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A New Method to Analyze CNC Lathe Faults Based on Gutenberg–Richter Curve

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Abstract

This paper collects and sorts out a large amount of fault data of a series of CNC lathes, and analyzes the fault data to classify fault levels. The values of a and b are obtained by Gutenberg–Richter (G-R) curve fitting, and then the relationship between a and b is used. The b value under each division criterion is obtained. By analyzing and comparing these b values, the rationality of classifying the fault levels according to these three methods is verified. The b-value is towards 1.0 when the reliability level of CNC lathes was promoted through ten years' reliability promotion.

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Keywords: Gutenberg–Richter (G-R) curve; b value; CNC machine tool; fault level; reliability;

1. Introduction

In 1944, Gutenberg and Richter proposed the famous earthquake magnitude relationship lgN = a-bM by studying the activity characteristics of the California earthquake. Since then, this relationship is one of the important properties of seismic activity research and has been widely used in the study of earthquake-related issues. In this relation, M is the magnitude, and N represents the number of earthquakes in the area with a magnitude greater than or equal to M in a certain period of time. The values of a and b are constants, a-values reflect the average level of seismic activity in the area, and b-values reflect the proportional relationship between large and small earthquakes [1, 2]. Yu Jie [3] proposed to use Gutenberg–Richter (G-R) curve analysis method to analyze the relationship between the failure level and the occurrence frequency of a series of CNC lathes. This is a useful attempt in the reliability analysis method research of CNC lathes, and some conclusions have been drawn. This paper continues to apply this relationship to the reliability analysis of CNC machine tools. In the curve, M is the failure grade of the CNC machine tool, and N is the number of failures when the failure grade is greater than or equal to M. In seismic research, the commonly used methods of b-value calculation include least square method, maximum likelihood method and moment method.

2. The Significance of Analyzing the Reliability Fault Data of CNC Machine Tools

Reliability data is defined as a general term for various data that can reflect its reliability level and reliability-related data in the reliability work at each stage of the product life cycle, mainly including various numbers, characters, graphics, tables, etc. [4]. The reliability data of CNC machine tools mainly include the design data, fault data and working environment of CNC machine tools. The reliability data collection, sorting, analysis and research of CNC machine tools have been carried out in foreign countries for a long time, and the reliability data management system has been established. In the application of CNC machine tool reliability data research, not only has achieved great economic benefits, but also saved a large amount of money. Compared with foreign countries, due to the lack of awareness of the reliability data collection, storage, analysis and application of CNC machine tools in China, a large amount of data is missing, leading to the failure of enterprises to implement reliability engineering.

The reliability data generated during the design of CNC machine tools can be used to obtain the initial reliability and failure modes of CNC machine tools. The reliability data of the production stage of CNC machine tools reflects the design and manufacturing level of CNC machine tools. The field data of the CNC machine tools in use truly reflects the reliability level of the machine tools in various environments. Therefore, it is necessary to collect, sort out and analyze the reliability data of NC machine tools, which is beneficial to the reliability engineering and machine tool maintenance and design.

2.1. Classification and b Value Calculation of a Certain Series of CNC Lathes

According to GJB431-88 “Product Level, Product Interchangeability, Prototype and Related Terms”, the vertical order of products from simple to complex is generally: parts, components, assemblies, unit parts, units,

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devices, subsystems and systems. In order to verify the rationality of CNC machine tool fault classification, this paper uses three classification methods: machine tool body, machine tool subsystem, and machine tool components. The division criteria are; fault downtime, subsystem fault frequency and component fault frequency [5].

From the previous research, we get that the failure interval of CNC machine tools submits to Weibull Distribution. We get the fitted curves of a series of CNC machine tools as given in Figure 1 and Figure 2.

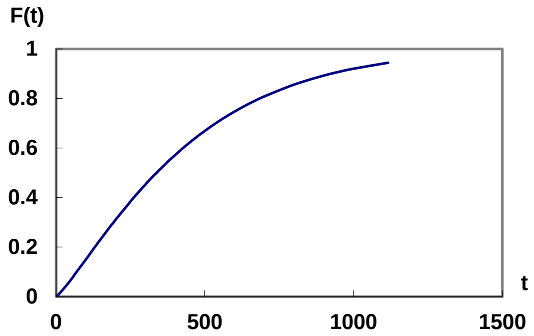

Figure 1. Fitting Diagram of Density Function Curve

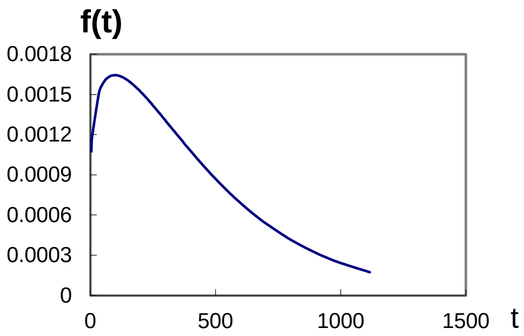

Figure 2. Fitting Diagram of Distribution Function Curve

At present, most reliability studies on CNC lathes are based on subsystems [6]. The subsystems of CNC lathes are divided according to the principles of functional independence, structural independence and convention. CNC lathe can be divided into 14 subsystems: basic components, spindle components, feed system, tool system, hydraulic system, lubrication system, cooling system, protection system, CNC system, electrical system, testing system, machine tool accessories, chip removal system and pneumatic system. In this paper, 11 subsystems with higher frequency of failures are selected for analysis.

The functional parts of CNC machine tools include: basic parts, NC rotary table, spindle parts, feed parts, CNC systems, automatic tool change parts, hydraulic system parts, cooling system parts, pneumatic system parts, lubrication system parts, chip removal system parts, and protection systems component. The accuracy, performance and stability of key components of CNC machine tools have the most direct impact on the reliability of CNC machine tools. Exploring the reliability of key functional components is of great significance to the reliability of CNC machine tool products [7-9]. Zhang Genbao [10] extracted the key functional components of CNC machine tools based on the four aspects of failure frequency, hazard, maintainability, and complexity, combined with experimental data and evaluation models, and provided theoretical basis and theoretical methods. Therefore, the analysis of functional components is conducive to the improvement of the reliability of the machine tool. In this paper, 11 fault components with high fault frequency are selected for analysis, most of which are key components. The specific division is shown in Table 1.

Table 1. Classification of fault levels

Failure grade	Downtime	Subsystem failure frequency	Component failure frequency
1	>0	Electrical system	Automatic tool changer
1.5	>0.5	Card attachment	Spindle component
2	>1	Chip removal system	Feeding component
2.5	>2	defensive equipment	CNC turntable
3	>5	servo system	Cooling system components
3.5	>8	Turret head	Hydraulic system components
4	>10	Hydraulic system	Pneumatic system components
4.5	>12	Spindle system	Protective system components
5	>20	Feed system	Chip removal system components
5.5	>24	Lubrication system	Lubrication system components
6	>30	cooling system	Basic component

In the table, the value of M represents the fault level. The fault level starts from 1 to 6, each 0.5 is a unit, and a total of 11 fault levels are divided. The unit of downtime is in hours.

The collected fault data is analyzed and sorted, and classified according to fault downtime, subsystem fault frequency, and component fault frequency. The number of fault occurrences at the corresponding fault level is obtained and the corresponding b value is calculated.

Table 2 to Table 8, where M represents the classification of fault levels, and N_1, N_2, and N_3 respectively represent the number of faults at the corresponding fault levels according to the breakdown time, number of subsystem faults, and number of component faults. $lgN=lg[(N_1+N_2+N_3)/3]$, a-value and b-value are calculated by fitting Gutenberg–Richter (G-R) curve with least square method. b_1, b_2 and b_3 can be obtained by substituting the value of a and the number of failures N_1, N_2 and N_3 under the corresponding fault level into the Gutenberg–Richter (G-R) relation.

Table 2. Failure data and b value of a series of CNC lathes from January 1998 to December 2000

M	N_1	N_2	N_3	lgN	a	b	b_1	b_2	b_3
1	2291	2399	2455	3.38	3.87	0.49	0.51	0.49	0.48
1.5	1303	1365	1396	3.13	3.87	0.49	0.50	0.49	0.48
2	741	776	794	2.89	3.87	0.49	0.50	0.49	0.49
2.5	422	442	452	2.64	3.87	0.49	0.50	0.49	0.49
3	240	251	257	2.40	3.87	0.49	0.50	0.49	0.49
3.5	136	143	146	2.15	3.87	0.49	0.50	0.49	0.49
4	78	81	83	1.91	3.87	0.49	0.50	0.49	0.49
4.5	44	46	47	1.66	3.87	0.49	0.49	0.49	0.49
5	25	26	27	1.42	3.87	0.49	0.49	0.49	0.49
5.5	14	15	15	1.17	3.87	0.49	0.49	0.49	0.49
6	8	9	9	0.93	3.87	0.49	0.49	0.49	0.49

Table 3. Failure data and b value of a series of CNC lathes from January 2001 to December 2003

M	N_1	N_2	N_3	lgN	a	b	b_1	b_2	b_3
1	1905	1995	1949	3.29	3.81	0.52	0.53	0.51	0.52
1.5	1059	1109	1083	3.03	3.81	0.52	0.52	0.51	0.52
2	588	616	602	2.78	3.81	0.52	0.52	0.51	0.52
2.5	327	342	334	2.52	3.81	0.52	0.52	0.51	0.51
3	181	190	186	2.27	3.81	0.52	0.52	0.51	0.51
3.5	101	105	103	2.01	3.81	0.52	0.52	0.51	0.51
4	56	58	57	1.76	3.81	0.52	0.52	0.51	0.51
4.5	31	32	31	1.50	3.81	0.52	0.52	0.51	0.52
5	17	18	17	1.24	3.81	0.52	0.52	0.51	0.52
5.5	9	10	9	0.97	3.81	0.52	0.52	0.51	0.52
6	5	5	5	0.70	3.81	0.52	0.52	0.52	0.52

Table 4. Failure data and b value of a series of CNC lathes from January 2004 to December 2006

M	N_1	N_2	N_3	lgN	a	b	b_1	b_2	b_3
1	1380	1318	1349	3.13	3.78	0.65	0.64	0.66	0.65
1.5	653	624	638	2.81	3.78	0.65	0.64	0.66	0.65
2	309	295	302	2.48	3.78	0.65	0.65	0.66	0.65
2.5	146	140	143	2.16	3.78	0.65	0.65	0.65	0.65
3	69	66	68	1.83	3.78	0.65	0.65	0.65	0.65
3.5	33	31	32	1.51	3.78	0.65	0.65	0.65	0.65
4	15	15	15	1.18	3.78	0.65	0.65	0.65	0.65
4.5	7	7	7	0.86	3.78	0.65	0.65	0.65	0.65
5	3	3	3	0.53	3.78	0.65	0.65	0.65	0.65
5.5	2	2	2	0.21	3.78	0.65	0.65	0.65	0.65

Table 5. Failure data and b value of a series of CNC lathes from January 2007 to December 2009

M	N_1	N_2	N_3	lgN	a	b	b_1	b_2	b_3
1	776	724	676	2.86	3.69	0.83	0.80	0.83	0.86
1.5	299	279	260	2.45	3.69	0.83	0.81	0.83	0.85
2	115	107	100	2.03	3.69	0.83	0.82	0.83	0.85
2.5	44	41	38	1.62	3.69	0.83	0.82	0.83	0.84
3	17	16	15	1.20	3.69	0.83	0.82	0.83	0.84
3.5	7	6	6	0.79	3.69	0.83	0.82	0.83	0.84
4	3	2	2	0.37	3.69	0.83	0.82	0.83	0.84

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Table 6. Failure data and b value of a series of CNC lathes from January 2010 to December 2012

M	N_1	N_2	N_3	lgN	a	b	b_1	b_2	b_3
1	479	457	490	2.68	3.65	0.9	0.97	0.99	0.96
1.5	313	160	172	2.33	3.65	0.9	0.77	0.96	0.94
2	110	56	60	1.88	3.65	0.9	0.80	0.95	0.94
2.5	38	20	21	1.42	3.65	0.9	0.83	0.94	0.93
3	13	7	7	0.97	3.65	0.9	0.84	0.94	0.93
3.5	5	2	3	0.51	3.65	0.9	0.85	0.93	0.92
4	2	1	1	0.06	3.65	0.9	0.86	0.93	0.92

Table 7. Failure data and b value of a series of CNC lathes from January 2013 to December 2015

M	N_1	N_2	N_3	lgN	a	b	b_1	b_2	b_3
1	363	380	417	2.59	3.56	0.97	1.00	0.98	0.94
1.5	119	124	136	2.10	3.56	0.97	0.99	0.98	0.95
2	39	41	45	1.62	3.56	0.97	0.99	0.98	0.96
2.5	13	13	15	1.13	3.56	0.97	0.98	0.97	0.96
3	4	4	5	0.65	3.56	0.97	0.98	0.97	0.96
3.5	1	1	2	0.16	3.56	0.97	0.98	0.97	0.96

Table 8. Failure data and b value of a series of CNC lathes from January 2015 to December 2017

M	N1	N2	N3	lgN	a	b	b1	b2	b3
1	380	417	398	2.60	3.67	1.07	1.09	1.05	1.07
1.5	111	122	116	2.07	3.67	1.07	1.08	1.06	1.07
2	32	35	34	1.53	3.67	1.07	1.08	1.06	1.07
2.5	9	10	10	1.00	3.67	1.07	1.08	1.06	1.07
3	3	3	3	0.46	3.67	1.07	1.08	1.06	1.07

3. Gutenberg–Richter (G-R) Curve Analysis

Taking the fault data of this series of CNC lathes from January 1998 to December 2000 as an example, analysis and Gutenberg–Richter (G-R) curve fitting are performed to obtain the fitted a and b values, and b value of corresponding fault level is calculated by fitting a-value.

In this paper, the least square method is used to fit the Gutenberg–Richter (G-R) curve. The fitting result is shown in Figure 3.

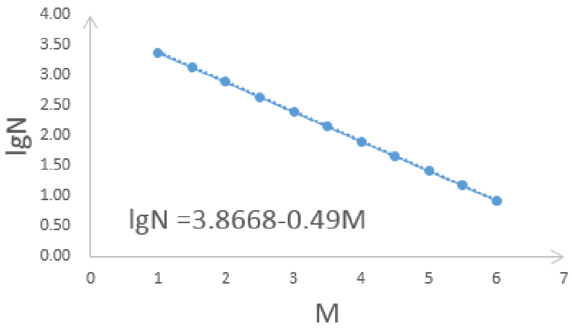

Figure 3. Gutenberg–Richter (G-R) fitting curve from January 1998 to December 2000

From the fitting relation in the figure, it can be concluded that fitting a=3.8668 and b=0.49. By substituting the fitting value of a and the corresponding failure times into the relational formula lgN= a-bM, the b-value of the corresponding fault level under the corresponding classification method can be calculated. The detailed calculation results are shown in table 2. The calculation methods for other years are the same and are not listed here one by one. The detailed fitting results are shown in Figure 4.

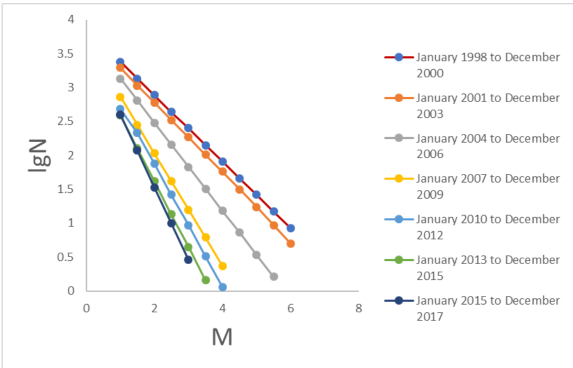

Figure 4. Gutenberg–Richter (G-R) fitting curve at each stage

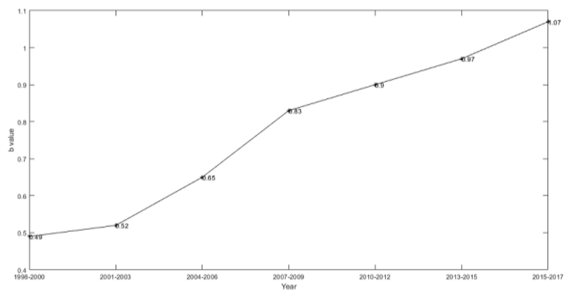

Figure 5. Variation curves of b-value at each stage

Notes: The abscissa values in Figure 5 correspond to the year of data collection in Tables 2 to 8 of the paper.

Through the analysis and comparison in Figure 4, it is known that the slope of the fitting curve increases with the increase of the year, that is, the greater the value of b. The corresponding b value of the fitted curve relation was extracted to make the change curve of b value, as shown in Figure 3. The curve showed an upward trend. In seismic research, many studies show that the decrease of b-value means the increase of large earthquake proportion, and vice versa [11-14]. Mean time between failures (MTBF) is the mean value of working time between two adjacent failures of CNC machine tools, which is the key index to measure the reliability of CNC machine tools.

The MTBF value of domestic CNC machine tools is more than 200 hours from the end of the "eighth five-year plan", more than 400 hours from the "ninth five-year plan", more than 600 hours from the" tenth five-year plan", and now more than 1000 hours. The reliability of CNC machine tools in China is constantly improving, which is also consistent with the gradual increase of b value. The rationality of the Gutenberg–Richter (G-R) curve relationship applied to the reliability of CNC machine tools is explained, which further proves the rationality of the fault classification method in this paper.

B-value is an important index in seismic research and is often used in seismic analysis and consultation system at all levels. If the b value is small, it means that the proportion of the number of large earthquakes is large. On the contrary, if the b value is large, it means that the proportion of the number of large earthquakes is small.

According to the dynamic change of B value, we can predict earthquakes; according to the G-R law, we can calculate the average recurrence period or average annual occurrence rate of earthquakes at all levels, we can infer the risk of earthquakes at all levels in a certain period of time in the future; according to the intercept a of Gutenberg–Richter (G-R) curves on the horizontal axis, we can predict the magnitude of strong aftershocks.

From Figure 4 and Figure 5, we can get that in the failure frequency period of CNC machine tool, b value is small, with the advance of reliability improvement measures, b value gradually increases, and finally in the stable period, b value tends to 1.0. This conclusion is very similar to that of seismology, so we can study parameter a again in order to predict the risk of CNC machine failure level.

4. Conclusion

The fault data analyses from 1998 to 2017 shows that b-values in frequent failure time are lower than in stable time. The b-value is towards 1.0 when the reliability level of CNC lathes was promoted through ten years' reliability promotion.

This article further collected a large amount of fault data, extended the time for collecting fault data, and further proved the rationality of using Gutenberg–Richter (G-R) curves to analyze fault data. Through the comparative analysis of the data collected in Table 2 to Table 8, corresponding values of b_1, b_2 and b_3 at each stage fluctuated up and down in the fitted b value, with a small difference. Thus, the rationality of fault classification in this paper is verified, and the application scope of Gutenberg–Richter (G-R) curve is further expanded, which is not only applicable to the whole machine, but also applicable to subsystems and components.

The result of this paper is very close to the conclusion of seismology, which verifies that the model hypothesis is correct and feasible.

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