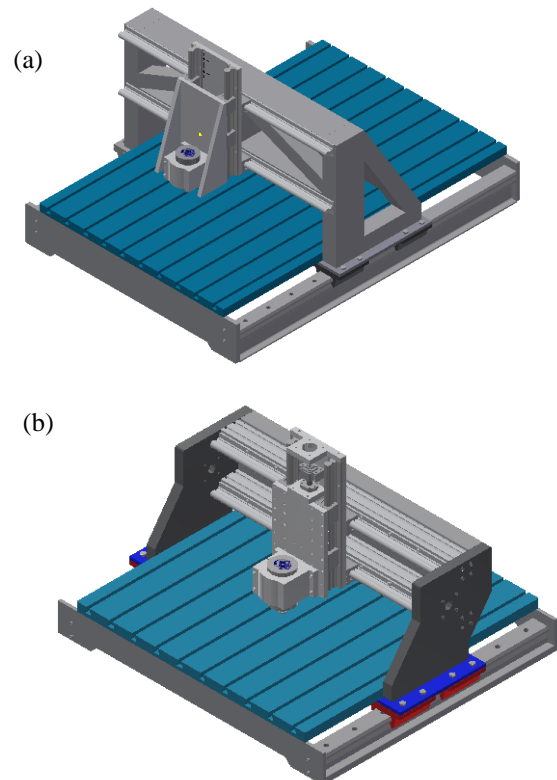
## 1 Introduction

Traditionally, the base and other major components of a machine tool have been made of gray or nodular cast iron, which has the advantages of low cost and good damping, but the disadvantage of heavy weight

In modern machine design, lightweight structures are desirable because of ease of transportation, higher natural frequencies, and lower inertial forces of moving members. Lightweight designs are a basic goal in machine tool design and require fabrication processes such as mechanical fastening (bolts and nuts) of individual components and welding. Bolted and welded machine tool structures consists of pre-cut stock materials such as plates, tubes, channels, and angles which are joined together to form the structure in Fig.1. Such stock items are available in a wide range of sizes and shapes and have some highly desirable mechanical properties such as formability, machinability and weldability. Of special interest are round and rectangular tubes whose closed cross sections have a very high stiffness-to-weight ratio [1].

Welded machine tool structures provide easy scalability in terms of size and outstanding flexibility in terms of fast design and fabrication; however, damping of the structure is a very critical issue. Unlike cast iron or polymer concrete-based components, welded steel plates have virtually no internal damping and are therefore prone to unwanted vibrations. Despite the shortcomings listed above, designing and building a machine as a welded structure has the big advantage of a much lighter

design with a substantially shorter lead time compared to a cast design.



**Figure 1.** The CNC machine tool structures: (a) Welded structure and (b) Bolted structure

The vibrations are induced due to machine faults, cutting parameters, cutting tool, work piece deformation, etc. Cutting parameters especially feed rate, depth of cut and spindle speed if not properly controlled can increase the vibration in the machining process. Too high vibration is very dangerous and may lead to serious injury. Therefore, vibration must be minimized to stabilize the cutting process, improve surface roughness and prevent tool from breaking. The effect of cutting tool vibration on surface roughness of workpiece in dry turning operation and a correlation between surface roughness and cutting tool vibration in turning [2]. Forced and self-excited vibration limits the stability of cutting and lead to tool and machine damage. It also limits the productivity of machining operation.

Controlling spindle vibration of machine tool is one of the approaches for enhancing the quality of the product. Investigated the Effect of spindle forced vibrations on surface roughness, dimensional accuracy, and tool wear in vertical milling of AISI P20 [3]. Several researchers have studied the effect of cutting parameters such as spindle speed, feed rate, axial and radial depth of cut, appropriate selection of tool material and tool geometry in machining of aluminum based alloys [4, 5] Prediction of surface roughness in end face milling based on Gaussian process regression and cause analysis considering vibration of cutting tool [6]. Developed experimental plan and conducted experiments based on central composite design (CCD) of response surface methodology (RSM) [7]. Experimental investigation on the effect of cutting parameters on the spindle vibration and surface roughness in the precision end-milling process using the singular spectrum analysis [8-10]. An experimental investigation on the effect of machining and geometrical parameters such as spindle speed, feed rate, axial and radial depth of cut and radial rake angle on responses during end milling operation on the surface

roughness and its defects of AL 6061-T6 [11]. Effect of tool vibration, cutting conditions on surface roughness during lathe dry turning process [12, 13]

Surface roughness is mainly affected by machine tool vibration. To improve the surface roughness, it is very essential to know the influences of cutting parameters on machine tool vibration. The purpose of this research is to investigate on the influences of cutting parameters such as feed rate, cutting speed and cutting depth on spindle vibration amplitude of welded structure of CNC wood milling machine structure using Box-Hunter quadratic experimental model.

## 2 Experimental methodology

### 2.1 Experimental setup

The experiments have been performed on welded structure of CNC wood milling machine. The lowest natural frequency of this machine is 250 Hz. The device used for the spindle vibration test of CNC milling machine consists of instrument accelerometer sensor PCB 603C01, PCB Group, the accelerometer sensitivity 10.2 mV/g. The Multi-Channel NI SCXI-1000DC System was used to analyze the vibration detected by the accelerometer. For a good operating of the NI SCXI-1000DC system, the NI Signal Express software displayed the result of vibration data and a personal computer. The workpiece material used in this study is fir wood. The experimental setup for operation is shown in Fig.2. In particular, the acceleration sensor is attached to the spindle head of the machine, the NI SCXI-1000DC measurement device is connected to the acceleration sensor and the computer. Measurement data is collected and displayed through the NI Signal Express software.



Figure 2. Experimental Setup

### 2.2 Design of Experiment (DOE)

The machining parameters were selected are spindle speed, feed rate and depth of cut. Cutting parameters were considered as input factors, spindle vibration were considered as output parameters during this analysis. The

number of levels for each factors considered in this DOE is as shown in Table 1.

Experimental matrix based on the symmetrically mixed quadratic planning model with 3 coded factors as shown in Table 2.

**Table 1.** Design schema of cutting parameters and their levels

Variables or parameter	Factor symbol		interval of variation	Variable range of cutting parameters				
	Actual factor	Code factor		level - $\alpha$	level (-1)	level (0)	level (+1)	level + $\alpha$
Spindle Speed [rev/min]	n	$x_1$	5000	2590	6000	11000	16000	19410
Depth of Cut [mm]	t	$x_2$	0.6	0.29	0.7	1.3	1.9	2.31
Feed Rate [mm/ min]	s	$x_3$	500	159	500	1000	1500	1841

**Table 2.** Experimental matrix of 3 factors

	$N^0$	$x_0$	$x_1$	$x_2$	$x_3$	$x_1x_2$	$x_1x_3$	$x_2x_3$	$x_{11}$	$x_{22}$	$x_{33}$
Number of experiments in nucleus $2^k$	1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
	2	+1	-1	+1	+1	-1	-1	+1	+1	+1	+1
	3	+1	+1	-1	+1	-1	+1	-1	+1	+1	+1
	4	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1
	5	+1	+1	+1	-1	+1	-1	-1	+1	+1	+1
	6	+1	-1	+1	-1	-1	+1	-1	+1	+1	+1
	7	+1	+1	-1	-1	-1	-1	+1	+1	+1	+1
	8	+1	-1	-1	-1	-1	+1	+1	+1	+1	+1
Number of experiments in point start (*)	9	+1	+1.682	0	0	0	0	0	$2\sqrt{2}$	0	0
	10	+1	-1.682	0	0	0	0	0	$2\sqrt{2}$	0	0
	11	+1	0	+1.682	0	0	0	0	0	$2\sqrt{2}$	0
	12	+1	0	-1.682	0	0	0	0	0	0	0
	13	+1	0	0	+1.682	0	0	0	0	$2\sqrt{2}$	$2\sqrt{2}$
	14	+1	0	0	-1.682	0	0	0	0	0	$2\sqrt{2}$
Number of experiments in the planning center	15	+1	0	0	0	0	0	0	0	0	0
	16	+1	0	0	0	0	0	0	0	0	0
	17	+1	0	0	0	0	0	0	0	0	0
	18	+1	0	0	0	0	0	0	0	0	0
	19	+1	0	0	0	0	0	0	0	0	0
	20	+1	0	0	0	0	0	0	0	0	0

The mean results of measuring the spindle vibration amplitude of 20 experiments and each experiment were repeated 7 times as shown in Table 3.

**Table 3.** The results the spindle vibration amplitude

$N^0$	$\bar{y}$	$s_i^2$	$N^0$	$\bar{y}$	$s_i^2$
1	0.351	0.0004	11	0.398	0.0006
2	0.581	0.0084	12	0.301	0.0014
3	0.116	0.0007	13	0.224	0.0025
4	0.525	0.002	14	0.176	0.0004
5	0.31	0.0015	15	0.075	0.0002
6	0.489	0.0021	16	0.07	0.0002
7	0.09	0.0005	17	0.075	0.0001
8	0.491	0.0022	18	0.07	0.0001
9	0.278	0.0007	19	0.075	0.0001
10	0.844	0.0158	20	0.07	0.0001

### 3 Results and discussion

#### 3.1 The coefficients of regression equation

With this Box-Hunter experimental model, the coefficients of regression equation were obtained by the results of experimental data and expressed by the following Eq. 1.

$$y = 0.0731 - 0.1597x_1 + 0.0498x_2 + 0.0208x_3 + 0.0489x_1x_2 - 0.0086x_{13} + 0.0104x_{23} + 0.1689x_1^2 + 0.0943x_2^2 + 0.0413x_3^2 \quad (1)$$

#### 3.2 The testing of the individual regression coefficients

After calculating the value of the coefficients of the regression equation, it is necessary to test their significance and eliminate the insignificant individual regression coefficients [14, 15]. The computational results are shown in Table 4.

**Table 4.** Significance test of individual regression coefficients

Tern	Value of Coefficient	SE coefficient	T	P-Value	
b <sub>0</sub>	0.0731	0.01048	6.977	0.00	
b <sub>1</sub>	-0.1597	0.006953	-22.861	0.00	
b <sub>2</sub>	0.0498	0.006953	7.078	0.00	
b <sub>3</sub>	0.0208	0.006953	3.183	0.086	Insignificant
b <sub>12</sub>	0.0489	0.006769	5.517	0.00	
b <sub>13</sub>	-0.0086	0.006769	-0.812	0.436	Insignificant
b <sub>23</sub>	0.0104	0.006769	1.004	0.339	Insignificant
b <sub>11</sub>	0.1689	0.009085	24.920	0.00	
b <sub>22</sub>	0.0943	0.009085	13.873	0.00	
b <sub>33</sub>	0.0413	0.009085	6.064	0.00	

In the Significance test table, P - value of less than 0.05 indicates that the model terms can be considered significant. Table 4 presented of Significance test table for regression equation coefficients. There are 3 coefficient  $b_3$ ,  $b_{13}$  and  $b_{23}$  are not significant because its P value is more than 0.05. We remove these coefficients, then we rewrite the matrix and recalculate the coefficients. Through the backward elimination process, the final quadratic models of response equation in terms of coded factors are presented as follows Eq. 2.

$$y = 0.0731 - 0.1597x_1 + 0.0498x_2 + 0.0489x_1x_2 + 0.1689x_1^2 + 0.0943x_2^2 + 0.0413x_3^2 \quad (2)$$

### 3.3 Testing lack of fit in regression

For testing lack of fit in regression, to perform the analysis of variance for Significance of regression is shown in Table 5

**Table 5.** Analysis of variance for Significance of regression

Source	Sum of Squares	DF	Mean Square	F	P-Value
Model	0.8847	6	0.14746	68.94	0.00
Residual Error	0.0278	13	0.00214		
Lack-of-Fit	0.027767	8	0.003471	462.78	0.00
Pure Error	0.000038	5	0.000008		
Total	0.9125	19			

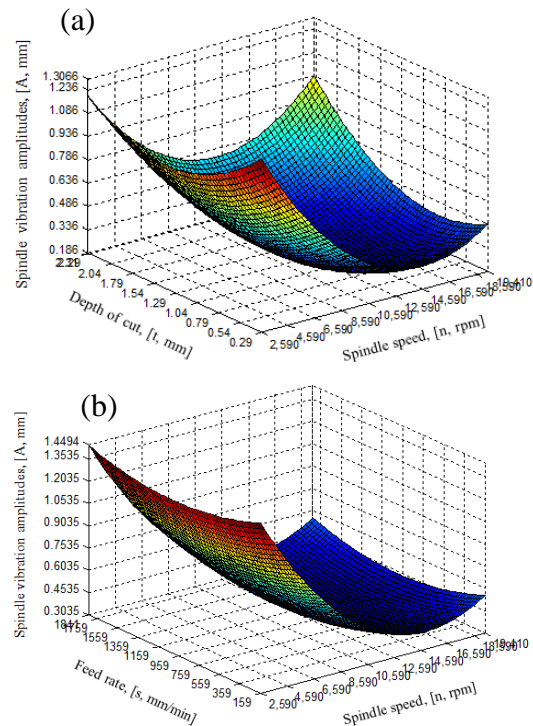
The model was developed with 95% confidence interval. Because  $F_{\text{model}} = 68.94 > F_{0.05,6,13} = 2.92$  and  $F_{\text{LOF}} = 462.78 > F_{0.05,8,5} = 4.82$ . Also, note that the P-value for  $F_{\text{model}}$  and  $F_{\text{LOF}}$  (shown in Table 5) is considerably smaller than  $\alpha = 0.05$ . The regression model is fitting well.

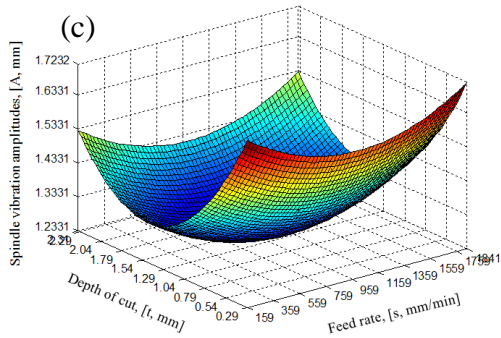
In the actual form, the regression equation shows the relation between the feed rate (s), cutting speed (n), cutting depth (t) and the spindle vibration amplitude (A) of the CNC machine are presented as follows Eq. 3.

$$A = 1.993 - 20.212 \cdot 10^{-5} n - 0.7807 t - 3.304 \cdot 10^{-4} s + 0.0166 \cdot 10^{-3} nt + 0.0676 \cdot 10^{-7} n^2 + 0.262 t^2 + 1.652 \cdot 10^{-7} s^2 \quad (3)$$

### 3.4 Evaluation of experimental results

In the milling process, the machining parameters adopting the spindle speed, the feed rate, and the depth of cut were chosen as the three factors so as to investigate the influences on the vibration amplitude. The influences of machining parameters on the performance of the vibration amplitude have been analyzed, which is based on the above proposed mathematical model.





**Figure 3.** (a) Effect of  $n$  and  $t$  on the spindle vibration amplitude; (b) Effect of  $n$  and  $s$  on the spindle vibration amplitude and (c) Effect of  $t$  and  $s$  on the spindle vibration amplitude

In graphs Fig. 3 shows the relationship between the feed rate, cutting speed, cutting depth and the spindle vibration amplitude of the CNC milling machine. It can be seen that the tendency of spindle vibration amplitudes slightly decreases with an increase of spindle speed. Increasing the spindle speed promotes the rotation stability of spindle head, which results in suppressing the vibration amplitude. As seen above, the spindle vibration amplitudes obviously increase with increasing the feed rate.

In the cutting process, the resistance force acting on the cutting tool is mainly generated by the status of feed rate and depth of cut. The increase of cutting depth and feed rate causes the increase in the resistance force at the tooltip and cutting feed direction, which excites more vibration appearance. It can be obviously seen that the spindle vibration amplitudes increase with increasing the value of cutting depth and feed rate. As the results of analysis discussed above, the spindle vibration amplitudes are principally influenced by the spindle speed, feed rate and cutting depth.

In Fig. 3, the local reasonable cutting parameters valued (within the scope of the survey) so that the spindle vibration amplitudes is minimal as follows:  $n = 14280$  rpm,  $s = 1043$  mm/min and  $t = 1.043$  mm  $\Rightarrow$  spindle vibration amplitude:  $A_{\min} = 0.017$  mm.

#### 4 The machine structure using the bolt joint

Machine structure using a bolt joint and an experimental setup of the spindle head of the CNC milling machine is shown in Fig. 4.

With the same cutting parameters as above, the results of measuring the spindle vibration of 20 experiments and each experiment were repeated 7 times as shown in Table 6.

The regression equation shows the relation between the feed rate ( $s$ ), cutting speed ( $n$ ), cutting depth ( $t$ ) and the spindle vibration amplitude ( $A$ ) of the milling machine are presented as follows Eq. 4.

$$A = 1.993 - 20.212 \cdot 10^{-5} n - 0.7807t - 3.304 \cdot 10^{-4} s + 0.0166 \cdot 10^{-3} nt + 0.0676 \cdot 10^{-7} n^2 + 0.262t^2 + 1.652 \cdot 10^{-7} s^2 \quad (4)$$



**Figure 4.** Machine structure using a bolt joint and Experimental Setup

**Table 6.** Experimental results

$N^0$	$\bar{y}$	$s_i^2$	$N^0$	$\bar{y}$	$s_i^2$
1	0.355	0.0014	11	0.0097	0.0006
2	0.576	0.0146	12	0.0056	0.0014
3	0.121	0.0004	13	0.001	0.0025
4	0.576	0.0059	14	0.0016	0.0004
5	0.34	0.0006	15	0.0001	0.0002
6	0.541	0.0211	16	0.069	0.0001
7	0.098	0.0005	17	0.067	0.0001
8	0.575	0.0119	18	0.07	0.0001
9	0.223	0.0002	19	0.075	0.0001
10	0.862	0.0133	20	0.072	0.0001

The comparison results of spindle vibration amplitude for two different machine structure types are the structures using the welded joint and the bolt joint. The results show that the spindle head vibration amplitude of the machine using the bolt joint is larger than the spindle head vibration amplitude of the machine using the weld joint.

#### 5 Conclusions

The paper presents the effect of the cutting parameters such as feed rate, cutting speed, and cutting depth on the vibration amplitude of the spindle when machined on CNC milling machine by experimental design method (DOE). Using the Box-Hunter method of experimentation to construct a second-order regression equation representing the relationship between the cutting parameters and the vibration amplitude of the spindle to survey the effect of the cutting parameters on the spindle vibration in machining process. The results show that as the spindle speed increases, the rotational

stability of the spindle head is promoted, which reduces the vibrations amplitude and the spindle vibration amplitudes increase with increasing the value of cutting depth and feed rate to cause the unstability of cutting process and exhibit the result of the worst machined surface. In addition within the scope of survey also identified the most appropriate cutting parameters for machining on CNC wood milling machine.

The comparison results of spindle vibration amplitude for two different machine structure types are the structures using the welded joint and the bolt joint show that the spindle head vibration amplitude of the machine using the bolt joint is larger than the spindle head vibration amplitude of the machine using the weld joint.

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