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Research Article

Dynamic Importance Analysis of Machining Center

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Abstract: As an important part of CNC machine tools, machining center's reliability, efficiency and accuracy measure the machining level of a CNC machine tool. Therefore, the research on the importance of CNC machine tools is particularly important. However, as a complex mechanical and electrical equipment, the traditional reliability importance analysis method is too simple. In order to solve this problem, this passage proposes to establish the reliability model of each part of the machining center, and then analyze its dynamic importance, which improves the limitation of only reliability importance analysis. Through the analysis the reliability importance and criticality importance, and then rank the result of importance analysis, finally it can get that the ranking results of the key components accord with the fact, so the results can provide support for the importance research of machining center.

Keywords: Machining center; Key components; Reliability model; Reliability importance; Criticality importance

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Introduction

The traditional importance analysis mainly began with the reliability importance and used the least square method to model and analyze[1]. However, according to the fact verification, the original transformation of each component in the system is different. If only relying on the reliability importance analysis, it can not reflect the influence of key components on the importance of the whole machine system. Moreover, as a complex mechanical and electrical equipment, the traditional reliability theory can not describe the multi failure mode and multi-performance system[2]. Nowadays, the research on the importance analysis of components in complex technical system has a wide range of practical significance, it is very important to further develop the importance analysis of mechanical operation[3].

The importance analysis of components is helpful to identify the loopholes in the system and quantify the importance of the system[4]. Therefore, this passage calculates the importance of each key component and rank the importance of each key component and then determine the impact of the failure of key components on the failure of the whole machine. According to the results of these importance degrees, reliability design and reliability growth can be further studied.

There are many disadvantages of the importance measurement base on the variance, the most obvious one is that the influence of different input variables on the output response may cancel each other[5], the second is that in different stages, the importance of each components is different, and if only analyzing the importance of components in one stage will have many problems during the actual operation[6], and as a complex mechanical and electrical equipment, the failure of a component may even cause the failure of the whole system, so during the process of reliability analysis of technical system, researchers usually find out the most sensitive components. Once the reliability of these components are improved, the reliability of the whole system can be improved, and finally the optimal solution model of the system can be obtained[7].

For the above problems, this passage establishes the subsystem reliability function of the key components of the machining center, and then calculate the importance of the subsystem to the whole machine, so that the traditional Bayesian theory is not used to calculate the importance any more, and the reliability importance only reflects the change of the system failure probability caused by the change of component failure probability[8]. However, it does not consider the difficulty of the change of failure probability and the interrelationship between components. Therefore, this paper not only considers the probability importance, but also considers the influence of the criticality importance.

Nowadays, China has made a lot of achievements in the research of the importance of CNC machine tools. Wu Qi has studied two kinds of special k-out-of-n: G reliability importance analysis[9], Wang Hongle used the method of multi-phase space reconstruction, error tracing method of chaos characteristics, geometric error inversion method, error modeling method, processing accuracy evaluation technology, global error compensation method and other methods to model the processing errors of different CNC machine tools, and made the compensation optimization scheme[10]. The existing reliability modeling methods of multistate system mainly include the multivalued model[11], the stochastic process model[12], the general generating function method[13] and the Monte Carlo simulation[14] which are extended from the binary system Boolean model.

In this essay, a certain type of machining center is selected to track and record the failure time for several months, and the detailed data are obtained. From the data, it is found that the spindle box (S), X-axis feed system (X), tool magazine (M), cooling system (W), electrical system (D) and exchange worktable (P) are the components with the most failures in the machining center. Therefore, after modeling all the sub-systems of the construction center, the reliability importance and criticality importance of the above six sub-system models are calculated and sorted

1 Establish subsystem reliability model

According to the data of a machining center, establish the reliability model of key components. Taking the spindle box as an example. Taking out the accumulated operation time of each fault point of the spindle box t_i, See Table 1. for details.

Table 1. Failure time of Spindle box

i	t_i	***i***	t_i
1	160	6	1578
2	1050	7	1610
3	1115	8	2038
4	1515	9	2372
5	1540	10	3175

1.1 Parameter estimation of reliability model

According to the previous research on the reliability of machining centers, we know that the cumulative fault distribution function of machining centers obeys the Weibull distribution[15]. The two parameter Weibull distribution function is:

$$F(t) = 1 - \exp[-(\frac{t}{\alpha})^{\beta}], \qquad t \geq 0 \tag{1}$$

The corresponding reliability function is:

$$R(t) = \exp[-(\frac{t}{\alpha})^{\beta}], \qquad t \geq 0 \tag{2}$$

Suppose the linear regression equation of one variable be:

$$y = A + Bx \tag{3}$$

According to the Weibull distribution of two parameters, the linear transformation of formula (1)can be obtained:

$y_i = \ln\ln\frac{1}{1-F(t_i)}$, $x_i = \ln t_i$, $A = -\beta\ln\alpha$, $B = \beta$, The value of F (t_i) needs to be estimated before calculation, use the median rank to estimate F(t_i), $\hat{F}(t_i) \approx \frac{i-0.3}{n+0.4}$.

According to the least square method, the parameters can be estimated as

$$\hat{B} = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}(\sum_{i=1}^{n} x_i)^2}$$

$$\hat{A} = \frac{1}{n}\sum_{i=1}^{n} y_i - \hat{B}\cdot\frac{1}{n}\sum_{i=1}^{n} x_i$$

Finally, we can get $\hat{\beta} = \hat{B}$, $\hat{\alpha} = \exp(-\hat{A}/\hat{B})$.

According to the above discussion, combined with the accumulated failure time data of the spindle box (as shown in Table 1), the reliability model parameters of the spindle box can be obtained as follows $\beta = 0.695$, $\alpha = 2025.350$.

1.2 Hypothesis test of reliability model

1.2.1 Linear correlation test

The linear correlation coefficient is

$$\hat{\rho} = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} y_i}{\sqrt{\left[\sum_{i=1}^{n} x_i^2 - \frac{1}{n}(\sum_{i=1}^{n} x_i)^2\right]\left[\sum_{i=1}^{n} y_i^2 - \frac{1}{n}(\sum_{i=1}^{n} y_i)^2\right]}} \quad (4)$$

If $|\hat{\rho}| > \rho_{(n-2,\alpha)}$, The linear correlation between X and Y is significant. $\rho_{(n-2,\alpha)}$ is critical value of correlation coefficient ρ, it can be found by looking up the table or by using approximate formula. In this passage, use the approximate formula and take the significance level α =0.1,

$$\rho_{(n-2,\alpha)} = \frac{1.645}{\sqrt{\upsilon + 1}} \quad (5)$$

$\upsilon = n - 2$, n is cumulative failure times.

Hypothesis test of spindle box fault distribution by correlation coefficient method. According to (4), $\hat{\rho}$ = 0.903, count as $\rho_{(n-2\upsilon)}$ =0.548, thus: $\hat{\rho} > \rho_{(n-2\upsilon)}$, therefore, the linear correlation between X and Y is significant, the fault distribution of spindle box system obeys Weibull distribution.

1.2.2 Hypothesis test of distribution fitting

Use d method of inspection to test the above fault time distribution function. If the distribution function obtained from the estimated parameters satisfies the following conditions, the parameter estimation is reasonable, then it can assumption that

$$D_n = \sup_{-\infty<x<+\infty} |F_n(x) - F_0(x)| = \max\{d_i\} \le D_{n,\alpha} \quad (6)$$

In the formula, $F_0(x)$—Original hypothesis distribution function. $F_n(x)$—The empirical distribution function of simple size n $D_{n,\alpha}$—critical value.

The detail of d_i is following:

$$d_i = \max\left\{F_0(x_i) - \frac{i-1}{n}, \frac{i}{n} - F_0(x_i)\right\} \quad (7)$$

D-test for the fault distribution function of spindle box.

$$F(t) = 1 - \exp[-(\frac{t}{2025.350})^{1.239}]$$

D_n =0.369, when significant level is 0.1, $D_{n,\alpha} = 0.515$. Because $D_n \le D_{n,a}$, accept hypothesis test.

According to the above argumentation, the cumulative fault distribution function and reliability function of six key components are listed in Table 2.

Table 2. Failure distribution function and reliability function of critical components

	Failure distribution function	Reliability function
S	$F(t)=1-\exp[-(t/2025.350)^{1.239}]$	$F(t)=1-\exp[-(t/1064.005)^{1.102}]$
X	$F(t)=1-\exp[-(t/1064.005)^{1.102}]$	$R(t)=\exp[-(t/1064.005)^{1.102}]$
M	$F(t)=1-\exp[-(t/1342.980)^{1.218}]$	$R(t)=\exp[-(t/1342.980)^{1.218}]$
W	$F(t)=1-\exp[-(t/740.536)^{0.965}]$	$R(t)=\exp[-(t/740.536)^{0.965}]$
D	$F(t)=1-\exp[-(t/1225.374)^{1.163}]$	$R(t)=\exp[-(t/1225.374)^{1.163}]$
P	$F(t)=1-\exp[-(t/1273.855)^{0.702}]$	$R(t)=\exp[-(t/1273.855)^{0.702}]$

2 Reliability importance model analysis

2.1 Reliability importance

Reliability importance was first proposed by Birnbaum[16] in 1967, and has been widely used in production. Reliability importance refers to the degree to which the change of reliability of the component causes the change of system reliability, which is the change rate of system reliability to component reliability[7]. The formula is as follows:

$$I_i^B = \frac{\partial F_s}{\partial F_i} = \frac{\partial R_s}{\partial R_i} \quad (8)$$

In the formula, I_i^B is components' reliability importance. F_s is the fault distribution function of the system, F_i is fault distribution function of the component. R_s is the reliability of the system, R_i is the reliability of the component.

Because the machining center is a complex mechanical and electrical equipment, there is a close relationship between each component, any fault will affect the reliability of the whole machine, and also increase the maintenance cost. Therefore, it can regard the machining center as a whole system composed of a series of subsystems. The detail is as follows:

$$R_s = \prod_{i=1}^{n} R_i \tag{9}$$

After data analysis, we can draw a conclusion that the failure causes of the system mainly focus on some key components, so from the perspective of practical application and simplified model, this passage only considers the importance of six key components. So the formula (8) can be written as:

$$I_i^B = \frac{\partial R_s}{\partial R_i} = \prod_{\substack{j=1 \\ j \neq i}}^{n} R_j \tag{10}$$

The machining center studied in this passage consists of 14 subsystems, thus during the formula n=14, $R_1 \sim R_6$ are spindle box, X-axis feed system, tool magazine, cooling system, electrical system and exchange worktable.

Taking the spindle box as an example, according to formula(10), $I_1^B = R_2 R_3 \cdots R_{14}$, According to table 2, it can be further obtained

$$I_1^B = \exp[-(t/2025.350)^{1.239} \ -(t/1064.005)^{1.102} \cdots -(t/1273.855)^{0.072}]$$

Similarly, the importance model of other key components can be obtained. In order to grasp it as a whole, the characteristic curve of reliability importance of six key components with time is shown in Figure 1.

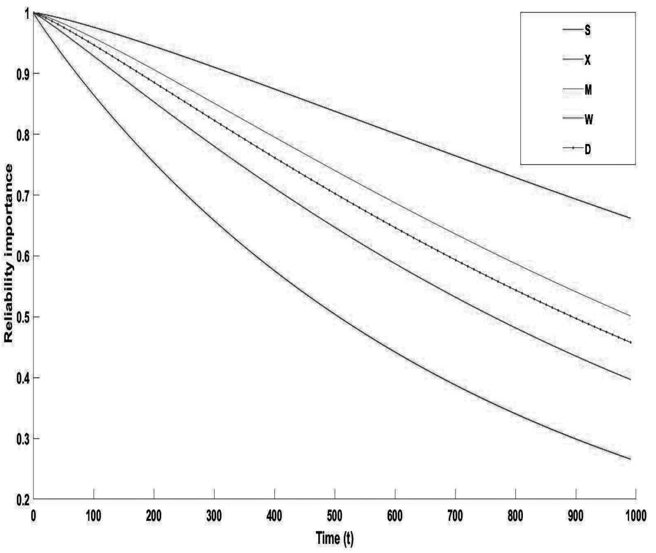

Figure 1. Reliability importance curve of critical components

From Figure 1., it can be seen that with the elimination of early faults, the importance of each subsystem shows a downward trend. When the time reaches 800 hours, the reliability importance curve tends to be stable. It can be seen from the figure that the importance of the spindle box is the most obviously, the X-axis feed system is the second, and the reliability importance of the exchange table is the smallest.

2.2 Criticality importance

Reliability importance only reflects the change of probability of a component to the whole system. But the change of each component itself is different, so the reliability importance can not reflect this property, the criticality importance can make up for this defect. Criticality importance refers to the change rate of system failure probability caused by the change of component failure probability, the criticality importance was proposed by Birnbaum[16] in 1967. The specific formula is as follows:

$$I_i^{Cr} = \frac{F_i}{F_s} \cdot \frac{\partial F_s}{\partial F_i} \tag{11}$$

In the formula, I_i^{Cr} is the criticality importance of component I.

Substituting formulas (8) and (10) into formula (11) can be further written as:

$$I_i^{Cr} = \frac{F_i}{F_s} \cdot I_i^B = \frac{1-R_i}{1-R_s} \cdot I_i^B = \frac{1-R_i}{1-\prod_{i=1}^{n} R_i} \cdot \prod_{\substack{j=1 \\ j \neq i}}^{n} R_j \tag{12}$$

The criticality importance function can be obtained by substituting the reliability function in Table 2. into formula (12). The characteristic curve of the criticality importance of six key components with time is shown

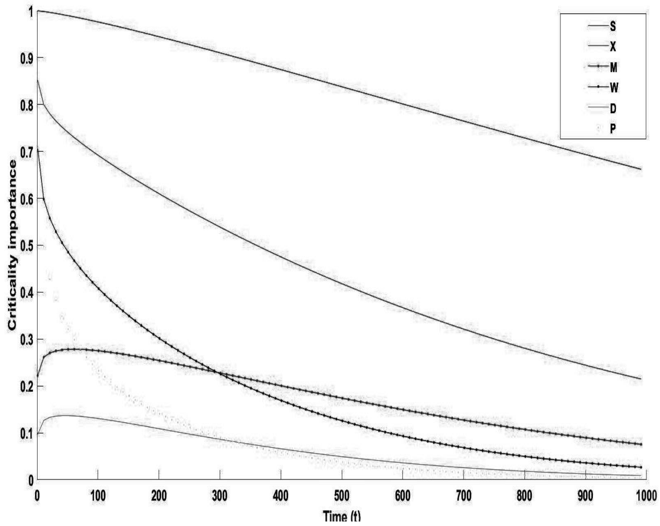

Figure 2. Criticality importance curve of critical components

in Figure 2.

It can be found from the criticality importance curve that in the whole process, each key importance curve shows a decreasing trend. By comparing the criticality importance of each key component, it is found that the criticality importance of the spindle box is the largest, followed by that of the X-axis feed system, tool magazine, cooling system, electrical system and the exchange table.

2.3 Ranking of importance

In order to directly reflect the importance of each key component, on the basis of the obtained dynamic importance curve, the importance of each key component is ranked by the integral mean method, and the formula is as follows:

$$\overline{y} = \frac{\int_a^b f(t)dt}{b-a} \tag{14}$$

Where, a = 0h, B = 1000h. The order of the average importance of each component is shown in Table 3.

Table 3. Importance average sort for critical components

	$\overline{I^B}$	$\overline{I^{Cr}}$
S	0.865	0.846
X	0.584	0.413
M	0.421	0.174
W	0.233	0.024
D	0.161	0.013
P	0.096	0.009

3 Conclusion

In this passage, firstly, established the reliability model of each part of the machining center, and then use the linear correlation test and distribution fitting test are carried out for the model. And then established the reliability importance and criticality importance models of six key components. Finally, sorted the importance of each component.

In this paper, firstly established the fault distribution function of the subsystem, and then calculated the importance of the whole machine, in these way, it can avoid establish of complex subsystem fault tree and make the obtained importance more accurate. Secondly, as a supplement to the reliability importance, after analyzing the reliability importance, this passage also considers the criticality importance, in this way, the importance of each component can be considered comprehensively from more aspects.

The sorting results (as shown in Table 3) show that the spindle box and the X-axis feed system are in the top two places in reliability importance and criticality importance. It can be seen that the spindle box has the greatest impact on the reliability of CNC machine tools. In the ranking of criticality importance, the average of criticality importance of electrical system, exchange table and cooling system are all in the last three places, which shows that these three subsystems have little impact on the reliability of the whole system, but the average of these three components is quite different in the ranking of reliability importance. It can be concluded that the greater the criticality importance of a component is, the easier it is to improve, and the cost of improving this component is lower. Therefore, when we consider to improve the reliability of the whole machine, we should pay attention to the dynamic importance of each key component. When the reliability importance of each component has little difference, we should consider the criticality importance of each components. Therefore, the improvement sequence of these components should be the spindle box, X-axis feed system, tool magazine, cooling system, electrical system and exchange workbench. In this way, not only the reliability of the whole machine can be effectively improved, but also the economic benefits can be improved. In particular, the spindle box should be the focus of reliability improvement.

According to the analysis of this passage, the manufacturer of machining center should focus on improving the product quality of key components, optimizing the structure of components, improving the use performance of key components, and at the same time, the user of CNC machine tools should be systematically trained to reduce the failures caused by operation reasons.

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