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RESEARCH

# A Method to Evaluate Wear and Vibration Characteristics of CNC Lathe Spindle

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A B S T R A C T

*When operating, the CNC turning machine has to stay in good spindle bearing, accurately detecting wear of spindle bearing basically to procedure manual and time-consuming process. The CNC machine tool's spindle bearing vibration analysis has enabled timely detection of wear phenomena over time and local wear, unbalance in rotating, round-trip moving parts. Determining the time of adjustment and maintenance to restore preload is usually based on the wear of the spindle bearing in the normal working period. However, the time of preload adjustment and maintenance of spindle bearing can be based on the RMS (Root Mean Square) vibration index if the relationship of RMS vibration characteristics with total wear over time and limit wear allowed for spindle bearing are defined.*

*This paper presents a research method to determine the relationship between the wear and RMS vibration characteristics of CNC lathe eclipse 300 spindles bearing under variable external load conditions.*

*From there, determine the limit value of RMS vibration characteristics corresponding to the limit wear value of the spindle bearing of the CNC lathe and estimated time of adjustment $T_h$ for preload restore and maintenance.*



## 1. INTRODUCTION

The CNC machine spindle has a decisive role in ensuring accuracy and efficiency in the machining process [1]. The CNC machine spindle assembly includes [2]: shaft, bearings, driusually use cooling system... Spindles usually use high-precision bearings and set preload to enhance stiffness and working accuracy [3]. However, when working under the influence of load and heat, the bearings will wear and decrease the stiffness of the spindle and the machining accuracy. It is necessary to monitor the quality of the spindle to provide replacement maintenance cycles. Many authors have studied the quality of machine tool spindles, including [4], who have shown that the technical condition of the bearing spindle plays a role in determining the working quality of the whole spindle assembly. The research [5] about spindle assembly has shown that the spindle bearing must be set preloaded in all CNC machine tools to ensure and maintain machining accuracy. Duong et al.

proposed a solution to reduce the friction loss of the mini CNC lathe spindle unit by segmenting preload. The axial displacement for preload is divided into two parts on a class B basis [6]. A method has been proposed to determine the life and reliability of the spindle assembly under random loads based on the allowable stiffness [7]. The research results show that the life expectancy increases by 12-15% compared to the case calculated according to the total axial wear. Te Li et al. [8] indicated that Preload has a great infuence on the spindle's dynamic and thermal characteristics. During operation, preload of the spindle bearing depends on the total wear value of the bearing. Preload of spindle bearing decreases as total wear increases. When the total wear of the spindle bearing reaches the limit value, defined by ISO 13041 - 1:2004 [9], adjustment and maintenance are required to restore and maintain preload of the spindle bearing. Due to the operated peculiarity of CNC machine tools, it is necessary to maintain stable working accuracy for a long time with mandatory bearing adjustment cycles. Replacement must be carried out even if localised spindle bearing failure has not appeared during service to ensure the quality of the workpiece is maintained [10].

It is difficult to check the wear of the spindle bearing during machine work. According to Randall [11], vibration analysis is one of the main techniques for obtaining information about internal conditions. Vibration analysis can diagnose the primary bearing failure and prevent undesirable consequences of failure. The vibration analysis technology is widely used with the advantages such as fast real-time response, high reliability, and reasonable cost [12]. Many studies have found a relationship between localised bearing failure patterns in devices such as outer rings, an inner ring or roller failure and vibration characteristics based on time-domain analysis—frequency domain or time-frequency domain [13]. Using vibration can be observed with typical wear-out mechanisms such as bearings, gears, chains, belts, brushes, shafts, coils in a machine, and has a plant to regular maintenance [14]. Using the vibration analysis method through the characteristic value of RMS (Root Mean Square) can evaluate the working quality of machine tools and CNC lathe spindle assemblies [15]. The Root Mean Square (RMS) characteristic value of the vibration is determined through the vibration (acceleration) sensor mounted on the flange mounted to the outer race of the bearing assembly. The vibration value is the maximum value at the measuring positions and measuring directions. The formula for calculating RMS[16]

$$RMS = \sqrt{\frac{1}{T}\int_0^T x(t)^2\,dt} \tag{1}$$

where:

*x(t)* is the oscillation acceleration with time;

*T* is the measurement time.

However, the relationship between the RMS vibration characteristics and the working quality of spindle bearing on the machine tool in general, and the CNC lathe in particular, has not been extensively studied. Zhang [17] established a dynamic bearing wear model based on starved lubrication condition, analysed the interaction of wear status existing on inner/outer ring and preload under various preload manners, and the comprehensive infuence on bearing life. Grzegorz Wszołek et al. [18] used a MEMS sensor for Measured vibrations on the spindle housing, indicating that it can be possible to check the condition of the bearings using vibration analysis synchronous (with RMS) to the spindle rotation. Jozef Žarnovský et al., Study on Vibration Diagnostics of CNC Machining Center Spindle using the Adash A4900 vibrio M [19]. The authors showed the machine's limited working speed based on price measured vibration value according to technical standard ISO 10816-3:2009. The influences of spindle speed and the bearing parameters on the vibration behaviours and stability of the spindle have been studied by Huihui Miao et al. [20]. The authors showed that the radial bearing clearance significantly influences the dynamic behaviours of the CNC vertical milling machine spindle system.

Most of the above studies mainly mention the quality monitoring method of the spindle through a vibration survey when there is preload. However, the relationship between vibration and wear of the spindle bearing depending on the load and speed during regular operation has not been discussed. It has not yet been the recommend estimated time of adjustment $T_h$ to restore the preload of the spindle bearing, based on the limit value of RMS vibration characteristics.

This paper presents a research method to determine the relationship between the wear and RMS vibration characteristics of CNC lathe eclipse 300 spindles bearing under variable external load conditions. The RMS vibration characteristics value corresponds to the limit wear of the spindle bearing; recommend estimated time of adjustment $T_h$ for restoring preload of the Eclipse 300 CNC lathe.

## 2. EXPERIMENTAL APPARATUS AND METHOD

The experimental equipment system is built based on a CNC lathe eclipse 300 spindles bearing specifications, as shown in Table 1.

**Table 1.** Basic parameters of Eclipse 300 CNC machine.

| Parameter of CNC Eclipse 300 | Value |
|---|---|
| Spindle rotation speed (rpm) | 100-4000 |
| Spindle motor (W) | 1500 |
| Longitudinal Z travel (mm) | 275 |
| Transversal X travel | 96 |
| Swing diameter (mm) | 230 |
| Distance between centres (mm) | 530 |
| Spindle bearing arranged DB | 7210B |

Based on the principle of vibration and total wear measurement of the lathe spindle [9,21], a diagram of the experimental equipment system is built, as shown in Figure 1. This system is set up directly on the CNC lathe eclipse 300 spindles.

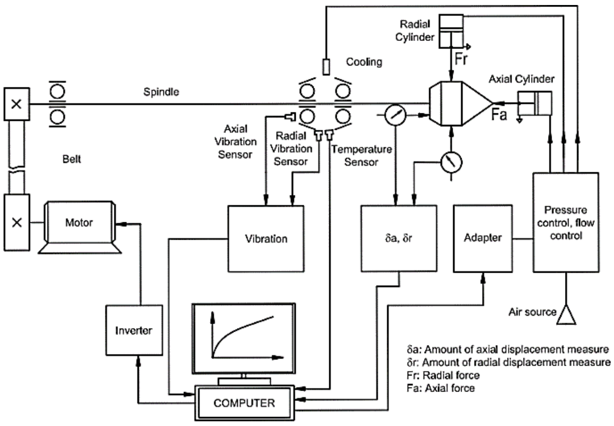



**Fig. 1.** A schematic view of the experimental apparatus.

In this system, 2 pneumatic cylinders are used to load for axial force and radial force. It is adjusted pressure corresponding to the computed cutting force. The experiment was conducted in the no lubricant conditional. The spindles bearing is guaranteed to work in stable condition with a temperature below 60⁰C by the pneumatic cooling system. Total wear measurement of Lathe spindle based on ISO 13041 – 1:2004. The axial and radial displacement is measured using the Mitutoyo 1/1000 mm, with a range of 0 ÷0.14 mm; Split: 0.001 mm. Measurement of vibrations based on ISO/TR 1086-1 [21]. The SKF microlog CMX-A44 vibration meter is used to monitor parameter RMS of spindle bearing in synchronous wear.

**Table 2.** The basic technical parameters of the experiments.

| Parameter | Value |
|---|---|
| Bearing type | 7210B, NSK |
| Spindle rotation speed, n (rpm) | 1800, 2000, 2200 |
| Equivalent load Load, P(N) | 1310, 1915, 2520 |
| Lubrication | No |
| Period (h) | 6 |
| Number of periods | 5÷8 |
| Cooling, Compressed air requirement | T< $60^0$C |

The basic technical parameters of the experiments are shown in Table 3.

**Table 3**: Specifications of the bearing 7210B, NSK.

| Bearing number | Basic load ratings | | D (mm) | d (mm) | α ($^0$) |
|---|---|---|---|---|---|
| | Cr(N) | $C_{0r}$(N) | | | |
| 7210B | 60500 | 57000 | 90 | 50 | 15 |

Test load and speed selection are based on bearing specifications, machine specifications, and experimental conditions. So that wear and vibration of spindles bearing over time can be monitored in a suitable laboratory.

Basic rating life is calculated by equation [22]

$$L_{10} = \left(\frac{C_r}{P}\right)^3 \tag{2}$$

where:

$L_{10}$: Basic rating life;

$C_r$: Basic dynamic radial load eating (Table 3);

$P$; Dynamic equivalent load;

for machine tools basic rating life in hours [23], select $L_{10h}$= 25.000 h. According to the technical features of the machine: $n$ = 100 ÷ 4000 rpm → selection of experimental speed range $n \sim 2000$ rpm.

$$L_{10h} = \frac{10^6 \cdot L_{10}}{(60.n)} \rightarrow L_{10} = 3300 \text{ million revolutions}$$

From (2) Dynamic equivalent load: $P$ = 4064 N.

The experiment was conducted in the no lubricant conditional. Thus, the selection of an average value of dynamic equivalent load $P$ ~ 1915 ± 605 N, ~ $n$ = 2000 ±200 rpm.


**Fig. 2**. The experimental apparatus; 1. Pneumatic cylinder generates a radial force; 2. Pneumatic cylinder generates an axial force; 3. Indicator; 4 . Vibration sensor; 5. Spindle bearing; 6. The temperature controller, 7. Spindle speed controller, 8. Vibration measurement and analysis equipment, 9. Pneumatic cooling lines.

Experiments about wear amount and RMS of spindle bearing were done with external load and speed according to Table 4.

**Table 4.** Experimental parameters.

| Parameters | No.1 | No. 2 | No. 3 | No. 4 | No. 5 |
|---|---|---|---|---|---|
| $P$ (N) | 1310 | 2520 | 1310 | 2520 | 1915 |
| $n$ (rpm) | 1800 | 1800 | 2200 | 2200 | 2000 |

Each set of experimental parameters uses a new pair of bearings. Build graphs of wear amount U and RMS over time. Time for each time stops the experimental apparatus from getting data to wear amount, and RMS is $t$. With the experimental conditions determined above, $t$ = 6 h. From the graph of wear amount $U$ and RMS over time, the wear rate γ and RMS will be determined. Using SKF's Microlog Analysis software to determine RMS vibration characteristics parameters, the calculation results are performed on Matlab software shown in Fig. 3.

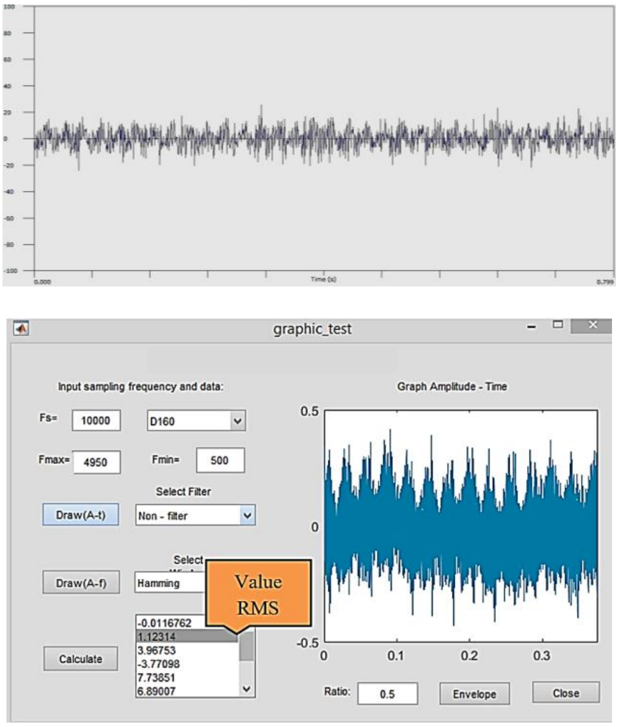



**Fig. 3**. RMS value when measuring vibration acceleration.

Experiment life $T_{h,exp}$ of each pair of bearings determined according to the wear [24]:

$$T_{h,\exp} = \frac{[U]}{\gamma}\,(\mathrm{h}) \tag{3}$$

$$[U] = m.[\delta] \tag{4}$$

where:

$T_{h,exp}$ - Experiment life;

[$U$] - Total allowable axial wear amount;

$\gamma$ - Wear rate;

[$\delta$] - the limited amount of axial; displacement according to ISO 13041 - 1:2004;

$m$ - Number of spindle bearing adjustments at the end of life, $m$ = 2÷3.

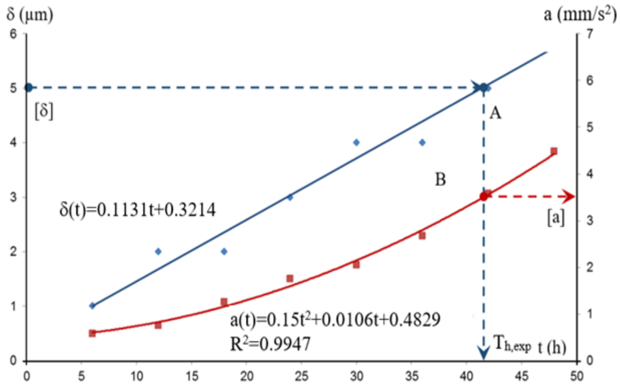
## 3. RESULT AND DISCUSSION

For each experiment (No. 1 ÷ No. 5), the axial displacement ($\delta$, μm) and RMS vibration characteristics ($a$, mm/s$^2$) of spindle bearing were measured after 6, 12, 18, 24, 30, 36, 42 and 48 h shown in Table 5. The axial displacement is determined with the standard axial preload (axial force $Fa$=250 N). The RMS vibration characteristics are determined with $P$=0, and n corresponds to each experiment.

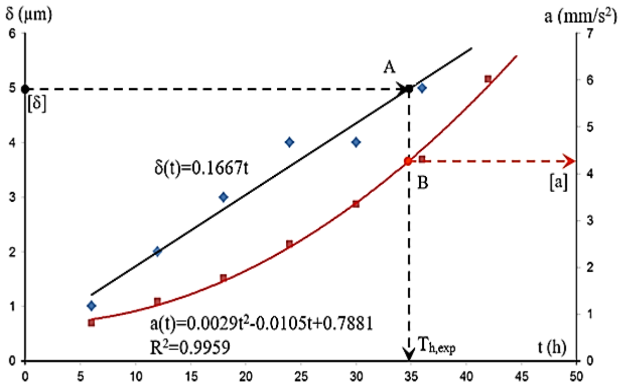
**Table 5.** Experimental data.

| No. | 6 h | | 12 h | | 18 h | | 24 h | | 30 h | | 36 h | | 42 h | | 48 h | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\delta a$ | $a$ | $\delta a$ | $a$ | $\delta a$ | $a$ | $\delta a$ | $a$ | $\delta a$ | $a$ | $\delta a$ | $a$ | $\delta a$ | $a$ | $\delta a$ | $a$ |
| 1 | 1 | 0.582 | 2 | 0.753 | 2 | 1.252 | 3 | 1.756 | 4 | 2.045 | 4 | 2.667 | 5 | 3.576 | 6 | 4.483 |
| 2 | 1 | 0.802 | 2 | 1.269 | 3 | 1.762 | 4 | 2.492 | 4 | 3.341 | 5 | 4.31 | 6 | 6.021 | | |
| 3 | 1 | 0.868 | 2 | 1.301 | 3 | 2.206 | 4 | 2.817 | 5 | 3.956 | 6 | 5.462 | | | | |
| 4 | 1 | 0.982 | 2 | 1.626 | 3 | 2.566 | 4 | 3.84 | 6 | 5.986 | | | | | | |
| 5 | 1 | 0.921 | 2 | 1.376 | 3 | 2.011 | 4 | 3.195 | 5 | 4.225 | 6 | 5.868 | | | | |

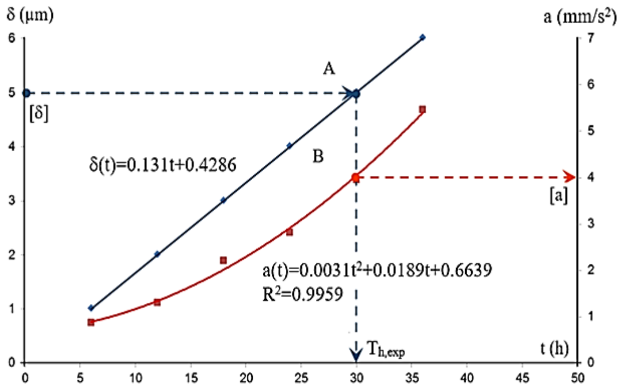
The experiment results indicated that: There is a relation between the experimental life $T_{h,exp}$ (h) and the permissible limit value of RMS vibration characteristics - [$a$], according to load $P$ and spindle speed $n$, as shown in Figure 4.



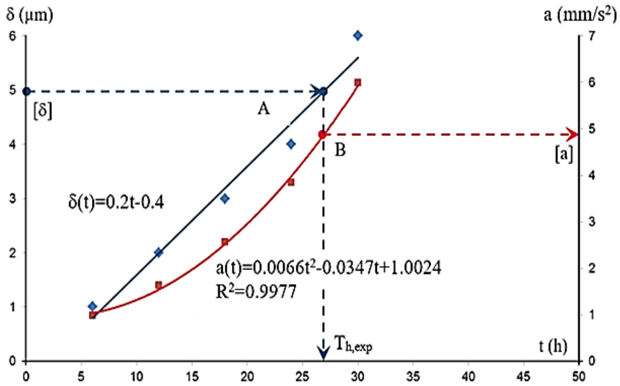

(a) No.1 (P = 1310 N, n = 1800 rpm)



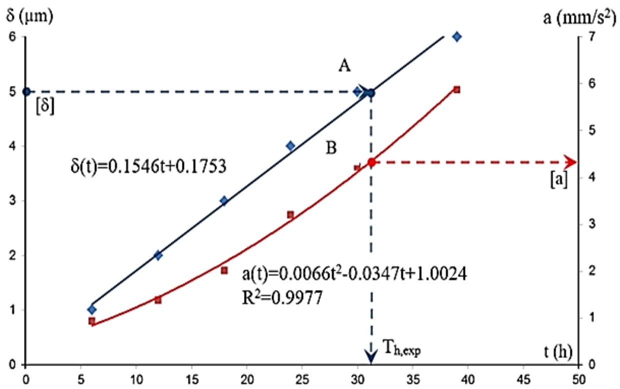

(b) No.2 (P = 2520 N, n = 1800 rpm)




(c) No.3 (P = 1310 N, n = 2200 rpm)




(d) No.4 (P = 2520 N, n = 2200 rpm)




(e) No.5 (P = 1915 N, n = 2000 rpm)

**Fig. 4.** Graph of [$\delta$] and [$a$] of the Eclipse 300 CNC lathe spindle at different loading modes $P$ and $n$

In Figure 4, the limit value [$a$] of RMS vibration characteristics can be determined from the total allowable wear limit [$\delta$] according to ISO 13041 - 1:2004 .

From the regression equation of the total wear $\delta(t)$ over time:

$$\delta(t) = b_{11}t + b_{12} \rightarrow t = \frac{\delta(t) - b_{12}}{b_{11}} \tag{5}$$

Calculated: $$T_{h,\exp} = \frac{[\delta] - b_{12}}{b_{11}} \tag{6}$$

From the regression equation of RMS vibration characteristics - acceleration $a(t)$ over time:

$$a\ \ t\ = b_{21.}\ t^2 + b_{22}.t + b_{23} \tag{7}$$

From (5) and (7), we get the equation to determine [a]:

$$[a] = b_{21}\left(\frac{[\delta]-b_{12}}{b_{11}}\right)^2 + b_{22}\left(\frac{[\delta]-b_{12}}{b_{11}}\right) + b_{23} \tag{8}$$

where:

$b_{11}$, $b_{12}$ are experimental coefficients of wear equation $\delta(t)$;

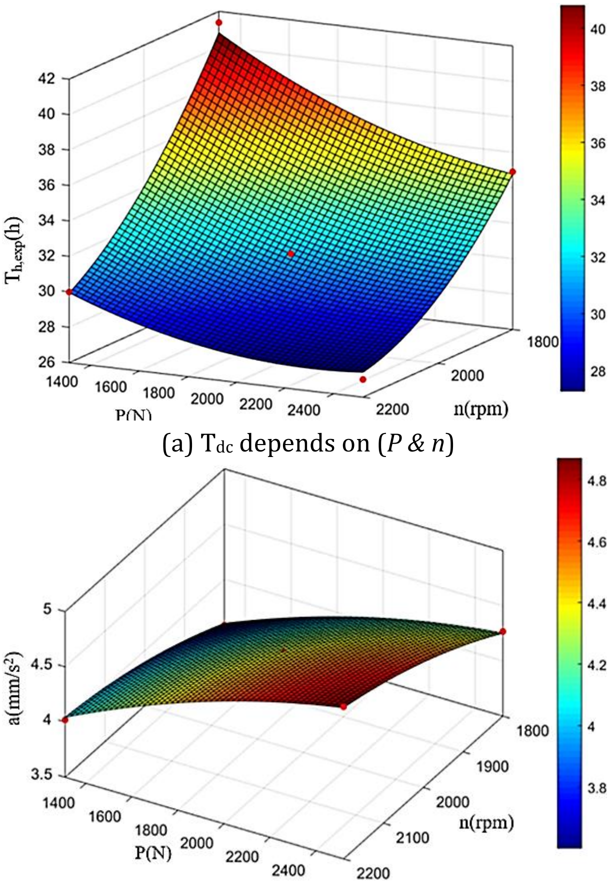
$b_{21}$, $b_{22}$, $b_{23}$ are experimental coefficients of RMS vibration characteristics - accelerative equation $a(t)$.

From equation (8), with the allowable limit total wear [$\delta$] (µm), it is possible to determine the experiment life (which is the expected adjustment time $T_h$) $T_{h,exp}$ (h) depending on the value of the permissible limit of RMS vibration characteristics - [$a$] (mm/s²). The calculated value of $T_{h,exp}$ and RMS - [$a$] is shown in Table 6.

From the experimental data and the calculated data in Table 6, the expected adjustment time $T_{h,exp}$ to restores the preload of the spindle bearing and the permissible limit value of the RMS characteristic vibration - [$a$] depending on the external load ($P$ & $n$) are shown in the graph of Figure 5 and equations 9 and 10.

**Table 6.** The calculated value of $T_{h,exp}$ và RMS - *[a]* when *[δ]*=5µm

| No. \ Value | $b_{11}$ | $b_{12}$ | $b_{21}$ | $b_{22}$ | $b_{23}$ | $T_{h,exp}$ (h) | RMS - [a] (mm/s²) | [δ] (µm) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.1131 | 0.3214 | 0.0015 | 0.0106 | 0.5793 | 41.37 | 3.585 | 5 |
| 2 | 0.131 | 0.4286 | 0.0029 | -0.0015 | 0.7881 | 34.90 | 4.267 | 5 |
| 3 | 0.1667 | 0 | 0.0031 | 0.0189 | 0.6639 | 29.99 | 4.020 | 5 |
| 4 | 0.2 | -0.4 | 0.0066 | -0.0347 | 1.0024 | 27.00 | 4.877 | 5 |
| 5 | 0.1546 | 0.1753 | 0.002 | 0.0646 | 0.3871 | 31.21 | 4.351 | 5 |




(b) [a] depending on ($P$ & $n$)

**Fig. 5.** Graph the relationship between $T_{h,\,exp}$ và [$a$] according to load and speed.

$$T_{dc\ n,P} = 257.7 + 0.1736 \cdot n - 0.02828 \cdot P + 3.425e^{-05} \cdot n^2 + 7.19e^{-06} \cdot n \cdot P + 2.705e^{-06} \cdot P^2 \tag{9}$$

$$[a]_{(n,P)} = -6.597 + 0.008164 \cdot n + 0.0009311 \cdot P - 1.883e^{-06} \cdot n^2 + 3.616e^{-07} \cdot n \cdot P + 2.728e^{-7} \cdot P^2 \tag{10}$$

The experimental results are presented on the graph of total wear, and RMS vibration characteristics show that having a direct relation between limit wear amount [$\delta$] (µm) and RMS limit vibration characteristics - [$a$] (mm/s²), where wear is linear, and RMS is nonlinear. The limit value of RMS vibration characteristics is completely determined - [$a$] corresponding to the limit amount of wear [$\delta$] of the CNC lathe spindle bearing.

Test conditions on the Eclipse 300 CNC lathe show that the RMS vibration characteristics value is measured at no-load according to ISO 10816, [$a$] reaches 3.5 ÷ 4.5 (mm/s²). At the time, It is necessary to stop the machine and adjust restoring preload of the spindle bearing to maintain the machining accuracy and reliability as designed. In other words, the spindle has been restored during the maintenance and repair cycle.

Equations (9) and (10) show that the limit value of RMS vibration characteristics *[a]* and time $T_h$ to adjust the restoring preload depend on load *P* and rotation speed *n*; but the limit value [*a*] depends on load *P* more than rotation speed n and time $T_h$ depends on rotation speed n more than load *P*.

The method and experimental results obtained on the Eclipse 300 CNC lathe under laboratory conditions, based on the [$\delta$] according to ISO 10816, can be referenced for RMS vibration characteristics determination studies [*a*] and adjustment time $T_h$ for CNC machines in general.

## 4. CONCLUSION

The study to evaluate the total wear and characteristic vibration of the CNC lathe spindle was conducted to draw the following conclusions:

1. The method of determining total wear and RMS characteristic vibration allows the quality supervision of the Eclipse 300 CNC Lathe spindle bearing under normal work conditions. It can indicate the timing of adjustment of the Spindle bearing during the duty cycle to maintain the working quality of the CNC machine.
2. There is a limited value [*a*] of RMS vibration characteristics on the CNC machine tool spindle bearing in the no-load state. At this value, the machine tool spindle bearing needs adjusting the preload to restore machining accuracy during the normal working period.
3. The limited value [*a*] of RMS vibration characteristics and time $T_h$ adjustment preload of CNC machine tool spindle bearing depend on the pairs of load *P* and rotation speed *n*, but It is in reverse order.
4. The permissible limit value [*a*] of RMS vibration characteristics of the CNC machine tool spindle bearing is directly related to the allowable displacement amount [$\delta$] of the main bearing assembly by ISO standards.

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