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Analysis of Activity Parameters of CNC Machine Tools Failures Based on Gutenberg–Richter Curve

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Abstract

Gutenberg–Richter (G-R) scaling relations are commonly used on seism prediction. The variance of b-values can reflect the seism active degree of the area. B value in frequent failure time is lower than in stable failure time. We use the curve to calculate the values of parameters a and b in the Gutenberg–Richter (G-R) relation, draw a graph of the b-value and the ratio of the number of failures over time, and find that the trend is reversed, which prove that the b-value can reflect the ratio of the number of failures. Draw the trend curve of a-value and lgN. By comparing and finding the same trend, it is proved that the a-value can reflect the overall level of failure data. The relationship between a and b-value is analyzed and the influencing factors on activity parameters are discussed.

Keywords: CNC machine tool, Gutenberg–Richter (G-R) curve, a-value, b-value, Gutenberg–Richter (G-R) scaling relation;

1. Introduction

In the manufacturing industry, CNC machine tools are the most fundamental processing equipment and a symbol of comprehensive national strength. With the modern advancements and the improvement of national demand, the requirements for CNC machine tools are constantly changing. In order to meet the market demand, CNC machine tools are developing towards high speed, multi-function, high reliability, intelligence, high precision and other directions [1]. With the increasing demand for CNC machine tools in the market, the reliability of China's machine tools is also constantly improving, but it is still insufficient compared with some advanced foreign machine tools. Therefore, the research on the reliability of CNC machine tools has not stopped. The research on the reliability of machine tools mainly improves the production efficiency by reducing the failure rate of machine tools as to reduce the number of failures and the impact of failures.

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.

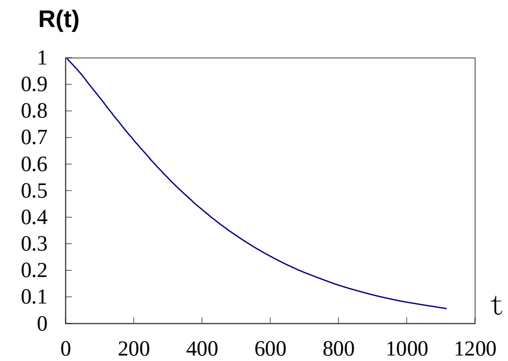

Figure 1. Fitting Diagram of Reliability Curve

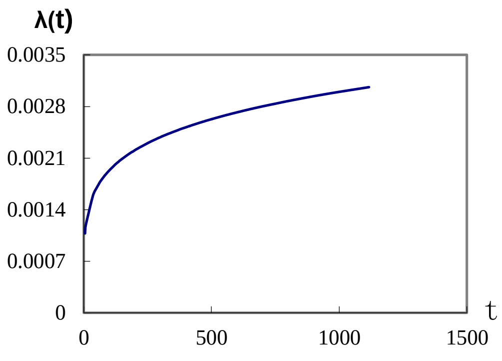

Figure 2. Fitting Diagram of Failure Rate Curve

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The Gutenberg-Richter relation (G-R curve: $\lg N = a - bM$), which reflects the relationship between magnitude and frequency, is usually used to study the seismicity characteristics of various regions of the world [2-4]. In the Gutenberg–Richter (G-R) curve, the parameter a is the intercept of the straight line and the vertical axis, indicating the overall activity level of the earthquake, and the parameter b is the slope of the straight line, indicating the proportional relationship of the large and small earthquakes [5, 6]. When the b-value is low, it indicates that the large earthquake accounts for a higher proportion in the study area. In most cases, the b-value will stabilize at around 1. When the value of a is large, it indicates that the number of earthquakes is greater. This relation is used in the study of failures of CNC machine tools, where *M* represents the failure level and *N* represents the number of failures greater than or equal to *M* in a certain period of time.

2. Applying Gutenberg–Richter (G-R) Scaling Relations to Describe the Failure Rate of the CNC Machine Tools

We analyze the failure data of a series of CNC machine tools according to different phases to inquire into the laws followed. As the drawing of Gutenberg–Richter (G-R) scaling relations in seismic research, we divide the failures into nine grades according to the extent of criticality and put into analysis.

We draw the curves of different stages as given below:

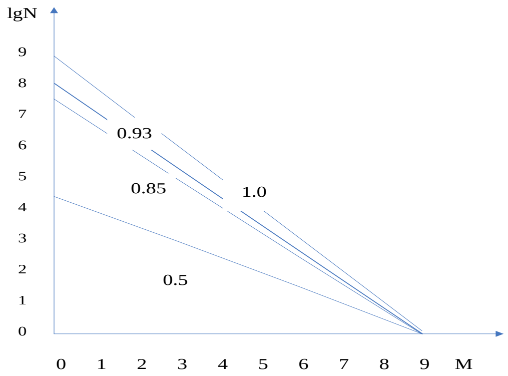

Figure 3. Gutenberg–Richter (G-R) scaling relations of a series of CNC machine tools

Notes: 0.5 shows the early research stage.

0.85 shows after the research stage.

0.93 shows after research (2001.1-2003.12) stage.

1.0 shows after research (2009.1-2015.12) stage.

The increase of the credibility of the CNC machine tools is a long-term and meticulous course of work. Through ten years' cooperation, the MTBF value of this series of machine tools has been increased greatly. It can be said that achievements in this research are still significant. For the length of the paper, we cannot list the overall measurements here. From the Gutenberg–Richter (G-R) scaling relations we can see that b-value is changed from 0.5 to 0.85 to 0.93 and the final b-value is 1.0.

2.1. Mean Time between Failures

The mean time between failures [7] (MTBF) is the mean value of the time between failures of the equipment. If the number of failures of the equipment is n and the time between failures is t_1, t_2, …, t_n, then the mean time between failures is

$$MTBF = (t_1 + t_2 + \cdots + t_n) / n \tag{1}$$

The reliability index of the CNC machine tool can be judged as MTBF, reflecting the ability of machine tools to complete the task within the specified time. The reliability index is divided into 5 grades [8-10], with "very high" about 1800 hours, "high" about 1200 hours, "intermediate" about 800 hours, "low" about 600 hours and "very low" about 400 hours. The MTBF value of early CNC machine tools in China was only over 200 hours, and the room for improvement was very large.

2.2. Collection and Division of Fault Data

CNC machine tools cannot complete the specified functions under the specified conditions and within the specified time, or the performance of one or several parameters beyond the allowable range is called failure. When studying the reliability of CNC machine tools, it is necessary to collect the failure data. Due to the timeliness and randomness of the data, it is also needed to sort the data.

The failure data of a CNC machine tool in recent years was analyzed, and the number of samples was 20, which lasted about 20 years. Due to the large amount of data, the data must first be sorted. Different ways of failure classification will lead to the difference in the number of failures corresponding to each grade. According to J.X. Ding's paper [8], the failure grade of CNC machine tools can be divided into three aspects: downtime, subsystem failure frequency and component failure frequency [11-15].

The number of failures is graded through the above three aspects, and each division method is fitted with MATLAB. As shown in Table 1, $N = (N_1+N_2+N_3)/3$, *a* and *b* are fitted by failure grade *M* and *lgN*. According to the obtained *b*-value, a_1, a_2, and a_3 corresponding to N_1, N_2, and N_3 are calculated. By comparing a_1, a_2 and a_3 with the a-value obtained by the previous fitting, the a-values obtained by the three classification methods are similar, which can be concluded that the three classification methods are feasible. From the sorted data, no reliability improvement was made from the very beginning, and after the improvement, the number of failures decreased significantly, and the production efficiency was further improved. Table 1 to Table 4 are the results of partial failure data processing

Table 1. Failure data and a-value of a CNC machine tool from January 2015 to December 2017

M	N_1	N_2	N_3	lgN	a	b	a_1	a_2	a_3
1	380	417	398	2.60	3.67	1.07	3.65	3.69	3.67
1.5	111	122	116	2.07	3.67	1.07	3.65	3.69	3.67
2	32	35	34	1.53	3.67	1.07	3.65	3.69	3.67
2.5	9	10	10	1.00	3.67	1.07	3.65	3.69	3.67
3	3	3	3	0.46	3.67	1.07	3.65	3.69	3.67
3.5	1	1	1	-0.07	3.67	1.07	3.65	3.69	3.67
4	0	0	0	-0.61	3.67	1.07	3.65	3.69	3.67

Table 2. Failure data and a-value of a CNC machine tool from January 2012 to December 2014

M	N_1	N_2	N_3	lgN	a	b	a_1	a_2	a_3
1	398	407	339	2.58	3.53	0.95	3.55	3.56	3.48
1.5	133	136	114	2.11	3.53	0.95	3.55	3.56	3.48
2	45	46	38	1.63	3.53	0.95	3.55	3.56	3.48
2.5	15	15	13	1.16	3.53	0.95	3.55	3.56	3.48
3	5	5	4	0.68	3.53	0.95	3.55	3.56	3.48
3.5	2	2	1	0.21	3.53	0.95	3.55	3.56	3.48
4	1	1	0	-0.27	3.53	0.95	3.55	3.56	3.48
4.5	0	0	0	-0.74	3.53	0.95	3.55	3.56	3.48

Table 3. Failure data and a-value of a CNC machine tool from January 2009 to December 2011

M	N_1	N_2	N_3	lgN	a	b	a_1	a_2	a_3
1	525	501	537	2.72	3.61	0.89	3.61	3.59	3.62
1.5	188	180	193	2.27	3.61	0.89	3.61	3.59	3.62
2	68	65	69	1.83	3.61	0.89	3.61	3.59	3.62
2.5	24	23	25	1.38	3.61	0.89	3.61	3.59	3.62
3	9	8	9	0.94	3.61	0.89	3.61	3.59	3.62
3.5	3	3	3	0.49	3.61	0.89	3.61	3.59	3.62
4	1	1	1	0.05	3.61	0.89	3.61	3.59	3.62
4.5	0	0	0	-0.40	3.61	0.89	3.61	3.59	3.62

Table 4. Failure data and a-value of a CNC machine tool from January 2006 to December 2008

M	N_1	N_2	N_3	lgN	a	b	a_1	a_2	a_3
1	891	832	871	2.94	3.71	0.77	3.72	3.69	3.71
1.5	367	343	359	2.55	3.71	0.77	3.72	3.69	3.71
2	151	141	148	2.17	3.71	0.77	3.72	3.69	3.71
2.5	62	58	61	1.78	3.71	0.77	3.72	3.69	3.71
3	26	24	25	1.40	3.71	0.77	3.72	3.69	3.71
3.5	11	10	10	1.01	3.71	0.77	3.72	3.69	3.71
4	4	4	4	0.63	3.71	0.77	3.72	3.69	3.71
4.5	2	2	2	0.24	3.71	0.77	3.72	3.69	3.71
5	1	1	1	-0.14	3.71	0.77	3.72	3.69	3.71
5.5	0	0	0	-0.53	3.71	0.77	3.72	3.69	3.71

Taking the failure data of Table 5 (January 2001-December 2003) as an example, the fitting is performed by MATLAB, and the fitted curve is $\lg N = 3.8001 - 0.51M$. As shown in Figure 4, the failure grade and the number of failures satisfy the relationship of Gutenberg–Richter (G-R) curve. Due to the initial reliability improvement, the failure rate is high, and the MTBF is about 400 hours. The b-value is relatively low.

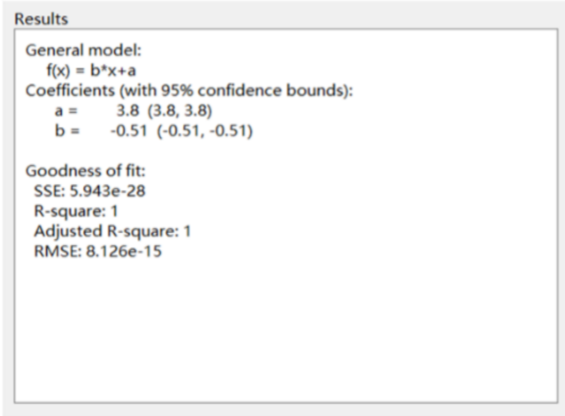

Figure 4. MATLAB fitting results Units

Table 5. First stage failure data after reliability study (January 2001 to December 2003)

M	N_1	N_2	N_3	lgN	a	b	a_1	a_2	a_3
1	1905	1995	1950	3.29	3.80	0.51	3.79	3.81	3.80
1.5	1059	1109	1084	3.04	3.80	0.51	3.79	3.81	3.80
2	589	617	603	2.78	3.80	0.51	3.79	3.81	3.80
2.5	327	343	335	2.53	3.80	0.51	3.79	3.81	3.80
3	182	191	186	2.27	3.80	0.51	3.79	3.81	3.80
3.5	101	106	104	2.02	3.80	0.51	3.79	3.81	3.80
4	56	59	58	1.76	3.80	0.51	3.79	3.81	3.80
4.5	31	33	32	1.51	3.80	0.51	3.79	3.81	3.80
5	17	18	18	1.25	3.80	0.51	3.79	3.81	3.80
5.5	10	10	10	1.00	3.80	0.51	3.79	3.81	3.80
6	5	6	5	0.74	3.80	0.51	3.79	3.81	3.80

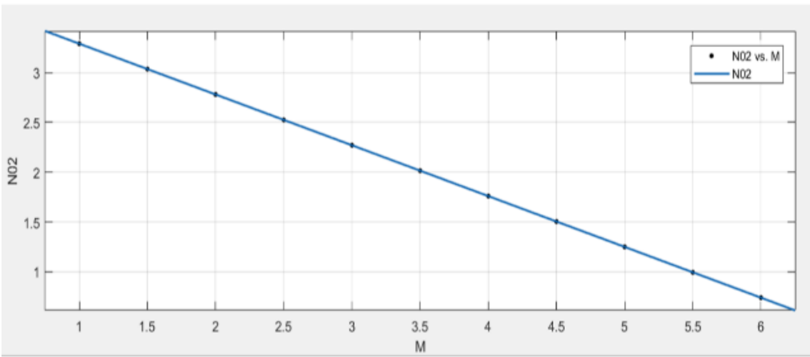

Figure 5. Initial magnitude-frequency graph

3. Analysis of Parameters

In the relationship between magnitude and frequency of earthquakes, b-value is the slope of the straight line in the logarithmic coordinate system, which is expressed as the proportional relationship between large and small earthquakes in a certain area. The larger the *b*-value is, the more the proportion of large earthquakes, so it has been studied by many scholars. In the use of the relationship between magnitude and frequency in the failure data of CNC machine tools, the b-value may be the ratio of the number of large failure grade to the number of small failure grade. We will verify this idea below; fitting the Gutenberg–Richter (G-R) curves of each year to obtain different *b*-values and plotting the *b*-value as a function of time. A failure grade greater than or equal to 4 is defined as a large failure, and a failure grade less than 4 is defined as a small failure. Draw a plot of the ratio of large failure to small failure. It can be seen from Figure 6 that the b-value curve and the curve of the ratio of the large failure to the small failure are basically opposite, that is to say, the larger the b-value, the smaller the proportion of the large failure, which shows that the b-value can reflect the ratio of large failure to small failure.

In Gutenberg–Richter (G-R) curve, a reflects the earthquake times over zero magnitude and represents the overall level. When m is zero, a represents the intercept. a values are greatly reflected by the initial data. So we should not ignore the lower level failures. In order to analyze the physical meanings of a values in the CNC machine tools faliure data, we collected a large amount of faliure data from 2003 to 2017 and drew the plot (M=1) . From Figure 7, we can see that the trend of a and lgN are similar. There is a certain connection between them . Figure 7 shows that a-values can reflect the level of integration of the CNC machine tools. We get the MTBF in 2017 of the series machine tools is more than 1000 hours. The reliability index can reach intermediate level.

4. Conclusion

the fault data of CNC machine tools have been collected and analyzed, and then the Gutenberg–Richter (G-R) curve relationship in the earthquake has been applied to CNC machine tools. Three methods are used to divide the fault levels, and the fault times of different levels are obtained. The physical meaning of the parameters is studied to describe the failure grade of the CNC machine. By comparing the b-value and the ratio of large failure to small failure with time, it is proved that b-value can reflect the ratio of large failure to small fault over a period of time. By comparing the relationship between a-value and lgN over time, it can be shown that they have a close relationship, and a-value can reflect the overall level of CNC machine tools.

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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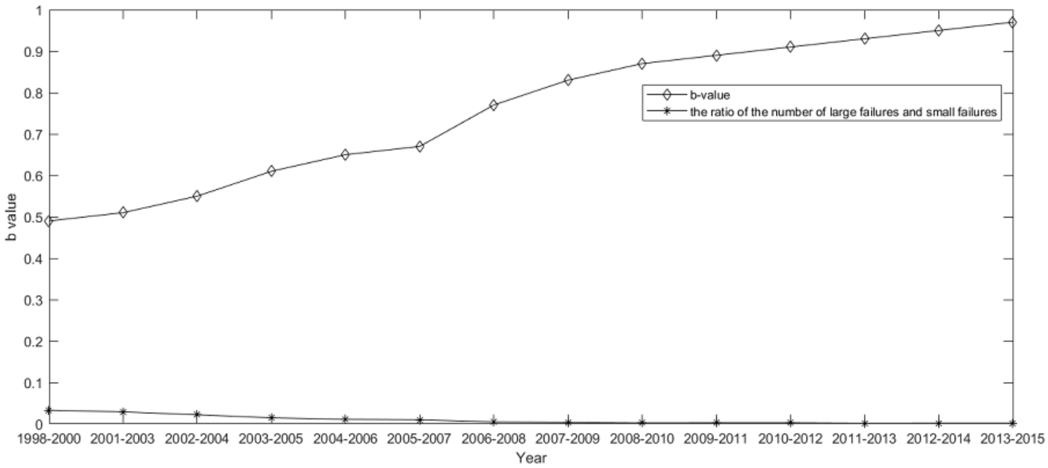

Figure 6. The trend of the b-value and the ratio of the number of large failures and small failures over time

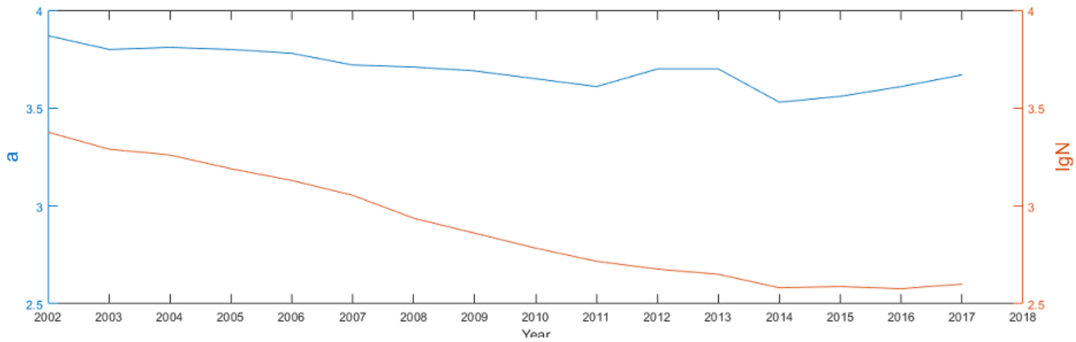

Figure 7. Comparison of a-value and lgN with time

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