

An experimental method for determining the service life and reliability of the CNC lathe main spindle bearing assembly

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Abstract. The main spindle bearing assembly (MSBA) plays an important role in the quality and service life of CNC machine tools and industrial equipment. The MSBA is usually evaluated based on the allowable wear or the stiffness independently combined with the vibration characteristics. Therefore, it is very important to determine the service life of MSBA when the wear reaches the allowable value, and the stiffness is reduced to the allowable value. This paper studies the simultaneous relationship of wear, stiffness, and vibration characteristics of MSBA in a CNC lathe. The results show that the service life of MSBA is different when evaluated based on each criterion (wear or stiffness). The stiffness of the MSBA is reduced to the allowable limit $[J] = 200 \text{ N}/\mu\text{m}$ with a Root Mean Square (RMS) value of about 5.75 mm/s^2 . The wear of the MSBA reaches the allowable limit $[\delta_a] = 5 \mu\text{m}$ with an RMS value of about 4.5 mm/s^2 . The life of MSBA calculated according to the stiffness criterion is about 1.18 times higher than that calculated based on the wear criterion. The average life of MSBA with standard lubrication according to the wear criterion reaches $\sim 15,799 \text{ h}$ and RMS reaches $\sim 2.4508 \text{ mm/s}^2$.

Keywords: CNC machine spindle / stiffness of CNC machine tool spindle / wear of bearing / bearing vibration

1 Introduction

One of the crucial modulators of machine tools that supply the necessary power for the cutting process is the main spindle bearing assembly (MSBA) [1]. High accuracy, wide speed range, high stiffness, vibration reduction, and temperature stability are essential for the MSBA of the CNC machine tool [2]. To attain initial stiffness, preload for the main bearing must be set. The functioning quality of the entire spindle assembly is dependent on the technical state of the bearing spindle, as demonstrated by Abe et al. [3]. Therefore, MSBA usually uses high-precision bearings to enhance working accuracy [4].

In practice, the stiffness of the MSBA is often used to evaluate the machining accuracy. Preload of the spindle bearing decreases as total wear increases. The limit value of the total wear of the spindle bearing is defined by ISO 13041-1:2004 [5], and it is difficult to check the wear of the spindle bearing during the machine-tool work. When the total wear of the main spindle bearing reaches a limit value, the preload of the spindle bearing needs to be restored to its original stiffness. The stiffness of MSBA in a CNC lathe

depends on the preload value and the selection of different configurations of the main bearing. Šarenac [6] selected the optimal structure for the bearing for the main shaft assembly, thereby ensuring the required stiffness for the main shaft assembly and improving the machining accuracy. Prakosa et al. [7] found that preload setting, bearing spacing, and the number of bearings could increase the stiffness of the main bearing assembly. Holroyd et al. [8] found that the option of integrating the bearing assemblies determines the relationship between the stiffness and the vibration of the main shaft assembly. During operation, the MSBA of the CNC machine is worn down over time, so the preload is reduced, leading to a decrease in the initial stiffness of the MSBA [8]. The stiffness of MSBA was reduced due to the wear of the main bearing assembly under external load conditions [9]. Li et al. [10] showed that preload of MSBA depends on the total wear value while operating the machine and it has a great influence on the dynamic and thermal characteristics. By subdividing preload, Duong et al. [11] suggested a way to decrease the friction loss of the mini-CNC lathe spindle unit. The axial displacement for preload is split in half on a class B basis [11]. Hung et al. [12] have determined the life and reliability of the MSBA under random loads based on the allowable stiffness and it increases by $\sim 15\%$ compared to

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the case calculated according to the total axial wear [12]. Accurately measuring the wear of MSBA is usually procedure manual and time-consuming process. It is usually only checking the total wear of the spindle bearing when the CNC machine tool is stopped. The CNC machine tools need to be maintained stable working accuracy for long periods with mandatory bearing adjustment cycles. It can eliminate the gap caused by the wear of the bearing assembly during operation and restore the original preload [13].

Currently, vibration analysis technology is the main method for obtaining information about the internal conditions of the operating machine. It is widely used with advantages such as fast real-time response, high reliability, and reasonable cost when the machine is running [14]. Randall [15] showed that vibration analysis can diagnose the main bearing failure and prevent undesirable consequences of failure. Harris [16] found the relationship between localized 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 [16]. Using the vibration analysis method through the characteristic value of RMS (Root Mean Square) can evaluate the working quality of machine tools and the MSBA of CNC lathes [17]. The formula for calculating RMS [18]:

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

where $x(t)$ is the oscillation acceleration with time. T is the measurement time.

The RMS characteristic value of the vibration is calculated through vibration responses (e.g., the acceleration) acquired by sensor mounted on the flange, and the flange is mounted to the outer groove of the bearing assembly. However, determining the relationship between the RMS characteristics vibration and the working quality of the MSBA on the machine tool still needs to be experimentally practiced for each type of machine tool with specific structures and power grams. Wszolek et al. [19] indicated that can be possible to survey the condition of MSBA rotation using vibration analysis synchronously (with RMS) to measure vibrations on the spindle housing. Mark [20] found that it can be observed typical wear-out mechanisms such as bearings, gears, chains, belts, brushes, shafts, and coils in a machine when using vibration analysis technology [20].

Žarnovský et al. [21] showed that the limited working speed of the CNC Machining Center Spindle is determined based on the vibration value measured according to ISO 10816-3:2009 when using the Adash A4900 vibrio M vibration diagnostic device [21]. Hung et al. [22] indicated that a method to determine the relationship between the wear and RMS vibration characteristics of CNC lathe spindles bearing under variable external load conditions with a limit value of RMS vibration characteristics corresponding to the limit wear value and the estimated time of adjustment T_h [22]. Miao et al. [23] showed that the radial bearing clearance has significant influences on the dynamic behaviors of the CNC vertical milling MSBA when studying the vibration behaviors and the stability of the spindle.

Most of the above research mainly deals with the use of vibration technology to determine the relationship between vibration and wear or vibration and stiffness of MSBA independently. It is all related to the lifespan of the MSBA under varying load and speed conditions. The simultaneous relationships between the lifespan of the MSBA and the three parameters, including stiffness, wear and RMS of vibration have not been fully studied and discussed [23].

This paper presents a result of accelerated wear testing to determine the simultaneous relationship between the three parameters of MSBA related to service life – i.e., stiffness, wear, and RMS vibration characteristics of CNC lathe eclipse 300 under variable external load conditions (without lubrication). The RMS vibration characteristics value corresponds to the limit wear and the limit stiffness of MSBA were different. Therefore, the results of calculating the service life of the MSBA CNC lathe based on the stiffness criterion, and the wear criterion were also different. The average life of the Eclipse 300 CNC lathe MSBA with standard lubrication according to the wear criterion was also calculated.

2 Method for calculating life and reliability of spindle assembly underwear and stiffness

2.1 Calculation of service life, reliability of MSBA on wear amount basis

The graph of wear principles of the friction pair in general and the MSBA in particular [24] is shown in curve 1 (red), Figure 1, which consists of three stages, as follows: the running-in phase (I) where the wear rate gradually decreases to a stability value; the stable wear phase (II) where the wear rate has a constant value. The life expectancy lies mainly in this period; and the intense wear phase (III) where the wear rate speed rapidly increases. Therefore, the machine must be stopped to adjust, repaired, and replace. The diagram for calculating service life and reliability on the wear basis is a linear straight line of the stage (II) that is extended to cut the vertical axis at the a_o .

The wear amount of the main shaft assembly U varies with time (t) [24]. It is assumed to obey the linear law and is expressed by the following equation:

$$U_m = a_{ou} + \gamma_{mu} \cdot t \quad (2)$$

Where U_m —Average wear amount of main bearing assembly over time, a_{ou} —Initial wear amount of main bearing assembly, γ_{mu} —Average wear rate of the main bearing assembly.

The average wear rate can be determined experimentally or calculated using the formula:

$$\gamma_{mu} = k_j \cdot p_m \cdot v_m \rightarrow \gamma_{mu} = k \cdot p_m \cdot n_m \quad (3)$$

where P_m is the average load, v_m is the average speed, n_m is the average rotational speed, k_j and k are the coefficients that can be determined experimentally.

Under normal operating conditions, it can be assumed that the load p and the speed v (or speed n) are two random variables with standard deviations σ_p (N) and σ_v (m/s).

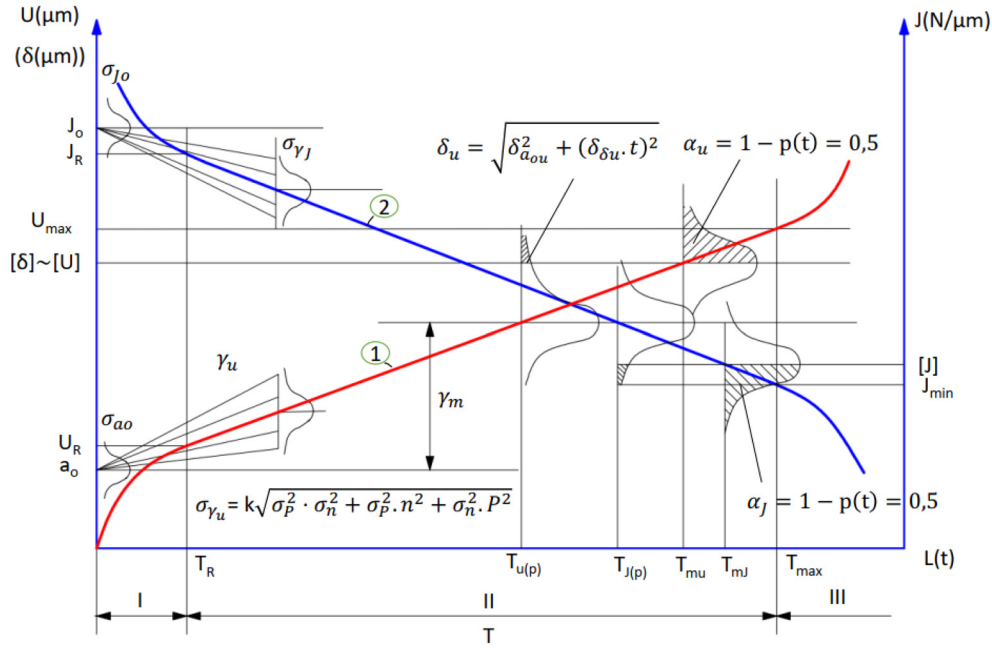


Fig 1. Diagram for calculating service life and reliability according to wear and stiffness.

Thus, the average wear rate is also a random variable that obeys the law of large numbers and has an expected and standard deviation of with the density function $f(\gamma)$ calculated by the formula (4):

$$f(\gamma) = \frac{1}{\sigma_\gamma \sqrt{2\pi}} \exp \left\{ -\frac{[\gamma - \gamma_{mu}]^2}{2\sigma_\gamma^2} \right\} \quad (4)$$

where

$$\sigma_\gamma = \sqrt{D(kpn)} = k \sqrt{\sigma_p^2 \sigma_n^2 + \sigma_p^2 n_m^2 + \sigma_n^2 p_m^2} \quad (5)$$

$$\gamma_{mu} = \frac{U_m}{T} \quad (6)$$

T is the expected lifespan, D is the variance.

The standard deviation of U_m is calculated:

$$\sigma_u = \sqrt{\sigma_{aou}^2 + \sigma_\gamma^2 T^2}. \quad (7)$$

The probability of failure-free operation of the spindle bearing assembly $P(t)$ is calculated according to the wear amount U at the time $t = T$. This amount corresponds to the area under the probability density curve of $U: f(U)$ and lies in the interval $a_{ou} \leq U \leq [U]$. The probability of working without failure $P(t)$ – characterizing the ability to work continuously, is calculated through the Laplace operator [24] as follows:

$$P(t) = 0.5 + \varphi \left[\frac{[U] - a_{ou} - \gamma_{mu} \cdot T}{\sqrt{\sigma_{aou}^2 + \sigma_\gamma^2 T^2}} \right] \quad (8)$$

where φ – Laplace operator, σ_{aou} – Standard deviation of initial wear amount, σ_γ – Standard deviation of wear rate, $[U]$ – Allowable limit wear amount.

The life equation T depends the reliability based on wear amount will be:

$$U_\alpha \left(\sqrt{\sigma_{aou}^2 + \sigma_\gamma^2 \cdot T^2} \right) = [U] - a_{ou} - \gamma_{mu} \cdot T \quad (9)$$

where $[U]$ – Allowable limit wear amount, U_α – The argument of the Laplace function, whose value depends on the confidence $P(t)$.

Equation (9) in principle has two solutions T_{1u} and T_{2u} , but the confidence level of 50% is the smallest, so the solution of this equation must be in the range $T_r < T < T_m$. The average lifetime T_m of the main bearing assembly when the allowable limit wear amount is $[U]$ will be determined by the formula:

$$T_m = \frac{[U] - a_{ou}}{\gamma_{mu}}. \quad (10)$$

2.2 Calculation of service life, reliability of MSBA on stiffness basis

According to ISO 13041-1 standard [5], the MSBA's stiffness J has been determined according to the formula:

$$J = \frac{F_r}{y} \text{ (N/}\mu\text{m)} \quad (11)$$

where F_r – radial force acting, y – displacement of MSBA in the radial direction.

Based on the method of calculating the service life and reliability of MSBA according to the wear amount above, it is possible to assume the law of changing stiffness J over time or the friction distance as depicted in curve 2 (blue) in Figure 1. In the condition of normal working, it includes three stages: In the running-in stage (I), the decreasing rate of stiffness decreases gradually. In the stability stage (II), the decreased rate of stiffness has a constant value, and the life expectancy lies mainly in this period. Lastly, the stiffness stage rapidly reduces (III). In this stage, the decrease rate of stiffness very strong increase, thus the machine must be stopped to adjust, repair, and replace.

The stiffness of MSBA J changes with time (t) and is also assumed to obey the linear law and is expressed by the following equation:

$$J_m = J_o + \gamma_{mj} \cdot t \quad (12)$$

where J_m is the average stiffness of main bearing assembly over time, J_o is the initial stiffness of main bearing assembly, and γ_{mj} is the average stiffness's decrease rate of the main bearing assembly ($\gamma_{mj} < 0$).

Like the wear rate, the average reduction rate of stiffness γ_{mj} over time can be calculated by the equation (13):

$$\gamma_{mj} = k_J \cdot p_m \cdot v_m \rightarrow \gamma_{mj} = k \cdot p_m \cdot n_m \quad (13)$$

where k_J and k are the coefficients that can be determined experimentally (k_J vs $k < 0$).

The stiffness's decrease rate is also a random variable that obeys the law of large numbers, the expected normal distribution γ_{mj} has standard deviation σ_γ with the density function $f(\gamma)$ calculated by the formula:

$$f(\gamma) = \frac{1}{\sigma_\gamma \sqrt{2\pi}} \exp \left\{ -\frac{[\gamma - \gamma_{mj}]^2}{2\sigma_\gamma^2} \right\}, \quad (14)$$

where:

$$\sigma_\gamma = \sqrt{D(kpn)} = k \sqrt{\sigma_p^2 \sigma_n^2 + \sigma_p^2 n_m^2 + \sigma_n^2 p_m^2}, \quad (15)$$

$$\gamma_{mj} = \frac{J_m}{T}. \quad (16)$$

The standard deviation of J_m is calculated:

$$\sigma_J = \sqrt{\sigma_{J_o}^2 + \sigma_\gamma^2 \cdot T^2}. \quad (17)$$

The probability of failure-free operation of the spindle bearing assembly $P(t)$, at time $t = T$ and calculated according to stiffness J , is equal to the area under the probability density curve of J : $f(J)$ lies in the interval $[J] \leq J \leq J_o$ (curve 2 in Fig. 1), and it is calculated through Laplace operator as follows:

$$P(t) = 0.5 + \varphi \left[\frac{[J] - J_o - \gamma_J \cdot T}{\sqrt{\sigma_{J_o}^2 + \sigma_\gamma^2 \cdot T^2}} \right], \quad (18)$$

where σ_{J_o} – Standard deviation of initial stiffness, σ_γ – Standard deviation of stiffness's decrease rate, $[J]$ – Allowable limit stiffness.

The life equation T depends on the reliability based on stiffness will be:

$$U_\alpha \left(\sqrt{\sigma_{J_o}^2 + \sigma_\gamma^2 T^2} \right) = [J] - J_o - \gamma_J T, \quad (19)$$

where U_α is the argument of the Laplace function, whose value depends on the confidence $P(t)$: $[J] - J_o < 0$ and $\gamma_J < 0$.

In principle, equation (19) also has two solutions T_{1J} and T_{2J} , but the 50% confidence level is the smallest. Therefore, the solution of this equation must be in the range $T_r < T_J < T_{mJ}$. The average service life T_{mJ} of the MSBA with the allowable limit stiffness $[J]$ will be determined by the formula:

$$T_{mJ} = \frac{[J] - J_o}{\gamma_{mj}}. \quad (20)$$

2.3 Experimental apparatus and method

To be able to simultaneously investigate the following parameters – wear amount, stiffness, and RMS vibration characteristic, and calculate the life and reliability of MSBA when external load changes, the experimental equipment system is shown in Figure 2. Based on the principle of vibration and total wear measurement of the lathe MSBA [5,25], this experimental equipment system is set up directly on the CNC lathe Eclipse 300 spindles [22].

In this system, two pneumatic cylinders are used to generate axial and radial forces. It is adjusted to produce a force corresponding to the cutting force. The experiment was conducted in a non-lubricant condition. A pneumatic cooling system is used to make sure the main bearing assembly's temperature is less than 60°C. The total amount of wear is determined according to the standard ISO 13041-1:2004 [5]. The Mitutoyo 1/1000 mm, with a range of 0 ÷ 0.14 mm is used to measure the axial and radial displacement. Vibration is measured as standard ISO/TR 1086-1 [25]. The SKF microlog CMX-A44 vibration meter is used to monitor the parameter RMS of the spindle bearing in the experiment.

The basic technical parameters of the experiments are shown in Table 1. The experiments about wear amount, stiffness, and RMS of spindle bearing were done with external load and speed according to Table 2. The experimental apparatus is shown in Figure 3.

Each set of test parameters uses a new pair of bearings. The time for each stop of the test equipment to get data on wear amount, stiffness, and RMS was 6, 12, 18, 24, 30, 36, 42, and 48 h. Using SKF's Microlog Analysis software to determine RMS vibration characteristics parameters, the calculation results are performed on Matlab software, as shown in Figure 4. After that we build a graph of wear amount U , stiffness J , and

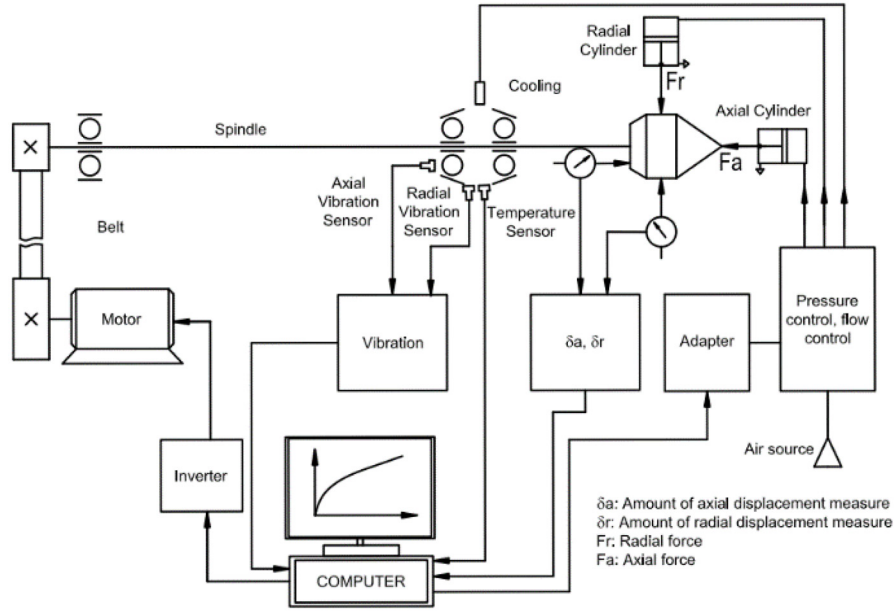


Fig. 2. A schematic view of the experimental apparatus.

Table 1. The basic technical parameters of the experiments [20].

No.	Parameter	Value
1	Bearing type	7210B, NSK
2	Spindle speed, n (rpm)	1800, 2000, 2200
3	Equivalent load Load, P (N)	1310, 1915, 2520
4	Lubrication	No
5	Period (h)	6
6	Number of periods	$5 \div 8$
7	Cooling, Compressed air requirement	$T < 60^\circ \text{C}$

RMS over time. From the graph of wear amount U , stiffness J , and RMS over time, the wear rate γ_u and γ_J will be determined.

3 Result and discussion

3.1 The experiments without lubrication (accelerated wear testing)

For each experiment ($1 \div 5$), the axial displacement $U(\delta, \mu\text{m})$, stiffness J ($\text{N}/\mu\text{m}$), and RMS vibration characteristics (a , mm/s^2) of spindle bearing were measured with time step 6 h, as shown in Table 4. The axial displacement is determined with the standard axial preload (axial force $F_a = 250 \text{ N}$). The RMS vibration characteristics are determined with $P = 0$, and n corresponds to each experiment. The results are shown in Table 3.

The graphs of wear amount U , stiffness J , RMS over time with allowable limit wear amount $[U]$, allowable limit stiffness $[J]$, and the limit value of RMS vibration

Table 2. Experimental parameters [20].

Parameters	Exp1	Exp2	Exp3	Exp4	Exp5
P (N)	1310	2520	1310	2520	1915
n (rpm)	1800	1800	2200	2200	2000

characteristics $[a]$ of the Eclipse 300 CNC lathe spindle at different loading modes P and n are showed in Figure 5.

Figure 5 shows that the stiffness and total wear amount of the Eclipse 300 CNC lathe spindle assembly are linearly dependent on the working time. However, the stiffness and total wear amount of the MSBA varied in opposite directions with time. As the total wear increases linearly with the working time, the stiffness also decreases linearly, indicating that the main cause of the decrease in stiffness of the main shaft is the wear of the main bearing assembly.

Based on the limit wear $[U]$ according to ISO 10816 standard, the value of limit vibration $[a]$ and the lifetime T_U of MSBA is completely determined. When the value of axial wear increases to the allowable limit value $[U]$, the vibration value on the main bearing assembly is at ~ 4.5 (mm/s^2 RMS), this is the time to stop. The machine adjusts the preload of the spindle assembly to maintain the machining accuracy and reliability as designed.

On the other hand, over working time, the spindle stiffness will be reduced. Based on the limited stiffness $[J]$, it is possible to determine the value of limit vibration $[a]$ and determine lifetime of MSBA T_J – the time to stop the machine for adjustment, maintenance, and restoration. When the stiffness of the main bearing assembly decreases to the allowable limit value $[J]$, the vibration value on the main bearing assembly is at $[a] \sim 5.75 \text{ mm/s}^2$.

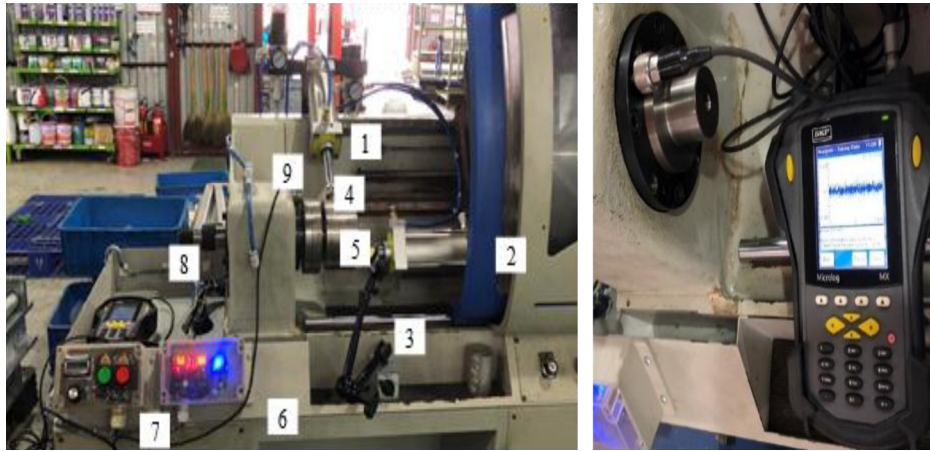


Fig. 3. The experimental apparatus. 1–pneumatic cylinder generates a radial force; 2–pneumatic cylinder generates an axial force; 3–indicator; 4–vibration sensor; 5–spindle bearing; 6–the temperature controller, 7–spindle speed controller, 8–vibration measurement and analysis equipment, 9–pneumatic cooling lines.

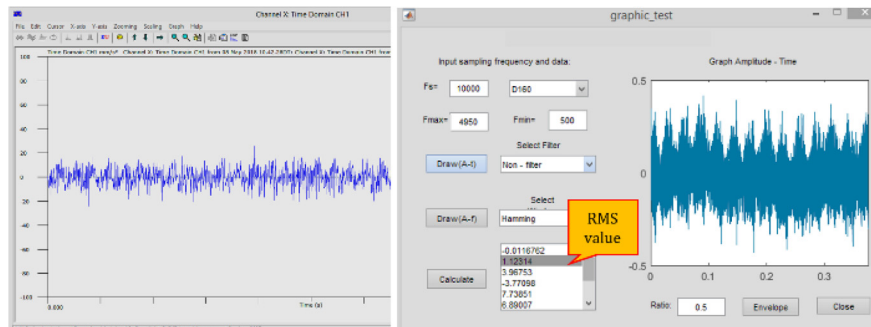


Fig. 4. RMS value when measuring vibration acceleration.

Table 3. Experimental data.

Time (h)	Factor	Exp1	Exp2	Exp3	Exp4	Exp5	Time (h)	Factor	Exp1	Exp2	Exp3	Exp4	Exp5
6	δ (μm)	1	1	1	1	1	30	δ (μm)	4	4	5	6	5
	RMS (mm/s^2)	0.582	0.802	0.868	0.982	0.921		RMS (mm/s^2)	2.405	3.341	3.956	5.986	4.225
	J ($\text{N}/\mu\text{m}$)	352	359	362	348	347		J ($\text{N}/\mu\text{m}$)	246	248	216	199	267
12	δ (μm)	2	2	2	2	2	36	δ (μm)	4	5	6	6	6
	RMS (mm/s^2)	0.753	1.269	1.301	1.626	1.376		RMS (mm/s^2)	2.667	4.31	5.462		5.868
	J ($\text{N}/\mu\text{m}$)	315	327	332	314	340		J ($\text{N}/\mu\text{m}$)	234	225	197		212
18	δ (μm)	2	3	3	3	3	42	δ (μm)	5	6			6
	RMS (mm/s^2)	1.252	1.762	2.206	2.566	2.011		RMS (mm/s^2)	3.576	6.021			
	J ($\text{N}/\mu\text{m}$)	301	310	280	282	308		J ($\text{N}/\mu\text{m}$)	218	200			196
24	δ (μm)	3	4	4	4	4	48	δ (μm)	6				
	RMS (mm/s^2)	1.756	2.492	2.817	3.84	3.195		RMS (mm/s^2)	4.483				
	J ($\text{N}/\mu\text{m}$)	292	289	265	248	276		J ($\text{N}/\mu\text{m}$)	192				

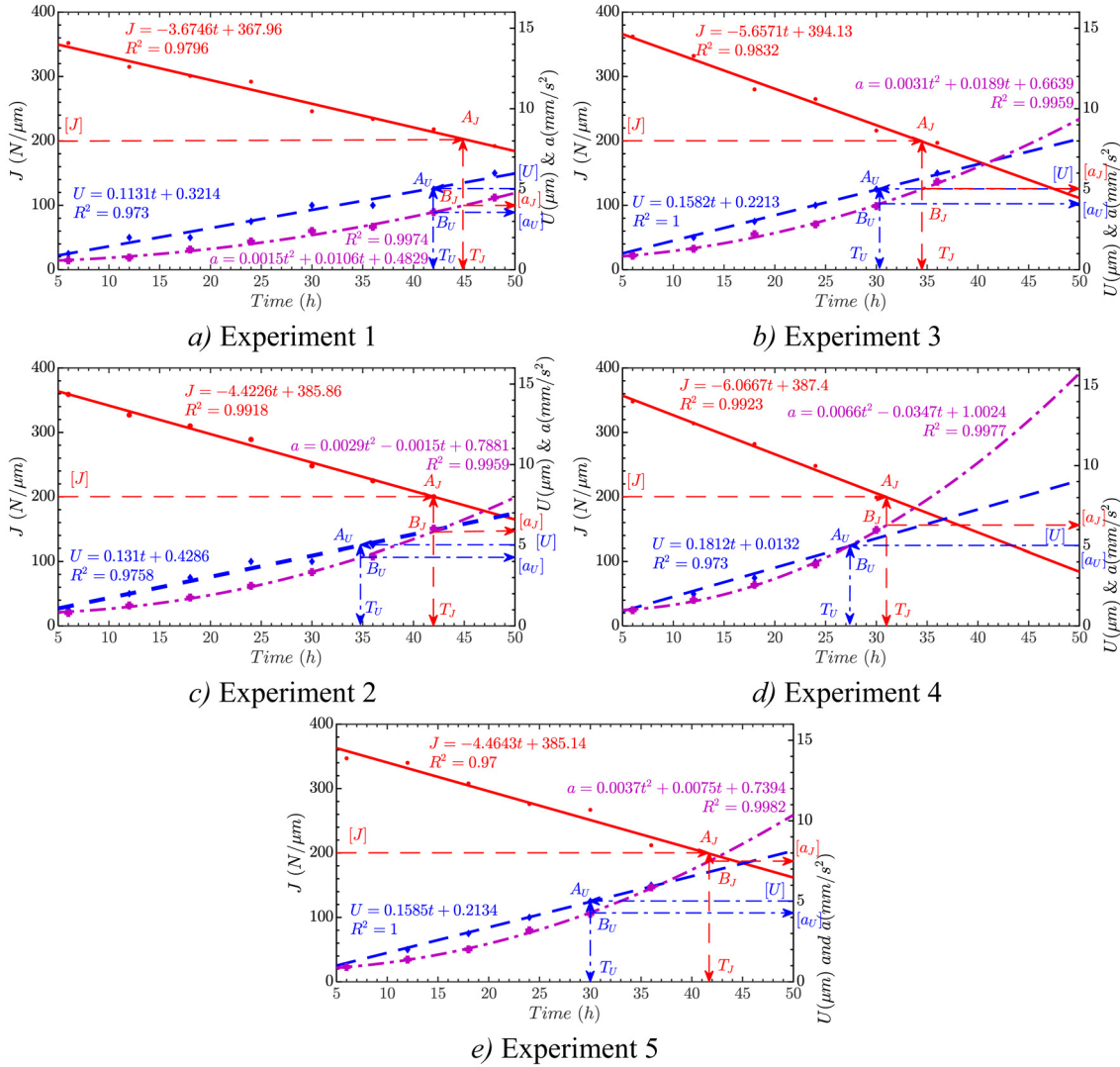


Fig. 5. Graphs of U , J , RMS over time of the Eclipse 300 CNC lathe spindle at different loading modes P and n .

Corresponding to the allowable wear limit value $[U]$ and the residual stiffness limit value $[J]$ of the machine tool, MSBA has different RMS values. The service life of the MSBA has a significant difference of about 1.18 times when determined according to two criteria. Therefore, when monitoring the quality of the spindle assembly, it is easier and more accurate to base it on stiffness than on wear criteria. Because determining the amount of axial displacement of the main bearing assembly due to wear during operation is complicated, the measurement standard is difficult to stabilize over long working hours while determining the stiffening of the spindle assembly in the radial direction is easier.

In practice, the allowable limit value $[a]$ of vibration is an important basis for determining when to stop the machine to adjust the initial tension of the main bearing assembly to the initial state or in other words main shaft assembly that has been restored the during the maintenance and repair cycle.

3.2 The experiments with standard lubrication

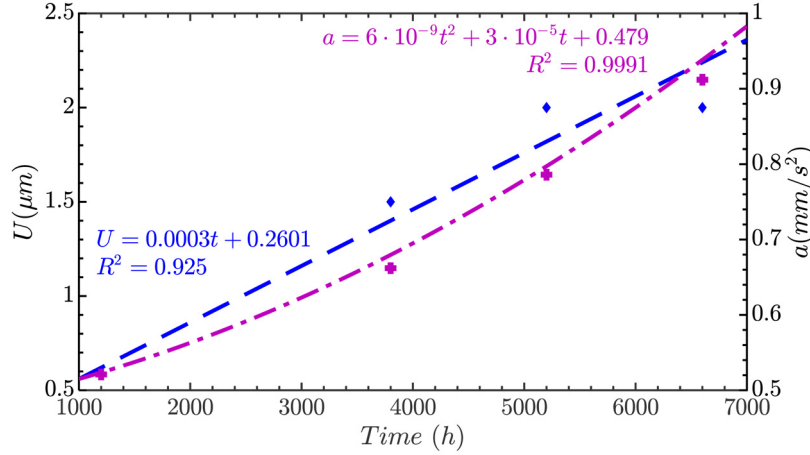
A standard lubrication test of MSBA was performed with two experimental parameters: P_m and n_m (center other f experiments). The wear amount of the CNC lathe MSBA is linear over time in the steady stage. Determining at least two wear amounts at two times with a sufficiently large time interval outside the run-in stage will build a graph and a wear amount equation. The results of data processing will determine the initial wear amount of MSBA a_{ouL} , and the average wear rate of MSBA γ_{muL} . The wear amount and RMS values for this case are given in Table 4. The graphs and equations of wear amount and RMS are shown in Figure 6.

3.3 The average service life of the Eclipse 300 CNC lathe spindle assembly

The calculation of the average service life of the Eclipse 300 CNC lathe spindle assembly is based on the following data: the average rotational speed $n_m = 2000$ rpm, sample

Table 4. The wear amount and RMS values of experiments Exp6 (P_m and $n_m \sim$ Exp5) with lubrication.

Time (h)	1200	3800	5200	6600
Wear amount (μm)	0.5	1.5	2	2
RMS (mm/s^2)	0.521	0.662	0.786	0.912

**Fig. 6.** Graphs and equations of wear amount and RMS with lubrication.

standard deviation $S_n = 200$, the average load $P_m = 1915$ N, and the sample standard deviation $S_p = 605$.

3.3.1 Determining the parameter from the graphs and equations of wear amount over time with accelerated wear testing

The initial wear amount of main bearing assembly $a_{ou} = 0.23958$, $S_{ao} = 0.15386$, $D_{ao} = 0.023671$. The average wear rate of the main bearing the assembly $\gamma_{mu} = 0.1484$, standard deviation $S_{yu} = 0.026565$, $D_{yu} = 0.0007$.

From formula (3), the wear coefficient k_u can be calculated:

$$k_u = \gamma_{mu} / p_m \cdot n_m = 3.87467\text{E}-08.$$

The average life of the spindle of Eclipse 300 CNC lathe spindle is calculated according to the wear criterion with the formula (10):

$$T_{mu} = \frac{[U] - a_{ou}}{\gamma_{mu}} = 32.1\text{h} \quad \text{and} \quad \text{RMS}_{mu} \sim 4.4434 \text{ mm/s}^2.$$

The probability of failure-free operation of the spindle bearing assembly $P(t) = 90\%$, 95% . The argument of the Laplace function, whose value depends on the confidence $P(t)$ so that $U_\alpha = 1.28$; 1.64 . Substituting U_α values into equation (9), the service life of the Eclipse 300 CNC lathe spindle under laboratory conditions is as follows:

$$T_{U,P(90\%)} \sim 25.73\text{h} \text{ and } \text{RMS}_{U,P(90\%)} \sim 3. \text{ mm/s}^2, \\ T_{U,P(95\%)} \sim 24.59\text{h} \text{ and } \text{RMS}_{U,P(95\%)} \sim 2.9185 \text{ mm/s}^2.$$

3.3.2 Determining the parameter from the graphs and equations of stiffness over time with accelerated wear testing

The initial stiffness of main bearing assembly $J_o = 384.098$, $S_{Jo} = 9.69755$, $D_{Jo} = 94.04242$. The average stiffness's decrease rate of main bearing assembly $\gamma_{mj} = -4.85706$, $S_{\gamma j} = 0.980372$, $D_{\gamma j} = 0.96113$.

From formula (13), the wear coefficient k_j can be calculated:

$$k_j = \gamma_{mj} / p_m \cdot n_m = -4.85706 / (2000 * 1915) \\ = -1.26816\text{E}-06.$$

The average life of the spindle of Eclipse 300 CNC lathe spindle is calculated according to the stiffness criterion with the formula (20):

$$T_{mj} = \frac{[J] - J_0}{\gamma_{mj}} = 37.9\text{h} \quad \text{and} \quad \text{RMS}_{mj} \sim 5.8959 \text{ mm/s}^2.$$

The probability of failure-free operation of the MSBA $P(t) = 90\%$, 95% . The argument of the Laplace function, whose value depends on the confidence $P(t)$ so that $U_\alpha = 1.28$; 1.64 . Substituting U_α values into equation (19). The service life of the Eclipse 300 CNC lathe spindle under laboratory conditions is as follows:

$$T_{J,P(90\%)} \sim 29.81\text{h} \text{ and } \text{RMS}_{J,P(90\%)} \sim 3.9358 \text{ mm/s}^2, \\ T_{J,P(95\%)} \sim 28.07\text{h} \text{ and } \text{RMS}_{J,P(95\%)} \sim 3.5752 \text{ mm/s}^2.$$

3.3.3 Determining the parameter from the graphs and equations of the experiments with standard lubrication

The initial wear amount of the main spindle bearing assembly $a_{ou} = 0.2601$. The wear rate of the main bearing assembly $\gamma_{mu} = 0.0002$. The average life of the MSBA of the Eclipse 300 CNC lathe is calculated with standard lubrication according to the wear criterion with the formula (10):

$$T_{mul} = 15799.7 \text{ h} \quad \text{and} \quad \text{RMS}_{mul} \sim 2.4508 \text{ mm/s}^2.$$

The coefficient between the standard lubricated and accelerated wear testing service life at the experimental center is determined by:

$$K_{LUL} = \frac{T_{mul}}{T_{mu}} = 492.5.$$

The coefficient between service life according to stiffness and wear at the experimental center in the accelerated wear testing's condition is determined by:

$$K_{JW} = \frac{T_{mj}}{T_{mu}} = 1.18.$$

In the accelerated wear testing's condition, the cooling of the compressed air $T < 60^\circ\text{C}$, the MSBA's service life with the probability of failure-free operation is 90% according to the wear criteria $T_{uP(90)} = 80.2\% T_{mu}$ and the stiffness criterion $T_{JP(90)} = 78.6\% T_{mj}$. Thus, the service life of the MSBA can be expected with a failure-free probability $P(t) = 90\%$ under standard lubrication conditions $T_{uL, P(90\%)}$:

$$T_{uL, P(90\%)} \sim 80\% T_{muL} = 12\,639 \text{ h} \quad \text{and} \quad \text{RMS}_{uL, P(90\%)} \sim 2.0695 \text{ mm/s}^2$$

The method of calculating the service life and reliability of the machine tool CNC MSBA is based on the wear criterion or the stiffness criterion. It allows determining that the service life depends on reliability. The average lifespan T_m was determined with failure-free probability $P(t) = 50\%$ and the service life $T_{P(t)}$ according to the failure-free probability $P(t) = 90\%$.

The average lifespan of the Eclipse 300 CNC lathe MSBA under standard lubrication and external load conditions at experimental center $T_{mul} = 15799.7 \text{ h}$. Thus, the average lifespan under standard lubrication is approximately 492 times greater than that of accelerated wear testing but air-cooled with $T < 60^\circ\text{C}$. The expected life of Eclipse 300 CNC lathe MSBA under standard lubrication and experimental center load with failure-free probability $P(t) = 90\%$: $T_{uL(90)} \sim 12639 \text{ h}$.

The average lifespan of the Eclipse 300 CNC lathe MSBA in the case of standard lubrication, the RMS value is about 55% of the acceleration test. In the case of standard lubrication, service Life with failure-free probability $P(t) = 90\%$, the RMS value is about 66% of that of the accelerated wear testing. This shows that the lubricating oil film has significantly reduced the vibration of the MSBA. This can be the basis for determining the RMS

value corresponding to the average life of a standard lubricated CNC machine spindle assembly when there is an accelerated wear RMS test data.

4 Conclusions

The main conclusion of the study on determining the service life and reliability of CNC lathe machine to spindle based on wear amount, stiffness, and RMS vibration characteristics in accelerated wear testing and standard lubrication can be drawn as follows:

- A method has been proposed to determine the vibration characteristic limit (RMS) of the main bearing assembly based on the limited wear and stiffness of the main bearing assembly. This value is the basis for determining the time to adjust and maintain the working quality of machine tools in general and CNC machine tools in particular.
- The expected life of spindle assembly in an accelerated wear test can be calculated according to 2 criteria of wear and stiffness, and it has a difference of 1.18 times. It is easier and more accurate to monitor the quality of the spindle assembly based on permissible stiffness and RMS.
- When standard lubrication, the vibration value of the main bearing assembly is reduced by 55–66% compared to the case of no lubrication. The average expected life of the MSBA of Eclipse 300 CNC lathe in standard lubrication conditions $T_{mul} = 15799.7 \text{ h}$. It is approximately the same as the supplier's declared service life zone.
- This research method can be applied to CNC machine tools in particular and industrial equipment in general. It reduces research, and testing time and determines life expectancy following reliability through RMS data income of operation machines and RMS data collection on accelerated test equipment.

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