Fuzzy FMECA for CNC machine tool spindle system

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Abstract. The spindle systems of the state-of-the-art computer numeric controlled (CNC) machine tools are increasingly important than ever, for that the even distinguished demand of higher efficiency, reliability and productivity of today’s manufacturing industry lead to the aforementioned system works under higher rotational speed and higher cutting performance. This paper extended the conventional failure modes, effect and criticality analysis by integrating which with fuzzy theory to finitizing a failure analysis of an electric spindle system of a CNC machine tool aims to avoid unwanted failures of the system and achieve safe and reliable operation of the device. Critical components, critical failure modes of the spindle system that call for special attention are ascertained. Root causes of the critical failure modes as well as recommendations e.g. periodical inspection of the bearings as well as robust design for electrical and electronical complements for avoiding their occurrence are obtained.

Keywords: FMECA, risk analysis, criticality analysis, spindle system, CNC

1. Introduction

The state-of-the-art Computer Numeric Controlled (CNC) machine tools incorporate a wide selection of mechanical and electrical systems e.g. main drive system, control system, electrical system, as well as spindle system [1]. Those systems work interactively together aiming to achieve designed functions of CNC machine tools, for instance, milling, drilling, grinding, etc. [2]. A foundational report of global machine tool market that was issued in 2019 announced that spindle systems of CNC machine tools are increasingly important than ever for that the even distinguished demand of higher efficiency, reliability and productivity of today’s manufacturing industry lead to the aforementioned system works under higher rotational speed and higher cutting performance [3].

Machine tool spindles fulfill two tasks [4. 5]: (i) rotate the tools (workpiece in some cases) precisely in space; (ii) transmit the designed mechanical energy to the cutting zone for metal removal. From these points of view, the reliability and performance of the spindle system is of a decisive factor that supports the required metal removal rates and quality of the machined parts and even significant to effectiveness as well as productivity of CNC machine tools. Generally, failures of spindle systems always give rise to disastrous consequences to CNC machine tools for the operational performance of which related not only to the cutting rates of the manufacturing tasks but also affect the machining prices of the object that to be manufactured.

Failure analysis, also known as risk analysis in some scenarios, of CNC machine tools as
well as key system e.g. main drive system and components e.g. control board is a mandatory work for the manufactory factory of CNC machine tools before the equipment to be delivered to their users. The computed results will be predetermined parameters in the user manual as a basis of that users can easily design inspection and maintenance strategies of CNC machine tools. Accordingly, safe, reliable, and optimized manufacturing processes can be expected [2], [4], [6-9].

Failure analysis is the initial step of reliability, availability, operation, and maintainability for devices as well as complex systems. Specifically, failure analysis of spindle system of CNC machine tools can identify [5], [10-14]: (i) the components and structures of the spindle system that more critical than others, together with (ii) their failure modes, failure effects, and failure causes that call for, particularly attention for safe and reliable operations. And accordingly, to (iii) suggest recommendations to end-users of CNC machine tools like preventive activities as well as correction measures to ensure the manufactory tasks can be achieved as they were designed and expected.

Methodologies of failure analysis can be divided into three categories subjective methodologies such as Monte Carlo simulation, objective methodologies e.g. what-if checklist, and semi-objective methods like failure mode and effect analysis (FMEA) or its upgraded methods failure modes, effect and criticality analysis (FMECA) [15, 16]. Among others, FMECAs, thanks to easy construction, highly hierarchical structures, and require not so much operational data, have been implemented in various fields of complex systems.

Considering that the reliability and quality researches of spindle systems of CNC machine tools recently focus the most on reliability analysis and assessment by using subjective methodologies, for instance, Li et al. [17] complete reliability analysis of a spindle system of a CNC machine tool by using the finite element analysis model and the analysis concluded the cumulative distribution curve of the random cutting load of the CNC machine tool. Jiang et al. [18] conducted a reliability assessment of machine tool spindle bearing based on vibration features identification and analysis. Janak et al. [4] discussed the opportunity of implementation of sensors to spindle system of CNC machine tools and further demonstrated the way of conducting the monitoring.

The aforementioned work cannot identify the critical components, failure modes, as well as failure causes of the spindle system of the CNC machine tool to be discussed in this study. One the other hand works on the implementation of FMEAs and FMECAs for failure analysis or risk analysis are hardly found in the published paper available. Hence, this paper put great emphasis on complete a thorough failure analysis of the spindle system of the CNC machine tool to identify it critical items like the components and structures that more critical than others, failure modes, failure effects, and failure causes that call for particular attention and suggest recommendations to end-users of CNC machine tools like preventive activities as well as correction measures by using FMECA technique. However, for overcoming the situation that restricting the field of failure analysis of spindle systems of the CNC machine tools as well as a complex system, that are, insufficient data and lacking deep, through knowledge about mechanisms of the objective aforementioned fuzzy theory is applied to combine with FMECA technique.

The remainder of this paper is organized as follows: Section 2 describes the fuzzy FMECA methodology to be used in this analysis. Section 3 demonstrates the spindle systems of the CNC machine tool that considered in this study together with the data source. Results in Section 4 and conclusions are provided in Section 5.

2. Methodology

The FMECAs are consist of two steps: FMEA and criticality analysis (CA). The former identifies the failure modes, their local and global effects, root causes of the collected failure modes, and actions (related to maintenances as well as operations) that designed to remove failure modes by avoiding the occurrence of their root causes, while, the latter is conducted to evaluate the consequences (credibility) of each effect of a failure mode.

The purpose of applying FMECA for failure analysis of spindle systems of CNC machine tools is to identify the critical failure modes that lead to malfunctions of the system and then
analyze the root failure causes from design, operation, and maintenance points of views by using FMEA methodology. Subsequently, priorities the effect of failure effect by CA, in this step, aims address restriction like insufficient data and lack of deep, through knowledge about mechanisms of the spindle system of CNC machine tool that considered, the fuzzy theory is selected to combine with conventional FMEA to complete the failure analysis work.

The procedure of conducting the proposed fuzzy FMECA technique is summarized as:
1. Ascertain the CNC machine tool and its spindle system to be analyzed.
2. Decompose the spindle system into components, parts, until elementary structures.
3. Trace the operation process in a certain period e.g. one year in this study and record failure modes that have been happened during the observation.
4. Collect the consequence of each failure that been mentioned in step (3) and record.
5. Analyze the failure causes (each failure mode may have several causes) of each failure that been mentioned in step (3) and record.
6. Find out severity as well as corrective and preventive actions to avoid failure cause(s) of each failure mode.
7. Priorities failure modes by quantification of their effects using fuzzy FMECA technique.

The way of implementing fuzzy FMECA is as follows. Select elements that affect the factors mechanisms of the spindle system of CNC machine tool that considered, the fuzzy theory is used to combine with conventional FMEA to complete the failure analysis work. Statistical methods are needed to determine the membership of the i factor u_i relative to the factor level v_j. That is: set up a group of h experts, and a certain failure mode influence factor u_i is judged by h experts to a judgement level v_j. If among h experts, there are h_j people who judge u_i to belong to v_j. Accordingly, the evaluation set for u_i is

\[ R^K = \{ \frac{v_1}{u_i}, \frac{v_2}{u_i}, ..., \frac{v_m}{u_i} \} = \{ r_{1i}, r_{2i}, ..., r_{mi} \} \]  

The obtained n fuzzy evaluation vectors are arranged into a matrix, that is, the factor fuzzy evaluation matrix \( R^K \)

\[ R^K = \begin{pmatrix} r_{1i} & r_{2i} & ... & r_{mi} \\ r_{1j} & r_{2j} & ... & r_{mj} \\ . & . & . & . \\ . & . & . & . \\ r_{ni} & r_{nj} & ... & r_{mn} \end{pmatrix} \]  

Because each factor has a different degree of influence on the research object, different weights need to be assigned. The weight set is represented as

\[ W = \{ w_i, w_2, ..., w_n \} \]  

Note that \( \sum w_i = 1 \) as well as \( w_i > 0 \).

According to the above, a first-level fuzzy evaluation matrix can be obtained, and the first-level fuzzy evaluation matrix \( R^K \) of the failure mode is used as the evaluation object for the entropy value. \( H_j = (h_{k}, h_{k_2}, ..., h_{j}) \) is the entropy value of \( i \) th evaluation object. \( h_j \) reflect the entropy value of \( j \) th index, which can be calculated as

\[ h_j = -p \sum f_j \ln f_j \]  

In which, \( p \) is the comment correlation coefficient (see equation (7)) and \( f_j \) represents the proportion of parameter anomalies in the entire indicator system (see equation (8)).
\[ p = \frac{1}{\ln m} \]  
\[ f_m = \frac{1}{\sum s} \]  

Determine the entropy weight vector \( W = \{ w_1, w_2, \ldots, w_n \} \) as
\[ w_j = \frac{1-h_j}{\sum_{j=1}^{n} (1-h_j)} \]

Transform the set of factor weights for the identified failure mode as a vector \( B^k \)
\[ B^k = W \times R^k = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix} \]

Determine the comprehensive hazard level \( C^k \) to indicate the degree of damage to the system by each failure mode as
\[ C^k = B^k \times V^T \]

3. The Considered Spindle System
The electric spindle system that to be analyzed assembled main motor and spindle and installed within the DMU nomoBLOCK100 CNC machine tool. The electric spindle system includes the electric spindle itself and its accessories: electric spindle, high-frequency variable frequency device, cooling device, built-in encoder, oil mist lubricator, broach device and broach cylinder. Through the broach cylinder, the piston rod in the broach cylinder pushes the loose ring of the broach device, so that the entire broach device is pushed out to complete the loosening process: The broach device can be pulled back to its entirety by its own butterfly spring elastic force. Device to complete the tool change action. The built-in encoder is a pulse encoder placed in the electric spindle to achieve automatic tool change and rigid threads, to achieve accurate phase angle control and feed coordination. The high-frequency frequency conversion device is to realize the rotation speed per minute of the electric spindle. A high-frequency frequency conversion device must be used to drive the high-speed motor built-in the electric spindle. The electric spindle system of the DMU nomoBLOCK100 CNC machine tool is demonstrated in figure 1.

![Figure 1. The schematic diagram of spindle system structure](image)
1-butterfly spring; 2-tool changing device; 3-clamping device; 4-front bearing; 5-front cover; 6-cooling system; 7-shell; 8-stator rotor; 9-rotating shaft; 10-rear Cover; 11-rear bearing; 12-piston; 13-cylinder.

The data that been used in this study is based on what been observed by authors from a manufacturing company. The observation interval is one year. During the data collection period, components that been encountered in failures, failure modes, failure causes, failure consequences, the severity of failures, as well as measures or actions been conducted for repair were recorded.

4. Results

Thorough failure analysis of the electric spindle system of the DMU nomoBLOCK100 CNC machine tool was carried out by employing the designed fuzzy FMECA technique. Initially, 13 failure modes of nine components of the spindle system were analyzed by using conventional FMEA methodology and the results of which was edited into a FMEA sheet see Appendix A.

Subsequently, CA by integrating the fuzzy theory was carried out. This study takes the probability of failure (PF), the severity of the impact of failure modes on the spindle system (S), detection (D), and difficulty in maintenance (M) are used as evaluation indices. Accordingly, the factor set of failures of the electric spindle system of the DMU nomoBLOCK100 CNC machine tool can be determined as \( U = \{PF, S, D, M\} \). Moreover, a four-level specialist opinion set is determined as shown in table 1.

### Table 1. the four-level specialist opinion set.

| Impact factors | 1     | 2     | 3     | 4     |
|----------------|-------|-------|-------|-------|
| Failure Probability Level | Few   | Occasional | Sometimes | Frequent |
| Severity Level | Slight | Medium | Serious | Fatal |
| Detection Level | Easy | Difficult | Hard | Cannot Be Detected |
| Maintenance Level | Debugging | Reinstallation | Replacement | Cannot Maintenance |

According to the experts’ opinion, failure probability fuzzy set, severity fuzzy set, detection fuzzy set, as well as maintenance fuzzy set of failure modes #1 (FM#1) is designed to be \( R^1_1 = \{0.1,0.7,0.2,0\} \), \( R^2_1 = \{0,0.2,0.8,0\} \), \( R^3_1 = \{0,0.7,0.3,0\} \), and \( R^4_1 = \{0,0.2,0.8,0\} \), respectively. Hence, the fuzzy evaluation matrix of FM#1 can be obtained according to equation (4) as

\[
R^1 = \begin{bmatrix}
0.1 & 0.7 & 0.2 & 0 \\
0 & 0.2 & 0.8 & 0 \\
0 & 0.7 & 0.3 & 0 \\
0 & 0.2 & 0.8 & 0 
\end{bmatrix}
\]

Similarly, the fuzzy evaluation matrixes of FM#2 to FM#13 ( \( R^2 \) to \( R^{13} \) ) can be obtained as

\[
R^2 = \begin{bmatrix}
0.2 & 0.2 & 0.6 & 0 \\
0.2 & 0.8 & 0 & 0 \\
0.1 & 0.8 & 0.1 & 0 \\
0.6 & 0.4 & 0 & 0 
\end{bmatrix}, \quad R^3 = \begin{bmatrix}
0.2 & 0.5 & 0.2 & 0.1 \\
0.7 & 0.3 & 0 & 0 \\
0.2 & 0.7 & 0.1 & 0 \\
0 & 0.2 & 0.8 & 0 
\end{bmatrix}, \quad R^4 = \begin{bmatrix}
0.1 & 0.1 & 0.3 & 0.5 \\
0.3 & 0.6 & 0.1 & 0 \\
0.2 & 0.7 & 0.1 & 0 \\
0.2 & 0.1 & 0.7 & 0 
\end{bmatrix}
\]
According to equation (6), the entropy value of each failure mode is computed as

$$H_1 = (0.5784, 0.3610, 0.4407, 0.3610);$$

$$H_2 = (0.6855, 0.3610, 0.4855, 0.2345);$$

$$H_3 = (0.8805, 0.4407, 0.6477, 0.3610);$$

$$H_4 = (0.5784, 0.3610, 0.4407, 0.2345);$$

$$H_5 = (0.6477, 0.4855, 0.4855, 0.2345);$$

$$H_6 = (0.5784, 0.4855, 0.4855, 0.4609);$$

$$H_7 = (0.5784, 0.3610, 0.4407, 0.2345);$$

$$H_8 = (0.8805, 0.4855, 0.4855, 0.2345);$$

$$H_9 = (0.5784, 0.3610, 0.4407, 0.2345);$$

$$H_{10} = (0.5784, 0.4855, 0.4855, 0.2345);$$

$$H_{11} = (0.5784, 0.3610, 0.4407, 0.2345);$$

$$H_{12} = (0.5784, 0.3610, 0.4407, 0.2345);$$

$$H_{13} = (0.5784, 0.3610, 0.4407, 0.2345);$$

Hence, the fuzzy weights of each failure mode are derived using equation (9) as

$$W_1 = (0.1866, 0.2829, 0.2476, 0.2829);$$

$$W_2 = (0.1567, 0.3184, 0.2688, 0.2563);$$

$$W_3 = (0.0687, 0.3215, 0.2424, 0.3117);$$

$$W_4 = (0.1162, 0.2604, 0.3117, 0.3117);$$

$$W_5 = (0.1851, 0.1851, 0.2939, 0.3358);$$

$$W_6 = (0.1521, 0.2415, 0.2759, 0.3305);$$

$$W_7 = (0.2188, 0.1657, 0.2188, 0.3970);$$

$$W_8 = (0.1994, 0.3994, 0.4014, 0.2215);$$

According to the above, factor weights fuzzy vectors of each failure mode is calculated as

$$B^1 = (0.01866, 0.4171, 0.56424, 0);$$

$$B^2 = (0.1567, 0.3184, 0.2688, 0.2563);$$

$$B^3 = (0.0687, 0.3215, 0.2424, 0.3117);$$

$$B^4 = (0.1162, 0.2604, 0.3117, 0.3117);$$

$$B^5 = (0.1851, 0.1851, 0.2939, 0.3358);$$

$$B^6 = (0.1521, 0.2415, 0.2759, 0.3305);$$

$$B^7 = (0.2188, 0.1657, 0.2188, 0.3970);$$

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$$B^4 = (0.1162, 0.2604, 0.3117, 0.3117);$$

$$B^5 = (0.1851, 0.1851, 0.2939, 0.3358);$$

$$B^6 = (0.1521, 0.2415, 0.2759, 0.3305);$$

$$B^7 = (0.2188, 0.1657, 0.2188, 0.3970);$$

$$B^8 = (0.1994, 0.3994, 0.4014, 0.2215);$$

$$B^9 = (0.01866, 0.4171, 0.56424, 0);$$

$$B^{10} = (0.01866, 0.4171, 0.56424, 0);$$
\[ B^9 = (0.1237, 0.2852, 0.5912, 0); B^{10} = (0.2750, 0.3400, 0.3724, 0.0125); \]
\[ B^{11} = (0.1600, 0.5201, 0.3198, 0); B^{12} = (0.2110, 0.5809, 0.2081, 0); \]
\[ B^{13} = (0.3306, 0.3763, 0.3931, 0) \]

The comprehensive credibly level of each failure mode can be obtained and as shown in table 2.

With the results, the critical components are bearing followed by spindle encoder, disc spring, solenoid valve coil. From failure modes point of view, bearing break, spindle encoder electronics aging, butterfly spring segment, solenoid valve coil burned, contactor contact point adhesion are critical failure modes that call for special attention at both design as well as at operation stogies of the electric spindle system of the DMU nomoBLOCK100 CNC machine tool. Specifically, bearings failure mainly resulted from fatigue and wear. Degeneration is blamed to cause spindle encoder electronics to fail.

Credibility values of an invalid solenoid valve adjustment, oil cylinder leakage, oil cylinder leakage, and reliability switch fatigue are higher than 2. And those failure modes would lead to the electric spindle system of the DMU nomoBLOCK100 CNC machine tool unstable or fail to accomplish predetermined functions and severely impact on the performance of the spindle system, which confirmed by the observation data that been collected.

Accordingly, periodical inspection and other preventive maintenance actions are suggested for the safe and reliable operations of the bearings of the electric spindle system of the DMU nomoBLOCK100 CNC machine tool. Additionally, robust design for electrical and electronical complements as well as elements are recommended for avoiding their random failures.

Table 2. The comprehensive credibly level of each failure mode.

| Failure Modes                          | Codes | Credibility | Failure modes                          | Codes | Credibility |
|----------------------------------------|-------|-------------|----------------------------------------|-------|-------------|
| Bearing Break                          | C^9   | 2.5456      | Contactor Contact Point adhesion       | C^8   | 2.2024      |
| Severe Bearing Wear                    | C^2   | 1.8456      | Spindle Encoder Electronics Aging     | C^9   | 2.4677      |
| Invalid Solenoid Valve Adjustment     | C^3   | 2.0584      | Cylinder Leaking                      | C^10  | 2.1222      |
| Solenoid Valve Coil Burned            | C^4   | 2.2121      | Leak in Cylinder                      | C^11  | 2.1596      |
| Invalid Relief Valve Pressure Adjustment| C^5   | 1.8313      | Cylinder Crawl                        | C^12  | 1.9971      |
| Broach Claw Crack                     | C^6   | 1.9283      | Overage Switch Fatigue Damage         | C^13  | 2.0625      |
| Butterfly Spring Segment              | C^7   | 2.4076      |                                        |       |             |

5. Conclusion
This paper extended the conventional failure modes, effect and criticality analysis by integrating which with fuzzy theory to finitizing a failure analysis of an electric spindle system of a DMU nomoBLOCK100 CNC machine tool. Critical components e.g. bearing, spindle encoder, disc spring, solenoid valve coil were identified. Moreover, critical failure modes of the spindle system that call for special attention that are bearing break, spindle
encoder electronics aging, butterfly spring segment, solenoid valve coil burned, contactor contact point adhesion were ascertained. Root causes of the critical failure modes as well as recommendations for avoiding their occurrence are obtained after a careful analysis.
## Appendix A. FMECA sheet for the spindle system of the CNC machine tool.

| Component       | Failure Mode                        | Failure Cause                      | Failure Effect          | Severity | Actions                      |
|-----------------|-------------------------------------|------------------------------------|-------------------------|----------|------------------------------|
| Bearing         | Fm#1 Bearing Break                  | Overload                           | Bearing Failure         | I        | Replace Bearing             |
|                 | Fm#2 Severe Bearing Wear            | Insufficient Lubrication Or Impurities | Imprecise Bearing | Bearing Failure | II | Replace Oil                 |
| Electromagnetic Valve | Fm#3 Invalid Solenoid Valve Adjustment | Spool Broken                  | Piston Failure           | Broach Stop | II | Replace Electromagnetic Valve |
| Relief Valve    | Fm#4 Solenoid Valve Coil Burned     | Overcurrent                         | Solenoid Failure | Solenoid Stop | II | Replace The Coil             |
| Broach          | Fm#5 Invalid Relief Valve Pressure Adjustment | Spool Broken                  | Abnormal Oil Tank | Abnormal Piston | II | Fix Relief Valve             |
| Butterfly Spring| Fm#6 Broach Claw Crack              | Material Failure                   | Abnormal Broach         | Manufacturing Fail | III | Replace Brouch               |
| Contactor       | Fm#7 Butterfly Spring Segment      | Material Failure                   | Low Elasticity          | Cannot Change Tools | III | Replace Butterfly Spring    |
| Encoder         | Fm#8 Spindle Encoder Electronics Aging | Aging                             | Hardware Fail           | Manufacturing Fail | I | Replace Encoder              |
|                 | Fm#9 Cylinder Leaking               | Seal Failure                        | Unstable Oil Tank | Cannot Change Tools | III | Replace Seal                 |
| Oil Tank        | Fm#10 Leak In Cylinder              | Seal Wear                          | Unstable Oil Tank | Cannot Change Tools | III | Replace Seal                 |
|                 | Fm#11 Cylinder Crawl                | Air In The Tank                    | Unstable Oil Tank | Cannot Change Tools | III | Exhaust Air                  |
| Switch          | Fm#12 Overage Switch Fatigue Damage | Frequent Operation                 | Switch Fail            | Unstable Rotating Speed | II | Replace Switch               |
|                 | Fm#13                             |                                    |                         |          |                              |
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