Fault Analysis of Machine Tools Based on Grey Relational Analysis and Main Factor Analysis

To cite this article: Guixiang Shen et al 2018 J. Phys.: Conf. Ser. 1069 012112

View the article online for updates and enhancements.
Fault Analysis of Machine Tools Based on Grey Relational Analysis and Main Factor Analysis

Guixiang Shen¹, Chenyu Han¹,², Bingkun Chen¹ Luyao Dong¹ and Peilong Cao¹
¹Industrial Engineering Department, Jilin University, China.
²Industral Engineering, Mechanical Engineering Department, Jilin University, China. 969929715@qq.com

Abstract. In order to realize the recognition of key subsystems of NC machine tools under fault-related conditions, a method of factor association analysis based on integrated grey relational analysis and principal factor analysis was proposed. According to the subsystem failure time series, the correlation of the failure process between the various subsystems of the machine tool is evaluated by the grey correlation degree calculation. In combination with the principal factor analysis method, the subsystem characteristic values are calculated and the key machine subsystems are determined accordingly. This method provides the basis for subsequent reliability improvement. Finally, a domestic CNC machine tool is used as an example to verify the effectiveness of the method.

1. Introduction
CNC machine tools are typical mechatronic systems. The complexity of their structure and the diversity of functions make their faults relevant. The decline in the operational reliability of CNC machine tools is a result of the combined effects of multiple subsystems' independent faults and propagation failures. At this point, how to identify the key subsystems of CNC machine tools and provide reliable basis for reliability improvement has become the focus and difficulty of current reliability research. The traditional identification method of key subsystems of machine tools is mainly from the perspective of fault analysis and reliability model.

For example, there are methods that calculate the hazard degree based on the failure mode, impact and criticality analysis (FMECA) or RNP values based on failure risk analysis [3-5]. Number of failures, the importance of the structure, the importance of the probability, the importance of the minimum cut set, the key importance, and the degree of joint importance [6-8] are widely used to identify key subsystems. There are also key subsystem identification methods based on reliability static, dynamic impact and dynamic core impact, etc.

The above papers achieve a significant increase in the reliability of machine tools. However, these methods ignore the impact of the time sequence of failure on its importance, so there is a certain bias in the identification of critical subsystems.

Therefore, this paper proposes a method of factor association analysis integrating the grey relational degree and principal factor analysis [9]. Finally, a domestic CNC machine tool is used as an example to verify the effectiveness of the method.
2. Analysis of Key Subsystems Combining with Degree of Grey Incidence and Principal factor analysis

2.1. Grey Relational Degree Calculation Based on Fault Time Series

The basic idea of grey relational analysis is to determine whether the connections between different curves are tight, based on the degree of similarity of the sequence curve geometry. The closer the curves, the greater the degree of correlation between the corresponding sequences, and vice versa.

Assume the failure time series of subsystem of machine tool \( h \) is \( X_h = \{X_{i1}, X_{i2}, \ldots, X_{in}\} \), the subsystem which compared with \( h \) is \( i \), failure time series of \( i \) is \( X_i = \{X_{i1}, X_{i2}, \ldots, X_{in}\} \); The absolute difference between the two sequences at point \( j \) is \( \Delta_i(j) = |X_{i j} - X_{h j}| \) \( (j = 1,2,\ldots,n) \).

The correlation coefficient at point \( j \) is

\[
\eta_{hi}(j) = \frac{\min_{j} \min_{j} [\Delta_i(j)] + \rho \max_{j} \max_{j} [\Delta_i(j)]}{\Delta_i(j) + \rho \max_{j} \max_{j} [\Delta_i(j)]}
\]

In equation (7), \( \min_{j} \min_{j} [\Delta_i(j)] \) -- minimum difference between two poles, it represents the minimum value of the absolute difference between the sequence \( X_i \) and the \( X_h \) in each corresponding point ; \( \max_{j} \max_{j} [\Delta_i(j)] \) -- maximum difference between the two poles, it indicates the maximum value of the absolute difference between the sequence \( X_i \) and the \( X_h \) in each corresponding point. \( \rho \) --Resolution, ...,it is usually 0.5.

The degree of association refers to the average value of the correlation coefficients of the failure time series of the two subsystems at each point. For example, the formula for calculating the degree of association between sequence \( X_i \) and sequence \( X_h \) is as follows:

\[
r_{hi} = \frac{1}{n} \sum_{j=1}^{n} \eta_{hi}(j)
\]

In the process of using the machine tool, the number of failures of each subsystem is different, which makes it difficult to calculate the degree of grey correlation. Therefore, this paper based on the data of fault time which have least data of failure to calculate. It can make the fault data interval and number consistent.

2.2 Main Factor Analysis Method

The principal component analysis method is a method that makes the principal component of the new variable a linear combination of the original variables through an appropriate mathematical transformation. The greater the proportion of the principal component in the amount of information for the variation, the greater its role in the overall evaluation. [5].

Firstly, Establishment of correlation matrix A between subsystems

\[
X = \begin{bmatrix}
1 & x_{12} & \ldots & x_{1n} \\
x_{21} & 1 & \ldots & \ldots \\
\ldots & \ldots & \ldots & \ldots \\
x_{n1} & x_{n2} & \ldots & 1
\end{bmatrix}
\]

(3)

Calculate eigenvalues and eigenvectors from the normalized correlation matrix \( X \).
\[ | \lambda_{in} - X | = 0 \] (4)

We can get \( n \) eigenvalues as \( \lambda_g (g = 1,2,...n) \), \( \lambda_1 \) is arranged in order of size \( \lambda_1 \geq \lambda_2 \geq ... \geq \lambda_n > 0 \).

The weight is the variance of each principal component. Contribution rate is \( \frac{\lambda_g}{\sum_{g=1}^{n} \lambda_g} \). The higher the contribution rate, the more important it is in the system.

Final evaluation value:

\[ F = \sum_{g=1}^{k} \left( \frac{\lambda_g}{\sum_{g=1}^{n} \lambda_g} \right) F_g \] (5)

3. Identification of Key Machine Subsystems Based on Integrated Grey Correlation and Principal Factor Analysis

This paper uses a total of 89 censored fault data of 15 CNC machine tools for research. As of the end of the experiment, there were a total of 89 failure data for the five subsystems. Use the method in the literature [6] to process the total fault time method. The processed fault data is shown in Table 1.

| Table 1. Fault data of five subsystems of machine tool |
|--------------------------------------------------------|
| Failure time                                          |
| Feed system                                           |
| 15.66724, 27.43279, 37.48416, 52.627, 61.752, 139.76, 209.4516 |
| Tool magazine system                                  |
| 212.3697, 321.8181, 333.5731, 444.8616, 545.0352, 604.5967, 694.0554 |
| Chip removal system                                   |
| 766.8948, 840.9221, 852.4746, 925.6691, 1064.38, 1186.914, 1196.513 |
| spindle system                                        |
| 1.001.095, 1134.298, 1149.143, 1380.939, 1406.598 |
| Electrical system                                     |
| 12.5645, 16.28667, 37.81778, 38.24857, 89.59561, 163.0335, 209.6303 |
| 532.8158, 533.3385, 579.4198, 604.3553, 629.666, 888.5943, 950.2262 |
| 1076.67, 1098.143, 1137.765, 1999.704 |
| 76.97717, 88.2042, 152.4425, 821.6122, 902.5695, 974.2479, 1087.53 |
| 1260.111, 1418.996, 1616.27, 1616.289, 1716.791, 2469.419 |
| 174.516, 275.2068, 779.8546, 830.2894, 1199.125, 1506.95 |

Take the feed system as an example and use the formula in [5] to get \( \hat{a} = 0.2791, \hat{b} = 0.6020 \). The formula can be used to get the cumulative fault distribution of the feed system as follows:

\[ N(t) = 0.2791t^{0.6020} \] (6)

According to the cumulative fault number corresponding to Table 1, it can be obtained within the fault time interval [0, 2500], there is \( D_n = 0.1935 \). At the same time, taking \( \alpha = 0.05 \), then \( D_n^\alpha = 0.2443 \), it can be seen that the cumulative failure of the system obeys the non-homogeneous Poisson process of \( N(t) = 0.2791t^{0.6020} \). Similarly, \( \hat{a} \) and \( \hat{b} \) of the remaining subsystems are available, and trend tests and goodness-of-fit tests are performed on the remaining subsystems. Using the above algorithm, all the subsystems can be passed. Finally you can get \( \hat{a} \) and \( \hat{b} \) as shown in Table 2. The cumulative failure distribution curve of each subsystem of the machine tool is shown in figure 1.
Table 2. Parameter Estimates of Machine Tool Subsystem

|       | Feed system (F) | Chip removal system (C) | Tool magazine (M) | Spindle system (S) | Electrical system (E) |
|-------|-----------------|-------------------------|-------------------|--------------------|-----------------------|
| $\hat{a}$ | 0.2791          | 0.0089                  | 0.4599            | 0.0229             | 0.0025                |
| $\hat{b}$ | 0.602           | 0.9854                  | 0.5358            | 0.8105             | 1.0528                |

Figure 1. Cumulative fault distribution curve for subsystems of machine tool

When the feed system is the compared subsystem and the chip removal system is the comparison subsystem, the minimum absolute error is 1.172, the maximum absolute error is 11.170, and $\rho$ is 0.5. Similarly, equations (7) and (8) can be used to calculate the degree of correlation between failures of other subsystems, as shown in Table 3.

Table 3. Failure correlation degree of five subsystems of machine tool

|       | F                | C                | M                | S                | E            |
|-------|-----------------|-----------------|-----------------|-----------------|--------------|
| F     | 1               | 0.5403          | 0.5169          | 0.5922          | 0.6533       |
| C     | 0.5403          | 1               | 0.5432          | 0.7592          | 0.6634       |
| M     | 0.5169          | 0.5432          | 1               | 0.5854          | 0.5805       |
| S     | 0.5922          | 0.7592          | 0.5854          | 1               | 0.5564       |
| E     | 0.6533          | 0.6634          | 0.5805          | 0.5564          | 1            |

According to formula (10), the matrix eigenvalue $\lambda_i$ and contribution rates of various subsystems are calculated, as shown in Table 3.

Table 4. Eigenvalues and Contribution Rate of machine tools’ Subsystem

|       | Feed system (F) | Chip removal system (C) | Tool magazine (M) | Spindle system (S) | Electrical system (E) |
|-------|-----------------|-------------------------|-------------------|--------------------|-----------------------|
| Eigenvalue | 0.1884          | 0.386                   | 0.4908            | 0.5342             | 3.4006                |
| contribution rates | 3.77%           | 7.72%                   | 9.82%             | 10.68%             | 68.01%                |

The eigenvectors corresponding to the five eigenvalues are:
It can be seen that the contribution of the electrical system, spindle system and magazine system exceeds 85%. And the credibility of the evaluation is 88.51%. So the comprehensive assessment of the machine tool is as follow:

\[
F = 0.0982F_1 + 0.1068F_2 + 0.6806F_3
\]

From Table 3, based on the contribution rates of the various subsystems of the machine tool, it can be seen that the contribution rate of each subsystem of the machine tool from high to low is electrical system, spindle system, tool magazine system, chip removal system and feed system.

4. Conclusion
According to this method, the electrical system is critical subsystem. This method establishes the cumulative failure distribution model, and fully considers the degree of correlation between failures of various subsystems in the machine tool system, and thus obtains key subsystems.

5. Acknowledgments
Research in this paper was supported by Major national science and technology projects of China (Grant no.2014ZX04015061) of High grade CNC machine tools and basic manufacturing equipment, and Jilin Provincial Natural Science Foundation of China (Grant no. 20170101212JC). In addition, Chenyu Han would also thanks the patience, care and support from my beyond loved fiancée, Meizheng Li. This paper and my love will last forever until the end of the world.

6. References
[1] Zhang Y, Shen G, Jia Y, et al. Research on the disciplinarian and reliability of failure distribution of CNC lathe[J]. Transactions of the Chinese Society for Agricultural Machinery, 2006, 37(1):156 - 159.
[2] Weckman G R, Shell R L, Marvel J H. Modeling the reliability of repairable systems in the aviation industry[J]. Computers & Industrial Engineering, 2001, 40(1–2): 51 - 63.
[3] Wang X F, Shen G X, Zhang Y Z, et al. Analysis on risk priority number of critical component of machining center based on group decision-making and various assignment ways[J]. Journal of Jilin University, 2011, 41(6):1630 -1635.
[4] Zhang Y Z, Zheng S, Shen G X, et al. Criticality analysis for CNC turret adopting importance and fuzzy reasoning [J]. Journal of Jilin University, 2012, 42(5):1157 - 1162.
[5] Louit D M, Pascual R, Jardine A K S. A practical procedure for the selection of time-to-failure models based on the assessment of trends in maintenance data[J]. Reliability Engineering & System Safety, 2009, 94 (10):1618 - 1628.
[6] Birnbaum Z W. On the importance of different components in a multicomponent system. Multivariate Analysis II, 581-592. [J]. Multivariate Analysis II, 1968:581 - 592.
[7] Wang Z M, Yang J G, Wang G Q, et al. Reliability assessment of multiple NC machine tools with minimal repair[J]. Journal of Harbin Institute of Technology, 2011, 43 (7): 127 - 130.
[8] Yu J, Zhu Z, Shi Y, et al. Failure Rate Evaluation of CNC Machine Tools Based on G-R Curves Analysis[C]// Third International Conference on Measuring Technology and Mechatronics Automation. IEEE, 2011:167 -169.
[9] GX Shen, SH Fan, YZ Zhang, et al. Reliability influence analysis of subsystem in NC machine tools. Journal of Jilin University, 2010, vol. 40: 266 - 0269.