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Design of Accelerated Reliability Test for CNC Motorized Spindle Based on Vibration Signal

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Abstract. Motorized spindle is the key functional component of CNC machining centers which is a mechatronics system with long life and high reliability. The reliability test cycle of motorized spindle is too long and infeasible. This paper proposes a new accelerated test for reliability evaluation of motorized spindle. By field reliability test, authors collect and calculate the load data including rotational speed, cutting force and torque. Load spectrum distribution law is analyzed. And authors design a test platform to apply the load spectrum. A new method to define the fuzzy acceleration factor based on the vibration signal is proposed. Then the whole test plan of accelerated reliability test is done.

1 Introduction

Motorized spindle is the key functional component of CNC machining centers and is the typical device for high speed machining [1, 2]. The machining accuracy and machining efficiency of CNC machining centers are largely determined by motorized spindle. So it's necessary to test the reliability of motorized spindle. However, traditional reliability test must take long time and more samples to test products' performance [3]. As motorized spindle has long life, high precision and reliability, its reliability test may not only take a long time, but also increase the time and cost of development. Although it takes so long time, it rarely gets much failure data. So it's necessary to design accelerated life test for motorized spindle reliability. Accelerated life test is a stress testing methodology for accelerating product reliability by subjecting it to conditions (stress, vibration, load etc.) to uncover faults and potential failure modes in a short time [4-6]. Through the test data, MTBF of the normal field life and maintenance intervals of a product can be predicted. Accelerated life test is supposed to only change the failure rate without changing the failure mechanism of motorized spindle [7]. But as a complex electromechanical system, motorized spindle has several subsystems and multifarious failure mechanism [8, 9] which severely limits the design of accelerated reliability test for motorized spindle. Great effort will be taken to make an effective relationship model between failure rate in high load condition and normal load condition.

For the accelerated reliability test of motorized spindle, there are three main challenges. First, there is scarcity of real load spectrum data of motorized spindle in working condition. Secondly, it's difficult to build loading condition of motorized spindle in lab without changing the failure mechanism. Thirdly, it's extremely hare to determine the accelerating factor. For above 3 points, authors propose a practical and effective solution.

The rest of the article is organized as follows: a brief introduction to the motorized spindle is provided in Section 2. Section 3 introduces the load data acquisition from field reliability test in factory, such as workpiece material, cutting condition, cutting parameter and so on. Then load spectrum including rotating speed, cutting force and torque are calculated by cutting force formula in Section 4. In the following section, authors build simulation test platform of the motorized spindle for loading spectrum of accelerated reliability test. Next authors proposes a method to make sure the fuzzy acceleration factor and determine the accelerating load of accelerated reliability test for motorized spindle in Section 6. At this point, the design of accelerated reliability test for motorized spindle is finished. At last, a short conclusion is drawn.

2 Structure of motorized spindle

Motorized spindle combines the structures of frequency conversion motor and mechanical spindle in machining centers. The shell of motorized spindle is the stator of frequency conversion motor. The rotor of motor is the spindle and gripper [10]. It implements 'zero-drive chain' between motor and spindle. Motorized spindle has compact structure, light weight, small rotational inertia and outstanding dynamic characteristics. Motorized spindle consists of spindle shell, drive cooling, stator, rotor, bearing, lubrication module, power module, rotary feedthrough and detection module and so on. Its structure is shown in Figure 1.

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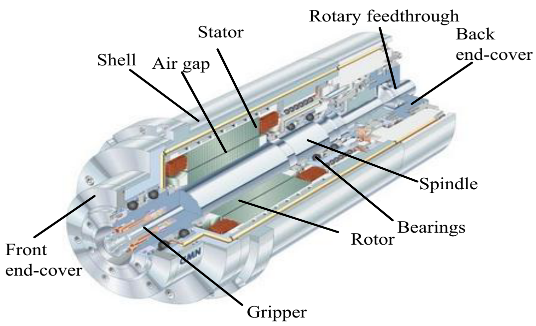

Figure 1. The structure of motorized spindle.

3 Load data acquisition

Load should be a generalized concept, such as force, torque, displacement, stress and strain, etc. Load spectrum of motorized spindle refers to the time-domain distribution of the load. Through statistics and analysis of the actual load data which is complex, chaotic in working conditions, load spectrum are shown in certain figures, tables or mathematical expressions [11].

To get the load data of motorized spindle in working condition, authors went to customers' enterprise using certain type CNC machining centers and carried out a large number of field reliability test for more than 3000h. The load data includes process data, cutting dosage, rotational speed of typical components. The load data acquisition form is shown in Table 1. As the blank materials and processing type of components are widely different, the load data have big differences. In order to facilitate the calculation, load data must be preprocessing. For instance, some processing steps rarely appear. And some processing steps, such as the chamfering process, need small cutting force, so the impact on motorized spindle is very tinny which has little significance for reliability research of spindle. These data cannot serve as the main basis for the reliability study of motorized spindle, only be used as auxiliary. Thus, in data preprocessing, these date should be removed. Then, by analyzing the processing, the load data after preprocessing can be used to calculate the cutting force and torque of motorized spindle in CNC machining centers.

Table 1. Load data acquisition form.

No.	1	2	3	4	…
Material of workpiece	Aluminum alloy	Aluminium alloy	Aluminium alloy	Aluminium alloy	
Process content	Rough milling convex	Precision milling convex	Precision milling gap	Countersink hole 68- ϕ16	…
Cutter	ϕ12 milling cutter	ϕ6 milling cutter	ϕ2.2 ball end mill	ϕ12 R0.9 milling cutter	…
Cutter material	Cemented carbide	Cemented carbide	Cemented carbide	Cemented carbide	…
Cutter type	End milling cutter	End milling cutter	End milling cutter	End milling cutter	…
Tool cutting edge angle K_r	90°	90°		90°	…
Rotational speed n(r/min)	800	900	3000	500	…
Feed speed V_c (mm/min)	36	40	10	48	…
Cutting depth a_p (mm)	3.5	0.5	1.59	3	…
Process redundancy h (mm)			1.6	3	…
Feed f(mm/r)	0.045	0.044444	0.003333	0.096	…
Feed per tooth f_z (mm/r)	0.01125	0.011111	0.001667	0.024	…
Cutting width a_e (mm)	12	6	2.2	16	…
Tool diameter d (mm)	12	6	2.2	12	…
Tool teeth z	4	4	2	4	…
Cutter life	60	60	66	60	…
Processing time t (min)	60	60	63	60	…

4 Load spectrum calculation and statistics

4.1 The calculation of cutting force

Motorized spindles in CNC machining centers include high-frequency/high-speed one and intermediate frequency one. When rough machining, the motorized spindle generally works at low or intermediate frequency. According to the previous data and experience, the force status of the motorized spindle is similar to turning. The decomposition and synthesis of cutting force is shown in Figure 2. And the key parameters of cutting fore are shown in Table 2.

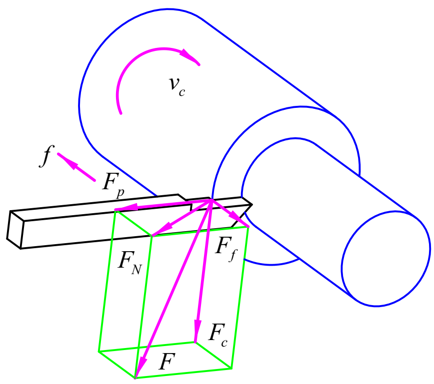

Figure 2. Cutting force of low/intermediate frequency motorized spindle.

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Table 2. Key parameters of cutting force.

Symbol	Description	Unit	Direction
F_c	Main cutting force	N	Main cutting direction, tangential to transition surface, vertical to the base plane
F_p	Back force	N	Tangential to the base plane, vertical to the axis of workpiece
F_f	Feed force	N	Tangential to the base plane, opposite to the cutter forward direction

The decomposition of forces and power are expressed as follows [12]:

$$F_c = C_{F_c} a_P^{x_{F_c}} f^{y_{F_c}} v^{\eta_{F_c}} K_{F_c} \tag{1}$$

$$F_p = C_{F_p} a_P^{x_{F_p}} f^{y_{F_p}} v^{\eta_{F_p}} K_{F_p} \tag{2}$$

$$F_f = C_{F_f} a_P^{x_{F_f}} f^{y_{F_f}} v^{\eta_{F_f}} K_{F_f} \tag{3}$$

$$P_z = F_z v \times 10^{-3} \tag{4}$$

where P_z is the power of CNC machining center; K_{F_c} is the correction factor of cutting force, v is the milling speed, m/s; C_{F_c}, C_{F_p} and C_{F_f} are the coefficient determined by the workpiece material and cutting condition; x_F, y_F and η_F are the indexes of a_p, f and v.

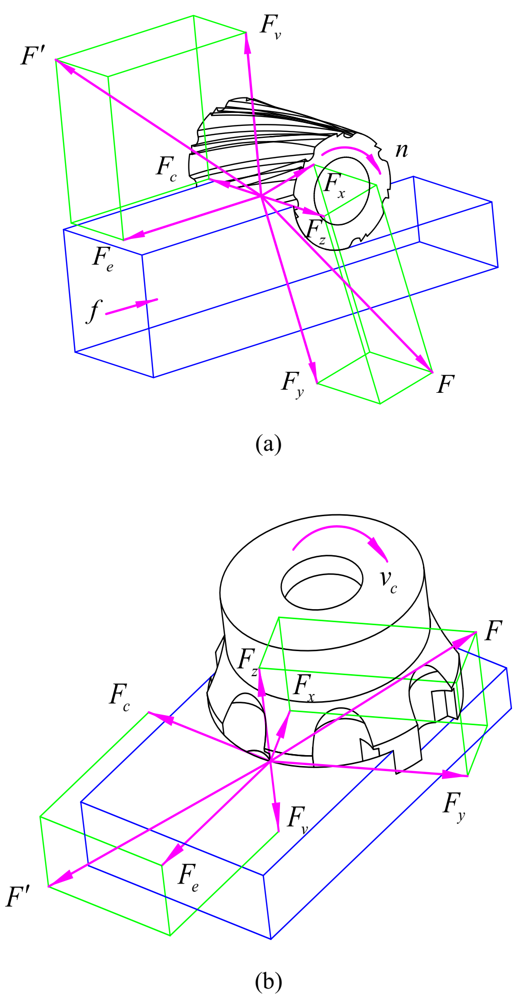


Figure 3. Cutting force of high frequency motorized spindle.

When precision machining, the motorized spindle generally works at high frequency/speed. According to the load data and experience, most of the processing technology is milling. The decomposition and synthesis of cutting force in milling is shown in Figure 3 (a) and (b) are 2 types of milling cutter. And the key parameters of cutting fore are as same as parameters in Table 2.

The milling forces, torque and power are expressed as follows:

$$F_c' = \frac{C_F a_p^{x_F} a_f^{y_F} a_w^{u_F}}{d_0^{q_F} n^{w_F}} k_{F_c} \tag{5}$$

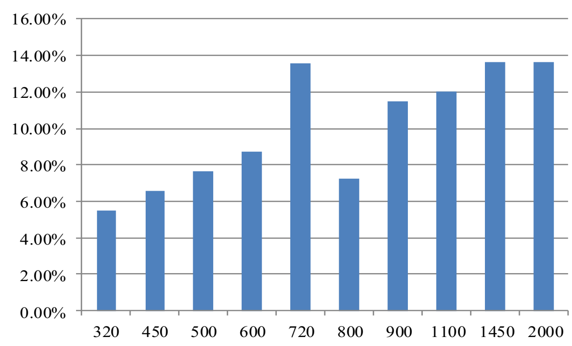
$$M = \frac{F_c' d_0}{2 \times 10^3} \tag{6}$$

$$P_m = \frac{F_c' v}{6 \times 10^4} \tag{7}$$

where, $F_c^{'}$ is the peripheral milling force; C_F is the coefficient determined by the workpiece material and cutting condition; x_F, y_F, u_F, q_F and w_F are the indexes of a_p, a_f, a_w, d_0 and n; k_{F_c} is the correction factor of cutting force; n is the revovling speed; M is the cutting torque; d_0 is the diameter of the milling cutter; P_m is the power of CNC machining center.

4.2 The load spectrum statistic of motorized spindle

According to formulas (1)-(7), based on the data from the field reliability test of certain type CNC machining center, authors calculated the sample data of motorized spindle in work condition. And the results are shown in Table 3. And Figure 4 illustrates the distribution law of rotational speed, torque, radial force and axial force in real work condition.



(a) Rotational speed /rpm

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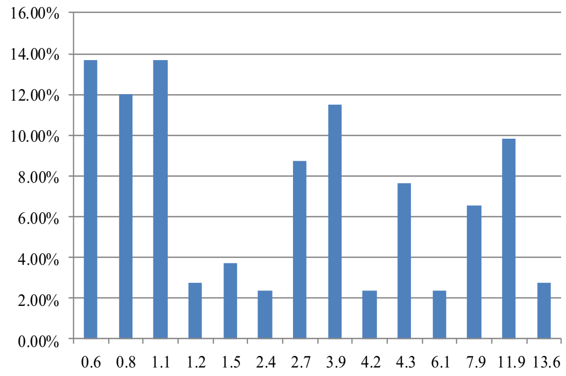
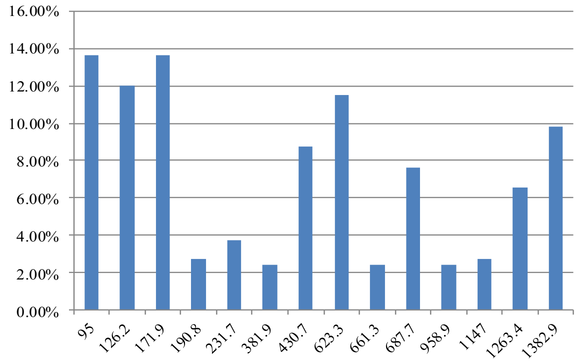
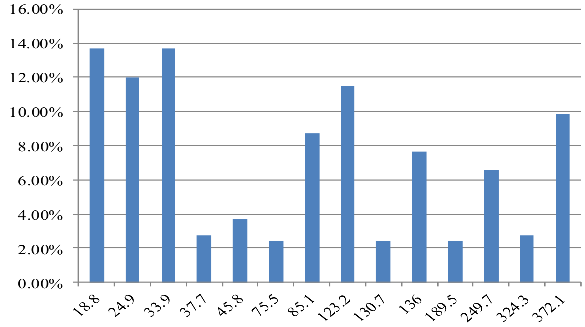


(b) Torque /N



(c) Radial force / N



(d) Axial force /N

Figure 4. The distribution of load spectrum for certain type motorized spindle.

According to Figure 4, the processing time percentage of motorized spindle under light torque (3 Nm) is more than 56%, under light radial force (300N) is 45.79%, and under tiny axial fore (80N) is 48.20%. The percentage of motorized spindle in high speed (larger than 1000rpm) is nearly 40%. Combine with the result in Table 3, they reveals that motorized spindle general works at low-speed-high- force (26%) and high-speed-low-force (39%) conditions. To conduct accelerated reliability test of motorized spindle, the proportion of high-speed-high-force should be increased. Then the reliability test time of motorized spindle will be shorten. In the next section, the fuzzy acceleration factor between normal load condition and high load condition is deduced.

Table 3. Load spectrum of certain type motorized spindle.

Rotational speed n /rpm	Torque M /Nm	Radial force F_r /N	Axial force F_a /N	The proportion of cutting time
320	1.2	190.8	37.7	2.732240500%
	13.6	1147.0	324.3	2.732240500%
450	7.9	1263.4	249.7	6.557377000%
500	4.3	687.7	136.0	7.650273000%
600	2.7	430.7	85.1	8.743169000%
720	11.9	1382.9	372.1	9.836066000%
800	1.5	231.7	45.8	3.715846400%
	2.4	381.9	75.5	2.404371200%
	4.2	661.3	130.7	2.404371200%
	6.1	958.9	189.5	2.404371200%
900	3.9	623.3	123.2	11.475410000%
1100	0.8	126.2	24.9	12.021860000%
1450	0.6	95.0	18.8	13.661200000%
2000	1.1	171.9	33.9	13.661200000%

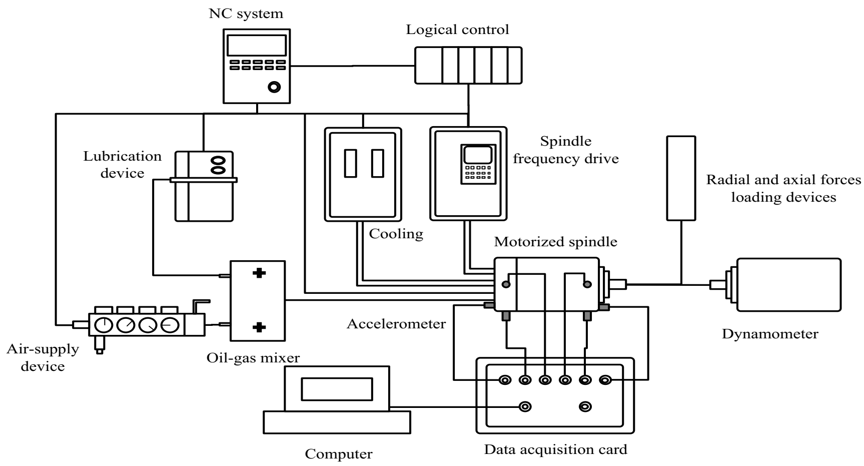


Figure 5. The simulation accelerated test platform of the motorized spindle.

5 Simulation accelerated test platform of the motorized spindle

The authors build simulation accelerated test platform of the motorized spindle which can load radicial force, axial force and torque. Figure 5 shows the skematic diagram of the test platform. The test platform can detect the vibration of bearing, frontend-cover and back end-cover. The radical and axial forces loading devices can apply these 2 forces to the spindle. And the torque are loaded and measured by the dynamometer. Figure 6 is the physical map of the loading devices.

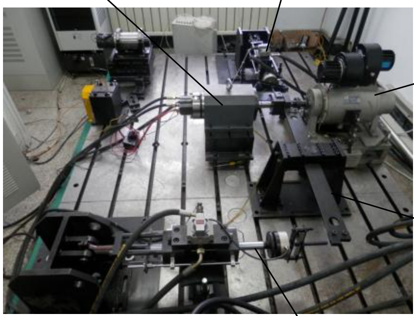


Figure 6. The physical map of the loading devices.

6 Fuzzy acceleration factor

Vibration is an index of the reliability test of motorized spindle [13].Torque, force and rotational speed all directly affect the vibration of motorized spindle. So the paper takes the vibration signal as the fuzzy standard of accelerated reliability test for motorized spindle. Assume the motorized spindle is a non-repairable system and it obeys cumulative damage (CD) law and inverse power law. Namely the life time of motorized spindle obeys the following formula:

$$\frac{T_1}{T_i} = \left[\frac{S_i}{S_1}\right]^N \tag{8}$$

where, T_1 is time to failure (TTF) of motorized spindle under average normal load S_1; T_i is TTF under high load S_i. The high load S_i is the variable of accelerated reliability test, namely the axial fore, radial force, torque and rotational speed on motorized spindle. N is the fuzzy acceleration factor.

However, the vibration and test time T satisfy the following formula:

$$\frac{T_p}{T_o} \propto \frac{V_o}{V_p} \tag{9}$$

where, V_p is the vibration under high load S_i; T_p is the test time when the vibration of motorized spindle is V_p under high load; T_o is the test time when the vibration of motorized spindle is V_p under normal load; V_o is the vibration of motorized spindle after test time T_o under average normal load S_1.

According to formula (8) and (9), the next formula can be obtained:

$$\frac{V_i}{V_1} \propto \left[\frac{S_i}{S_1}\right]^N \tag{10}$$

where, V_1 is the vibration under average normal load S_1; V_i is the vibration under high load S_i. The high load S_i is the variable of accelerated reliability test, namely the axial fore, radial force, torque and rotational speed on motorized spindle. N is the fuzzy acceleration factor.

According to formula (10), the relationship between vibration and load is set. And the fuzzy acceleration factor can be calculated after accelerated reliability test in simulation accelerated reliability test platform of motorized spindle. The series of high load S_i are determined by N and data in Table 3 and Figure 4. Finally, all parameters and test platform are ready and the design of accelerated reliability test for motorized spindle is finished. Next work is to conduct the accelerated reliability test to verify whether the fuzzy accelerated factor is correct and feasible.

7 Conclusions

The accelerated reliability test of the motorized spindle is of great significance to the research on motorized spindle reliability. The main conclusions about this study are as follows:

(1) Based on the field reliability test, authors collect load data in work condition, statistic and calculate the load spectrum;

(2) According to the load spectrum, the time distribution tables of load, such as the force, rotational speed and torque are obtained for CNC machine tools;

(3) Author proposed vibration signal as the index of accelerated reliability test for motorized spindle. The fuzzy accelerated factors on variables, namely force, rotational speed and torque is deduced.

(4) The accelerated test platform of motorized spindle is built which can apply the load spectrum and simulate the work condition of motorized spindle in CNC machining center. The accelerated reliability test also can be carried forward by changing the load which will shorten the reliability test cycle.

In the future, authors will carry out the accelerated test of motorized spindle to validate fuzzy accelerated factors.

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