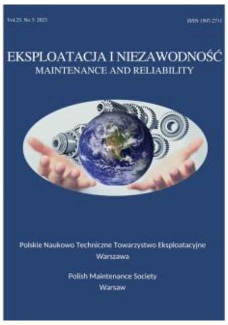

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Key fault propagation path identification of CNC machine tools based on maximum occurrence probability

Indexed by: Web of Science Group

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Highlights

- The dynamic nature of fault propagation is considered.
- Dynamic identification method of key fault propagation path is proposed.
- The maximum occurrence probability model is established.
- This method is proved to be rationality compared with the traditional method.
- Provide a foundation for reliability analysis and maintenance strategies development.

Abstract

In order to revise the deviation caused by ignoring the dynamic character of fault propagation in traditional fault propagation path identification methods, a method based on the maximum occurrence probability is proposed to identify the key fault propagation path. Occurrence probability of fault propagation path is defined by dynamic importance, dynamic fault propagation probability and fault rate. Taking the fault information of CNC machine tools which subject to Weibull distribution as an example, this method has been proven to be reasonable through comparative analysis. Result shows that the key fault propagation path of CNC machine tools is not unique, but changes with time. Before 1000 hours, key fault propagation path is electrical component (E) to mechanical component (M); after 1000 hours, key fault propagation path is auxiliary component (A) to mechanical component (M). This change should be taken into account when developing maintenance strategies and conducting reliability analysis.

Keywords

fault propagation, CNC machine tools, key fault propagation path, improved Pagerank, fault propagation probability.

1. Introduction

A CNC machine tool is a complex system with multiple components such as mechanical component, electrical component, hydraulic component and so on [1]. High coupling of the functionality between components provides possibility for fault propagation [2]. Accurate and reasonable fault propagation analysis can provide an important foundation for identifying key fault propagation paths in the system, thus can provide theoretical support for maintenance strategies and fault analysis [3]. The current methods for fault propagation analysis include Petri net method [4], cellular automata [5], topological network models based on complex network theory [6,7], Bayesian networks [8], and graph theory [9,10] and so on. Wu et al. studied the importance of fault and fault propagation mechanism by high-level Petri net [4], although the Petri net model has strong simulation capabilities, it is difficult to analyze the model for systems with too many nodes and high complexity. Cellular automata have been widely used in the fields of power grids, complex circuits, information

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propagation, but its considerations of changes in system structure and basic components are not comprehensive

[5]. For complex network theory methods, the small world network model is the most classic, which is widely used due to it close to real networks most [6,7]. Although this method compensates for the shortcomings of traditional "experiential knowledge based" modeling, it fails to fully consider the functional coupling relationship between components within the system, resulting in biased analysis results. Qiu et al. proposed

a modeling method based on explicit and implicit Bayesian network (BN) to describe the common-cause failure system [8]. However, the application of Bayesian network method is limited because it needs abundant prior knowledge. Graph theory can be summarized into two types: tree and graph. Much of the data used in fault tree (FT) study are uncertain, Raymond proposed

a methodology to determine the impact of uncertainty on FT study results [9]. Other graph theory methods include bond graph [10], directed graph [11] and so on. Among them, the directed graph model takes the structural characteristics of the system into account and has obvious advantages in dealing with complex systems. Therefore, fault propagation models are often expressed in directed graph models [12,13].

CNC machine tool’s fault propagation process is a step-by-step spread process [14]. The fault propagation path is a series of sequential nodes from the source fault node to the termination fault node in fault propagation process. The fault propagation between two nodes sometimes has two or more fault propagation paths. The key fault propagation path plays a major role in the fault propagation, and its correct identification is of great significance for determining the key fault sources, formulating effective fault prevention strategies and preventing faults propagation in complex system [15]. The correct identification of key fault propagation paths requires accurate and reasonable indicators, for example, Wang et al. used fault propagation strength as the indicator to obtain the key path of fault propagation, where the fault propagation strength is defined by the fault propagation probability and the hazard degree [16]. Hou et al. also used the fault propagation intensity as the indicator to search for the key fault propagation path with the maximum intensity, where the fault propagation intensity is defined by the fault load, the propagation probability between fault nodes, and the output loss caused by equipment failures [17]. Wang et al. used maximum probability as the indicator to search for the key fault propagation path with maximum probability, where the maximum probability is defined by combining fault propagation probability, failure rate, out degree of node edge and betweenness [18]. However, in these studies, the fault characteristics and fault propagation characteristics (such as fault rate, fault propagation probability, etc.) are considered as constant values which are remain unchanged throughout the entire analysis process, ignoring the functional correlation, fault time correlation, and fault propagation dynamics between system components, resulting in significant deviations in the estimation of fault propagation effects, thereby affecting the accuracy of key fault propagation path identification and making it difficult to fully utilize the role of reliability work.

At present, the research on dynamic analysis of key fault propagation path identification is rare and the mainly methods are dynamic fault tree analysis and dynamic Bayesian network. The dynamic fault tree analysis model introduces a dynamic logic gate to represent the time correlation between events, by calculating dynamic probability importance, critical fault events and the fault propagation chain can be obtained [19,20]. By introducing the time dimension, dynamic Bayesian network can establish the importance model of complex system components according to the conditional probability of components at the initial time and the state transition probability between adjacent time slices [21]. These methods have complex modeling and calculation processes and cannot fully explain the dynamic propagation characteristics during fault propagation. For CNC machine tools, Zhang et al. used dynamic fault propagation intensity as an indicator to conduct fault propagation analysis and key fault propagation path identification, where the dynamic fault propagation intensity is defined by the dynamic fault probability, invariant fault impact degree, and betweenness [22]. However, the existing research methods on dynamic fault propagation path identification have a common problem, only considering the dynamic impact of the component's own fault characteristics, ignoring the impact of the dynamic nature of fault propagation between components, thus component importance and fault strength obtained by these methods may deviate, thereby affecting the identification results of the fault propagation key path.Based on the above reasons, this article fully considers the dynamic impact of fault propagation, proposes a key fault propagation path identification method. Firstly, establish fault propagation directed graph based on component partitioning and fault correlation analysis. Secondly, considering the impact of censored data on the rank of component fault data, Johnson's method is used to correct the rank and establish the component failure models. Thirdly, applying the definition of conditional probability, the dynamic model of direct fault propagation probability between components is derived. Fourthly, the dynamic importance of component is obtained by using the improved Pagerank algorithm. Finally, according to dynamic importance dynamic fault propagation probability and fault rate, the occurrence probability model of fault path is established. The key fault propagation path can be identification based on the maximum occurrence probability. In the end, this paper takes the fault information of CNC machine tools which subject to Weibull distribution as an example to illustrate the rationality of the proposed method.

2. Key fault propagation path identification method

The flow chart of key fault propagation path identification based on maximum occurrence probability is shown in Fig. 1.

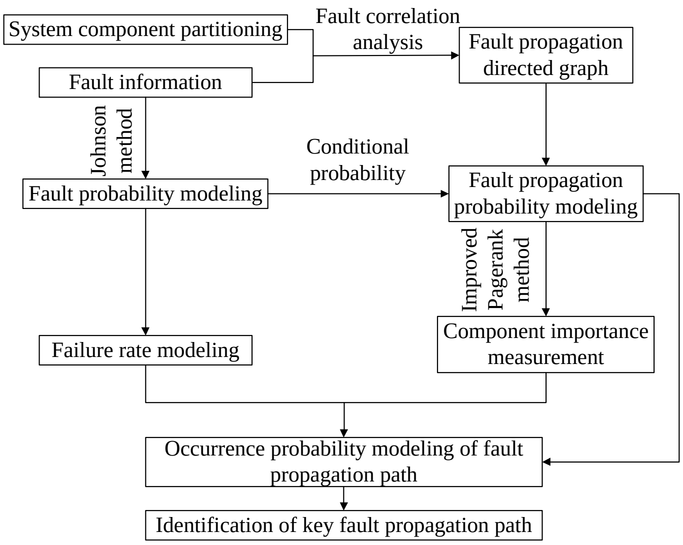

Fig. 1. Flow chart of key fault propagation path identification of CNC machine tools based on maximum occurrence probability.

2.1. Establishment of fault propagation directed graph

This paper uses fault propagation directed graph to describe the direct fault propagation relationship between components. Fault propagation directed graph is established based on the results of component partitioning and fault correlation analysis [23]. First, according to the structure and working principle of the CNC machine tool, the whole CNC machine tool system is divided into *n* components. Then, according to the collected field fault information and the relevant experience knowledge in system function and structure, the fault cause analysis method is adopted to determine the fault correlation between components of the CNC Machine Tools. Finally, components are taken as nodes set $V=\{v_1,v_2,\dots,v_n\}$, the fault propagation relationship between components are taken as directed edges set $E=\{e_{ij}\}(1\le i,j\le n)$, where *n* is the number of components. Then fault propagation directed graph $G=\{V,E\}$ is established, if the fault of component *i* causes the fault of component *j*, then there is a directed edge from node *i* to node *j*.

2.2. Modeling of component fault probability

Considering the impact of censored data on the rank of component fault data, Johnson's method is used to correct the rank. Least square method is used to estimate parameters, and linear correlation coefficient method is adopted to carry out hypothesis testing. Then the component fault probability model can be established.

(1) Ranking of component fault data based on Johnson method

Arrange all the k data from small to large in integer, including fault data and right truncation data, and note the rank number as $j(1\le j\le k)$.Then arrange the *m* fault data of the component which we are interested in from small to large in integer, and note the rank number as $i(1\le i\le m)$. The revised fault data rank $r_i$of the component *i* is calculated by equation (1):

$$r_i=r_{i-1}+\frac{(k+1-r_{i-1})}{(k+2-j)} \tag{1}$$

Where $r_0=0$.

According to the revised rank, distribution function is obtained by equation (2) :

$$F(t_i)=\frac{r_i-0.3}{k+0.4} \tag{2}$$

(2) Parameter estimation of components fault probability model

Assumed that components of CNC machine tool are respectively subject to Weibull distribution [24], then component reliability function and fault probability function are respectively as follows:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}, \quad t \geq 0 \tag{3}$$

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{4}$$

Take logarithm to both sides of equation (4):

$$ln\left[ln\left(\frac{1}{1-F(t)}\right)\right] = \beta\, ln\, t - \beta\, ln\, \theta \tag{5}$$

The Weibull model parameters θ and β can be estimated by fitting the left side $ln\left[ln\left(\frac{1}{(1-F(t))}\right)\right]$ and the right side $ln\, t$ in equation (5) to a linear regression model [25].

(3) Hypothesis testing of component fault probability model

The linear correlation coefficient test method [26] is used to conduct hypothesis testing. When significance level $\alpha = 0.1$, the critical value of the correlation coefficient $\rho_0 = \frac{1.645}{\sqrt{n-1}}$, n is fault data number. Calculate the test value ρ of the model, When $\rho > \rho_0$, it is considered that the correlation between $ln\, t$ and $ln\left[ln\left(\frac{1}{(1-F(t))}\right)\right]$ is linear, and the component fault follows the hypothesis distribution.

2.3. Modeling of direct fault propagation probability between components

The faults between components may be related. The fault may start from a certain component and then cause other component fault through fault propagation. Because the structure and function of each component are different and the influence of fault propagation among components is different, the direct fault propagation probability between component cannot be calculated in accordance with equivalent value.

The probability that one component's fault causes another component fault is called fault propagation probability between components. Applying the definition of conditional probability, direct fault propagation probability between components refers to a ratio, which is equal to the probability difference between comprehensive fault probability (CFP) and individual fault probability (IFP) of the terminal component in a certain directed edge to the comprehensive fault probability (CFP) of the source component. CFP is component fault probability calculated by component self faults and propagation faults caused by other components. IFP is individual fault probability calculated by component self faults. IFP can be directly calculated according to section 2.2. CFP can be obtained through fault propagation data statistics and the methods in section 2.2.

Direct fault propagation probability between components can be calculated according to equation(6).

$$P_{(i\to j)}(t) = \frac{n_{i\to j}(t)}{n_i^{\Sigma}(t)} = \frac{n_j^{\Sigma}(t) - n_j^{I}(t)}{n_i^{\Sigma}(t)} = \frac{F_j^{\Sigma}(t) - F_j^{I}(t)}{F_i^{\Sigma}(t)} \tag{6}$$

Where: $n_{i\to j}(t)$- statistics number of fault propagation data from component i to j;

$n_i^{\Sigma}(t)$, $n_j^{\Sigma}(t)$- statistics number of fault data containing its individual fault and propagation fault of component i and component j.

$n_j^{I}(t)$- statistics number of individual fault data of component j;

$F_i^{\Sigma}(t)$,$F_j^{\Sigma}(t)$, $F_j^{I}(t)$- CFP of component i and component j, IFP of component j.

2.4. Component dynamic importance evaluation based on improved Pagerank algorithm

The component with higher importance has a greater impact on fault propagation. Assuming that the process of fault propagation between components is a Markov process, Pagerank algorithm is introduced by drawing lessons from nodes importance evaluation method of complex network. The PR value obtained from Pagerank algorithm represents the component importance. Considering the dynamicity of fault propagation, the PageRank algorithm is improved contrapuntally. The adjacency matrix is used to describe the network structure; direct fault propagation probability between components obtained in section 2.3 is used as the weight of the directed edge; then component importance can be calculated through iterative calculation.

(1) Basic PageRank principles

PageRank is a classic webpage importance ranking algorithm [27]. The algorithm idea is that if there is a link from page A to B, then page A assigns a PR value to B, and page B accepts the PR value from A. The calculation process is iterated based on equation (7).

$$PR(t) = \frac{1-d}{n} e + dQ^T PR(t-1) \tag{7}$$

Where d is damping factor, usually set $d = 0.7 \sim 0.9$ [28,29], n is the total number of pages, Q is the state transition probability matrix of the network, where q_{ij} represents the probability of node v_i reaching node v_j. It is obtained from adjacency matrix $A = [a_{ij}]_{n\times n}$.

$$a_{ij} = \begin{cases} 1 if(v_i, v_j) \in E \\ 0 if(v_i, v_j) \notin E \end{cases}$$

q_{ij} is obtained through matrix transformation,

$$q_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}$$

Set ε as the specified iteration convergence stable threshold, assign each page node an initial PR value, and when the iteration calculation is satisfied $|PR(t) - PR(t-1)| < \varepsilon$, the iteration ends.

(2) Improved PageRank principles

From the state transition probability matrix Q, it can be seen that the PR value of node is evenly distributed to its outbound nodes in traditional Pagerank algorithm. Due to neglecting the authority of certain page nodes, the traditional Pagerank algorithm exposed many shortcomings in practical applications. Many references have studied improved Pagerank algorithm, such as reference [30] and reference [31], etc. However, these improvements are not applicable to CNC machine tools.

This article defines the state transition probability matrix $Q = [q_{ij}]_{n\times n}$ based on direct fault propagation probability between components obtained in section 2.3

$$q_{ij} = P_{i\to j}(t)$$

If component v_e does not have an outbound component, then the values of the matrix elements in row v_e of Q are all 0. In order to facilitate the calculation of the node importance, replace the rows with all elements being 0 in matrix Q with vectors $\left(\frac{1}{n}, \frac{1}{n}, \dots, \frac{1}{n}\right)$, and establish the final state transition matrix $Q' = [q_{ij}']_{n\times n}$.
where $q_{ij}' = P_{i\to j}(t) + \eta(1/n)$.

Iterative equation of the improved Pagerank algorithm is:

$$IPR(t) = \frac{1-d}{n} e + dQ'^{T} IPR(t-1) \tag{8}$$

The flowchart of the improved Page Rank algorithm is shown in Fig. 2

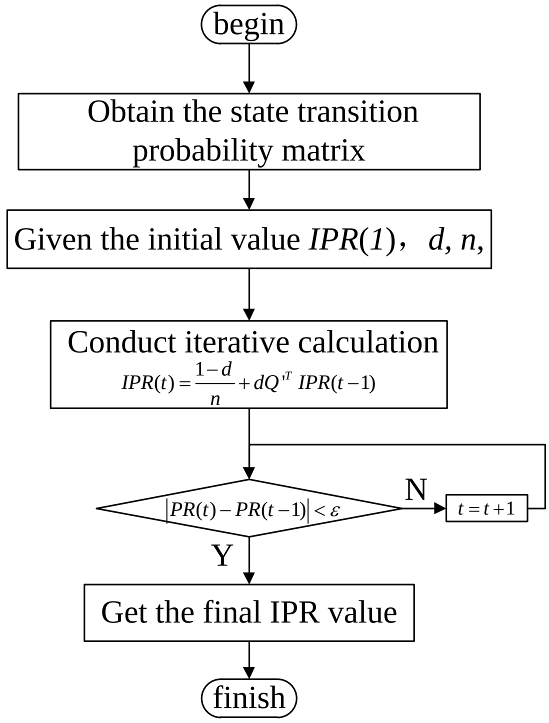

Fig. 2. Flow chart of the improved Page Rank algorithm.

2.5. Key fault propagation path identification based on maximum occurrence probability

This paper identifies the key fault propagation path based on the occurrence probability of the fault propagation path, and the path with the maximum occurrence probability is the key path. Note fault propagation path between components i and j as $l_{ij=}\{e_{ia_1}, e_{a_1a_2}, \dots, e_{a_nj}\}$, the occurrence probability of the fault propagation path is:

$$p(l_{i\to a_1\to\dots\to j}) = \prod_{k=i}^{j-1} exp^{IPR_K(t)} \times \lambda_k(t) \times P_{k\to k+1}(t) \tag{9}$$

$$k \in [i, a_1, \cdots j]$$

Where exp^{IPR_k} is the coefficient that explains the impact of component dynamic importance on the occurrence probability of fault propagation path; $\lambda_k(t)$ is failure rate of component k .$\lambda_k(t) = \frac{f_k(t)}{R_k(t)}$, and $\lambda_k(t)$ can be calculated according to section 2.2. $P_{k\to k+1}(t)$ is direct fault propagation probability between component k and its next node.

3. Case analysis

Taking the data in reference [32] as an example, fault data of 6 CNC machine tools are obtained, which are divided into three types of component faults: mechanical component (M), electrical component (E) and auxiliary component (A) according to the components partition and fault correlation analysis. The fault data of the three types of component are shown in Table 1, where * is on behalf of the fault propagation information, and the letter after the number represents the fault component

Table 1. Fault data of 6 CNC machine tools.

No.	Fault time/h	Truncation time/h
1	30 M 168 M 426 A 46 E	438+
2	311 E 63* E (E→M)	335+
3	107 E 161* A (A→M)	256+
4	82M 63 A 213 M 455* A (A→M)	90+
5	285 A 42* E (E→M) 193* E (E→A)	262.5+
6	8 M 3* E (E→M) 6* E (E→M)	1226+

Including truncation data, there are 24 fault data in Table 1. According to the fault propagation information, fault propagation directed graph is obtained as shown in Fig. 3.

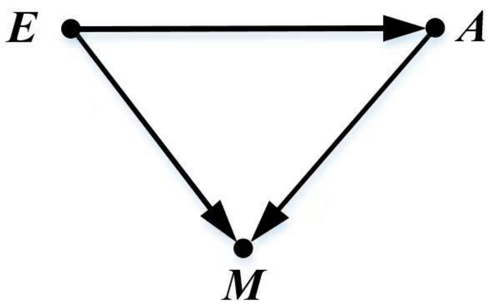

Fig. 3. Fault propagation directed graph (E-electrical component A- auxiliary component M-mechanical component)

3.1. Result of key fault propagation path identification based on maximum occurrence probability

According to section 2.2, the component individual fault probability (IFP) model and comprehensive fault probability (CFP) model can be obtained, which are shown in Table 2

Table 2. Component fault probability distributions model.

Meaning	Fault probability model	Meaning	Fault probability model
IFP model of component E	$F_E^I(t) = 1 - exp\left[-\left(\frac{t}{919.15}\right)^{0.585}\right]$	CFP model of component M	$F_M^{\Sigma} = 1 - exp\left[-\left(\frac{t}{510.28}\right)^{0.616}\right]$
IFP model of component A	$F_A^I(t) = 1 - exp\left[-\left(\frac{t}{1111.08}\right)^{1.116}\right]$	CFP model of component M containing propagation fault from component A	$F_M^{\Sigma A \to M}(t) = 1 - exp\left[-\left(\frac{t}{816.08}\right)^{0.767}\right]$
IFP model of component M	$F_M^I(t) = 1 - exp\left[-\left(\frac{t}{1430.33}\right)^{0.661}\right]$	CFP model of component M containing propagation fault from component E	$F_M^{\Sigma E \to M} = 1 - exp\left[-\left(\frac{t}{605.00}\right)^{0.590}\right]$
CFP model of component A	$F_A^{\Sigma}(t) = 1 - exp\left[-\left(\frac{t}{815.92}\right)^{1.266}\right]$	Notes: IFP-individual fault probability CFP-comprehensive fault probability	

The comprehensive fault rate of the three components can be obtained as follows.

$$\lambda_E^{\Sigma}(t) = \left(\frac{0.585}{919.15}\right)\left(\frac{t}{919.15}\right)^{0.585-1}$$

$$\lambda_A^{\Sigma}(t) = \left(\frac{1.266}{815.92}\right)\left(\frac{t}{815.92}\right)^{1.266-1}$$

$$\lambda_M^{\Sigma}(t) = \left(\frac{0.585}{510.28}\right)\left(\frac{t}{510.28}\right)^{0.616-1}$$

Based on Table 2, applying equation (6), direct fault propagation probability between three components are obtained.

$$P_{(E\to A)}(t) = \frac{F_A^{\Sigma}(t) - F_A^I(t)}{F_E^{\Sigma}(t)}$$

$$P_{(E\to M)}(t) = \frac{F_M^{\Sigma E}(t) - F_M^I(t)}{F_E^{\Sigma}(t)}$$

$$P_{(A\to M)}(t) = \frac{F_A^{\Sigma A}(t) - F_A^I(t)}{F_A^{\Sigma}(t)}$$

Curves of $P_{(E\to A)}(t)$,$P_{(E\to M)}(t)P_{(A\to M)}(t)$are shown in Fig. 4.

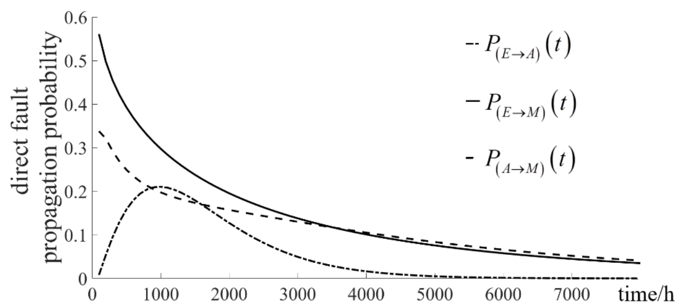

Fig. 4. Curves of $P_{(E\to A)}(t)$,$P_{(E\to M)}(t)P_{(A\to M)}(t)$.

According to 2.2, improved state transition probability matrix is

$$Q' = \begin{bmatrix} 1/3 & 1/3 & 1/3 \\ P_{E\to A}(t) & 0 & 0 \\ P_{E\to M}(t) & P_{A\to M}(t) & 0 \end{bmatrix}.$$

Applying equation (8) , component importance dynamic evaluation is obtained, as shown in Fig. 5

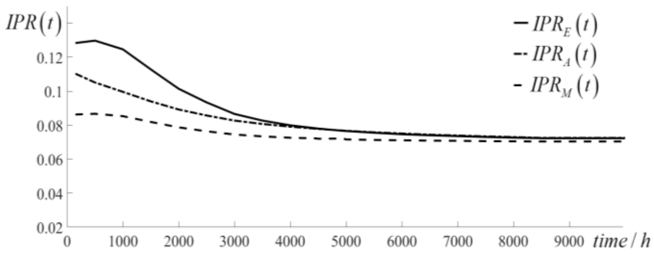

Fig. 5. Curves of component importance dynamic evaluation value.

As can be seen from Fig. 3, there are three one-step propagation paths: E→A, E→M, A→M, in addition, there is a cascade fault propagation path: E→A→M. According to the analysis above and equation (9); occurrence probability of fault propagation path can be obtained, as shown in Fig. 6.

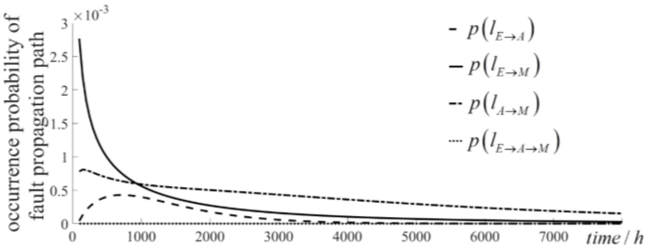

Fig. 6. Curves of occurrence probability of fault propagation path.

From Fig. 4, we can see that: $P_{E\to A}(t)$ increases first and then decreases, reaching the maximum at about 986 hours. $P_{E\to M}(t)$ and $P_{A\to M}(t)$ decreases monotonically with time. The ranking of direct fault propagation probability is variable, and the order from large to small is shown in Table 3

Table 3. Order of direct fault propagation probability from large to small.

Time/h	Order
(0,866]	$P_{E\to M}(t) > P_{A\to M}(t) > P_{E\to A}(t)$
(866, 1606]	$P_{E\to M}(t) > P_{E\to A}(t) > P_{A\to M}(t)$
(1606, 3550]	$P_{E\to M}(t) > P_{A\to M}(t) > P_{E\to A}(t)$
after 3550	$P_{A\to M}(t) > P_{E\to M}(t) > P_{E\to A}(t)$

From Fig. 5, we can see that component importance value is time-varying, before 5000 hours, electrical component (E) have the greatest failure impact degree.After 5000 hours, importance values of electrical component (E) and auxiliary component (A) are similar. This indicates that before 5000 hours , emphasis should be placed on the impact of electrical component failures on other components; after 5000 hours, attentions to failures of electrical component and auxiliary component are equally important.

From Fig. 6, we can see that before 1000 hours, occurrence probability of fault propagation path E→M is the maximum. After 1000 hours, occurrence probability of fault propagation path A→M is the maximum. This indicates that the key fault propagation path of CNC machine tools is not unique, but changes with the running time. Before 1000 hours , key fault propagation path is E→M ; after 1000 hours, key fault propagation path is A→M .

Occurrence probability of fault propagation path at 300h, 600h, 1000h,1500h, 2000h are shown in Fig.7.

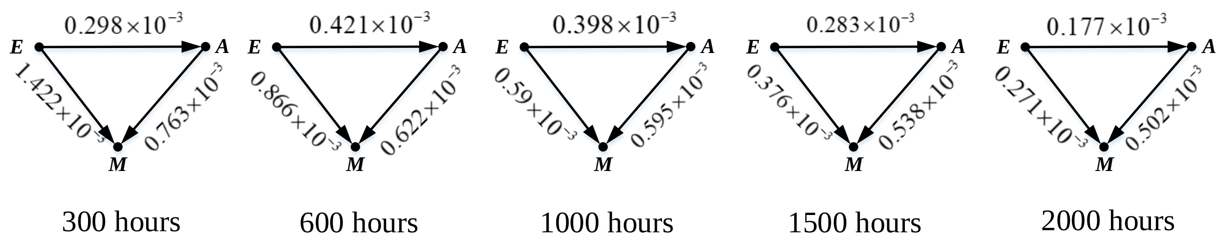

Fig. 7. Occurrence probability of fault propagation path at difference time point.

From Fig.7 we can see that before 1000h, the difference of occurrence probability between E→M and A→M became smaller and smaller. After 1000h, difference of occurrence probability between A→M and E→M became larger and larger. At 1000h, occurrence probability of A→M and E→M are basically the same, indicating that around 1000h, both A→M and E→M should be given attention equally. Before 1000h, E→M should receive more attention, and after 1000h, A→M should receive more attention. This change should be taken into account when developing maintenance strategies and conducting reliability analysis.

Occurrence probability of cascade fault path E→A→M is the smallest all the time. The rate of occurrence probability of cascade path to the max occurrence probability of fault path will be more than 1000. Therefore, the impact of cascade fault propagation E→A→M can be ignored.

3.2. Result of key fault propagation path identification based on traditional method

This article adopts the method of reference 22 for comparative verification. In reference 22 , key fault propagation path can be obtained by the maximum fault propagation intensity,which is defined by propagation probability and edge betweeness.Fault propagation probability is calculated by equation(10).

$$P'_{i\to j}(t) = F_i(t)R(e_{i\to j}) \tag{10}$$

Where $F_i(t)$ is fault probability of component i, $R(e_{i\to j})$ is fault impact degree between component i and component j.$R(e_{i\to j}) = \sqrt{R(v_i)R(v_j)}$,$R(v_i)$、$R(v_j)$ are importance values of component i and component j.

After calculation, the fault propagation intensity curve of each fault propagation path can be obtained, and is shown in Fig. 8.

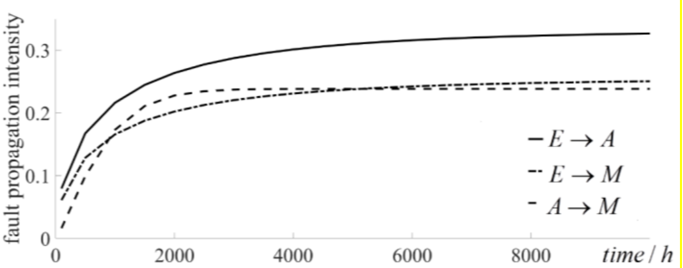

Fig. 8. Curves of fault propagation intensity.

From Fig. 8, we can see that fault propagation intensity curve of each fault propagation path is dynamically changing, but the key fault propagation path is E→A all the time.

3.3. Comparative analysis

According to the analysis results of section 3.1 and 3.2, key fault propagation path identification result obtained by two methods can be displayed in Fig.9. It can be seen that the key fault propagation path obtained by traditional methods has always been E→A, while the key fault propagation path obtained by the maximum occurrence probability method proposed in this article is variable, before 1000 hours , key fault propagation path is E→M ; after 1000 hours, key fault propagation path is A→M. The reason is that traditional methods only consider the dynamic nature of component failure probability, without considering the impact of fault propagation dynamics.

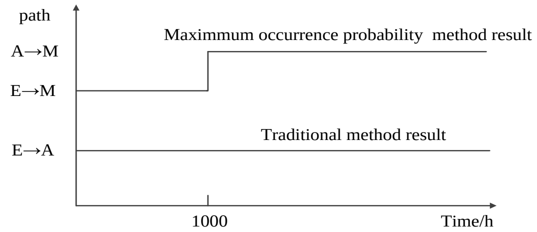

Fig. 9. Key fault propagation path identification result.

4. Conclusions

In order to revise the deviation caused by ignoring the dynamic character of fault propagation in traditional fault propagation path identification methods, a method based on the maximum occurrence probability is proposed to identify the key fault propagation path. Occurrence probability of fault propagation path is defined by dynamic importance, dynamic fault propagation probability and fault rate.

In order to illustrate the rationality of the proposed method, this paper takes the fault information of CNC machine tools which subject to Weibull distribution as an example and is compared with the traditional method based on fault propagation intensity. The analysis results indicate that, after considering the dynamic impact of fault propagation, the key fault propagation path of CNC machine tools is not unique, but changes with the running time. Before 1000 hours, key fault propagation path is electrical component (E) to mechanical component (M); after 1000 hours, key fault propagation path is auxiliary component (A) to mechanical component (M). This change should be taken into account when developing maintenance strategies and conducting reliability analysis.

The proposed method can dynamically perform fault analysis and achieve fault tracing. If M fails, before 1000 hours, the component most likely to cause propagation failure of M is E. After 1000 hours, the component most likely to cause propagation failure of M is A. It has certain guiding significance for identifying key fault sources, developing effective fault prevention strategies, and preventing the spread and spread of complex system faults.

It can be seen that if the component division of CNC machine tools is more refined, the dynamic changes of key fault propagation paths will be more complex. Therefore, the future work is to further divide the components and study the dynamic changes in the key fault propagation paths between more complex components

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