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Reliability and Modal Analysis of Key Meta-Action Unit for CNC Machine Tool

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ABSTRACT Dynamic characteristics have an important impact on the reliability of computer numerical control (CNC) machine tool. As the basis of dynamic characteristics analysis, the modal analysis should be conducted. However, the current modal analysis methods have some shortcomings. For example, the selected research object cannot reflect the dynamic characteristics of the CNC machine tool, the selection of research object lacks a scientific basis, and the influence of coupling factors is also often ignored. To address these problems, the concepts of meta-action failure mode and the latest research results about meta-action were given herein. Meta-action unit is the smallest structural unit to ensure the normal operation of the machine tool, and it can fully reflect the dynamic characteristics of a machine tool, so it is taken as the research object. In order to reduce the blindness of selecting the analytic object when implementing the reliability improvement measures, we put forward the concept of a key meta-action unit and gave the corresponding extraction method. Meanwhile, electromechanical coupling was considered when built the dynamic model of a key meta-action unit. A CNC machine tool made in China was taken as an example, and a key meta-action unit was extracted and analyzed, then the corresponding reliability improvement measures were also given. The results verify the applicability and effectiveness of this method. The proposed method can solve the shortcomings of the current methods, which lays a foundation for further research of mechanical properties and reliability based on machine tool meta-action unit.

INDEX TERMS CNC machine tool, modal analysis, failure mode, reliability, key meta-action unit.

I. INTRODUCTION

CNC machine tool is a large and complex product. It is the ''mother machine'' of machinery manufacturing industry, which represents the manufacturing level of a country. It is well known that modal analysis is the basis of dynamic characteristics analysis, and dynamic characteristics have an important influence on the reliability of CNC machine tool. Therefore, it is necessary to carry out the modal analysis for CNC machine tool. The main modal characteristics of machine tool in a certain frequency range can be obtained by modal analysis, and the actual vibration response of machine tool under external or internal vibration sources can also be predicted. Meanwhile, modal analysis can explain the failure causes and failure mechanism of machine tool, then help us find a way to prevent or eliminate the similar failures. At present, scholars have done a lot of research on the modal analysis of mechanical products, such as literature [1]–[6]. Most of these studies are based on static components, which can't reflect the dynamic characteristics of mechanical products. Besides, the life cycle of CNC machine tool is a complex dynamic process. Therefore, it is necessary to select a target that can reflect the dynamic characteristics of machine tool as the analysis object. Meanwhile, there are so many parts in CNC machine tool that it is difficult to build the model of whole machine. It is also easy to ignore many influencing factors, which will reduce the accuracy of analysis results [7]. So it is necessary to find a reasonable machine tool decomposition method. So far, a lot of work on the decomposition methods of mechanical products has been done. For example, Vezzoli and Sciama [8] formulated modular design criteria, which provided a new idea for the structural decomposition

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of mechanical products. Lambert and Surendr [9] proposed a Components-Parts-Suite (CPS) decomposition method based on mechanical products' structure. Eppinger *et al.* [10] proposed a heuristic transformation algorithm for mechanical product decomposition, which greatly improved the efficiency of product development. Wang and Liu [11] proposed a product structure decomposition method for collaborative assembly planning, which laid a foundation for the further research related to product assembly. However, these decomposition methods ignore the characteristics of ''function and motion'' of mechanical products, and the decomposition results are still static parts which can't reflect the dynamic characteristics of mechanical products. So it is particularly important to explore new decomposition methods for mechanical products. To address these problems, the Function-Motion-Action (FMA) decomposition method was proposed by the team of Professor Zhang of Chongqing University. Some research results have been obtained. For example, Zhang [12] decomposed a CNC machine tool by FMA method and studied the failure formation mechanism of meta-action. Zhang *et al.* [13] used FMA method to decompose a CNC machine tool and built the failure model of meta-action unit. Ran *et al.* [14] studied the correlation between the quality characteristics of meta-action assembly units and found a way to improve the assembly quality of machine tool. Li *et al.* [15] decomposed a machine tool into meta-action units by FMA method and established the error transfer model of the meta-action assembly unit. In order to make the obtained meta-actions more accurate, the latest research results about meta-action and FMA method are presented in this paper.

In consideration of the difficulty degree, time, cost and benefit for implementing reliability improvement measures in enterprises, it is impossible to analyze all meta-actions of machine tool. Different meta-actions have different influences on the whole machine reliability, so it is reasonable and realistic to find out the meta-action that has a great influence on the whole machine reliability and analyze it. To this end, the concept of key meta-action is proposed in this paper. In order to get the key meta-action, all the machine tool meta-actions obtained by FMA method must be sorted according to their criticality. The traditional criticality matrix method comes from electronic products, which is not suitable for mechanical products. The criticality sorting obtained by traditional criticality matrix method only considers the criticality and severity of product failure, which is not reasonable, such as literature [16]–[18]. On this account, an improved criticality analysis method suitable for mechanical products is proposed in this paper.

After considering the factors affecting the meta-action failure criticality comprehensively, we correct the meta-action criticality sorting result by introducing a meta-action criticality correction coefficient vector, which improves the accuracy of key meta-action extraction. After obtaining the key meta-action, it is necessary to choose an appropriate method to establish its analytical model. Finite element method (FEM) is an indispensable tool in engineering analysis [19], and it has been applied in many fields, such as literature [20]–[26]. So FEM is used to build the dynamic model of key meta-action unit herein. Coupling factors have a great influence on the reliability of machine tool, but these are often ignored by current methods. Therefore, the electromechanical coupling is taken into account when build the analytical model of key meta-action unit herein.

In this paper, a CNC machine tool made in china is taken as the study object. The concepts of meta-action chain, meta-action failure mode and key meta-action are proposed for the first time. The latest research results about meta-action and FMA method are also given. Meanwhile, an efficient key meta-action extraction method suitable for the machine tool products is also proposed. The key meta-action unit which can reflect the dynamic characteristics of whole machine is taken as the analysis object, and the dynamic model considering electromechanical coupling is also built by FEM. Based on these, the modal analysis and reliability analysis of key meta-action unit are carried out, and the improvement measures to improve the machine tool reliability are also put forward. The proposed method plays an important role in improving the market competitiveness of machine tool. The reliability and modal analysis process of key meta-action for CNC machine tool proposed in this paper is shown in Fig. 1.

II. META-ACTION DECOMPOSITION METHOD

A. META-ACTION

The function and performance of machine tool are guaranteed by the relative motion between components, and the component's motion is guaranteed by the action of parts. Therefore, the function of machine tool can be decomposed into components' motion, and the components' motion can be further decomposed into parts' action. The definition of meta-action can be given as the following.

Meta-action (MA) is the most basic motion form used to transmit motion and power in mechanical products, and it is the smallest motion unit for mechanical products.

B. META-ACTION UNIT

As we know, it is impossible for any single part to perform an action independently. So the operation of meta-action also requires assistance from other parts.

Meta-action unit (MAU) is the smallest and complete structure composed of all parts that can guarantee the normal operation of meta-action according to the assembly relationship.

C. META-ACTION FAILURE MODE

Generally speaking, failure mode is a normative description of the failure phenomena that can be observed or measured. It is also the manifestation of failure. Similarly, meta-action failure mode can be defined as follows.

Meta-action failure mode (MAFM) is an event that meta-action cannot normally realize its function.

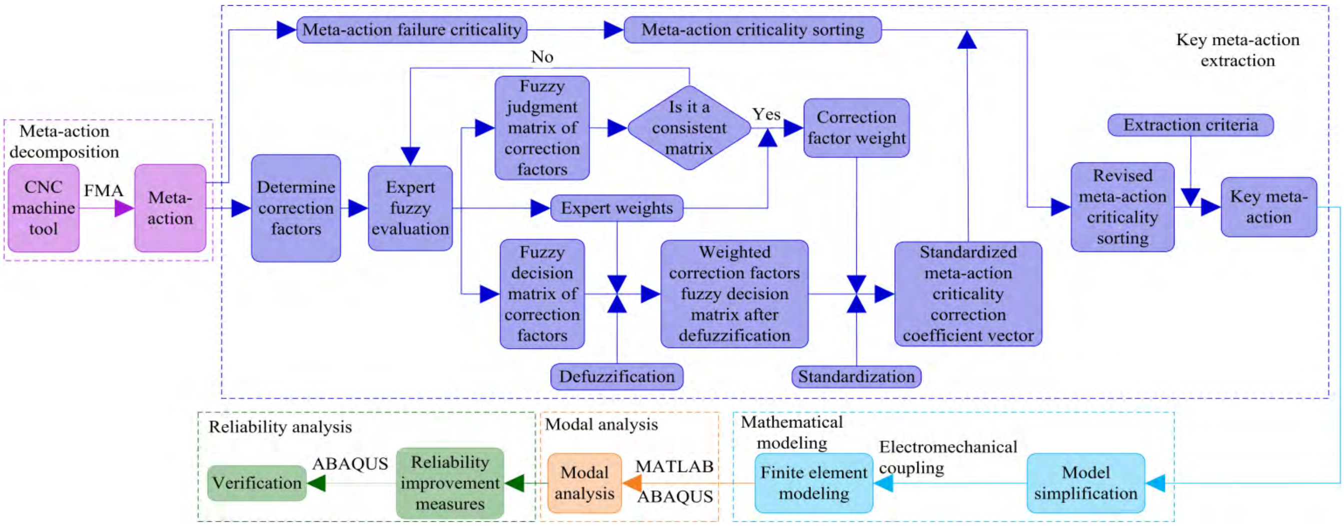

FIGURE 1. Key meta-action unit reliability and modal analysis flow chart.

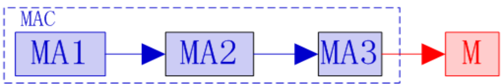

FIGURE 2. Series meta-action chain.

D. META-ACTION CHAIN

For some meta-actions, they can run only after the former meta-actions have run. Then the expected motion can be achieved. Therefore, it is necessary to link them by a certain mandatory relationship when they are used to complete a certain motion.

Meta-action chain (MAC) is an action sequence composed of meta-actions according to certain rules to perform a predetermined motion.

Generally speaking, there is only series mode for meta-action chains of machine tool. The only difference is that their lengths are different. For example, the meta-action chain, which can realize the rotary motion of numerical control (NC) rotary table, includes worm rotation meta-action, gear shaft rotation meta-action and rotary body rotation meta-action. But the meta-action chain which can realize the up-and-down motion of NC rotary table only includes rotary body moving meta-action. The process of linking meta-actions into motion by series mode is shown in Fig. 2.

E. META-ACTION DECOMPOSITION

In order to get the meta-action of CNC machine tool, a functional structure decomposition method was proposed by our team. The decomposition idea is "Function-Motion-Action", which is called FMA. The structural decomposition process of machine tool by FMA method is shown in Fig. 3.

III. KEY META-ACTION EXTRACTION

A. KEY META-ACTION

Different meta-actions have different influence on the reliability of whole machine, so the key meta-action is defined as the following.

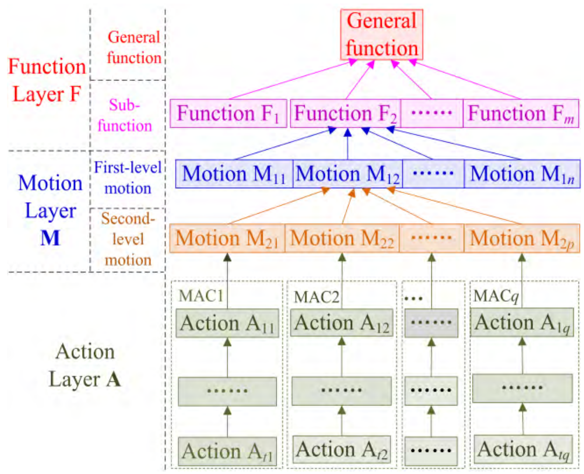

FIGURE 3. FMA decomposition process of machine tool meta-action.

Key meta-action (KMA) is the meta-action that has a great influence on the reliability of whole machine in all the machine tool meta-actions.

To get the key meta-action of CNC machine tool, it is necessary to sort the criticality of all meta-actions. The criticality herein refers to the meta-action relative criticality. Based on the criticality matrix method of electronic products, this paper introduces a meta-action criticality correction coefficient vector $\boldsymbol{P}$ after comprehensively considering various factors that affect the reliability of meta-action. It will make the sorting result more accurate and realistic. Pareto principle is used to extract the key meta-action herein. It is considered that the first 20% meta-actions in the criticality sorting have the greatest influence on the reliability of whole machine. So they can be regarded as the key meta-actions of machine tool.

B. MA FAILURE CRITICALITY ANALYSIS

The purpose of meta-action failure criticality analysis (MA-FCA) is to classify each failure mode of meta-action

TABLE 1. Meta-action failure severity level definitions.

Level	definition
I	Machine tool system function is lost and cannot be repaired.
II	Machine tool system function decreases and can be repaired, but it is difficult to maintain.
III	Machine tool system function is unstable, but it can run normally through maintenance.
IV	Machine tool system function is unstable, and it can run normally just by simply repairing or replacing parts.

TABLE 2. Selecting rules for β_{ij}.

Criteria	GJB1391—92		Reference for a fighter design	
	Descriptions	Values	Descriptions	Values
B_{ij}	Actually happened	1	Certainly happen	1
	Very likely to happen	0.1～1	Very likely to happen	0.5～0.99
	May happen	0～0.1	May happen	0.1～0.49
	Hardly happen	0	Almost never happen	0.01～0.09
	/	/	Never happen	0

according to its severity, occurrence probability and impact, so that the impact of all possible failure modes of the meta-action can be evaluated comprehensively. The severity of meta-action failure mode is determined by the severity of its final impact. The severity level can generally be determined by Table 1.

The Quantified Consequence Matrix Analysis is used to sort the criticality of meta-action in this paper. The criticality of meta-action single failure mode and the criticality of meta-action failure will be used in this analysis and calculation process. They are described as follows.

1) MA SINGLE FAILURE MODE CRITICALITY

The criticality C_{ij} of the j-th failure mode of meta-action i under a certain severity level can be expressed by formula (1).

$$C_{ij} = \lambda_i \alpha_{ij} \beta_{ij} \tag{1}$$

While $\lambda_i = r_i/t$ is the failure frequency of the i-th meta-action, r_i is the failure number of meta-action i, and t is the mission time or statistical time; $\alpha_{ij} = n_{ij}/\sum_{j=1}^{n_i} n_{ij}$ is the ratio of failure mode frequency of the i-th meta action, n_{ij} represents the number of the j-th failure mode of meta-action i, n_i represents the number of failure mode types of meta-action i; β_{ij} is the probability of failure mode influence.

Generally speaking, not all the β_{ij} can be calculated. But they can be estimated by national standards and experience, which can be seen in Table 2.

2) MA FAILURE CRITICALITY

The criticality C_{si} of meta-action failure can be expressed as formula (2).

$$C_{Si} = \sum_{j=1}^{n_i} C_{ij} \tag{2}$$

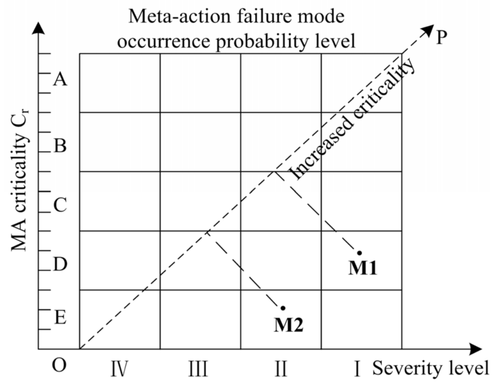

FIGURE 4. MA criticality matrix diagram.

TABLE 3. Correction factors and scoring rules.

Correction factors	Scoring rules
Importance	Evaluate importance according to the contribution of meta-action failure to the whole machine failure, the higher the meta-action importance, the greater its influence on the quality characteristics of machine tool.
Occurrence degree	Evaluate occurrence degree according to the possibility of the meta-action failure occurrence, the higher the meta-action occurrence degree, the greater its influence on the quality characteristics of machine tool.
Detection degree	Evaluate detection degree according to the difficulty level of the meta-action failure detection, the lower the meta-action detection degree, the greater its influence on the quality characteristics of machine tool.
Maintainability	Evaluate maintainability according to the difficulty degree of repairing meta-action that has failed, the lower the meta-action maintainability, the greater its influence on the quality characteristics of machine tool.

While C_{Si} is the sum of all single failure mode criticality of meta-action i which has the S-level severity.

The priority order of meta-action failure mode criticality can be obtained by the matrix diagram method. The criticality matrix diagram is shown in Fig. 4. In Fig. 4, the point M representing the failure mode criticality is perpendicular to the line OP, and the longer the distance from the intersection to the origin, the more harmful the failure mode is to the system, such as the criticality of M_1 is more than that of M_2.

From formula (2) and Fig. 4, we can get the sorting of meta-action criticality.

C. MA CRITICALITY CORRECTION COEFFICIENT VECTOR

The meta-action criticality sorting obtained by criticality matrix method only considers the criticality and severity of meta-action failure, which is not comprehensive. In fact, the factors that have great influence on the reliability of CNC machine tool also include importance, occurrence degree, detection degree and maintainability. Only when these factors are considered comprehensively, can we get a more reasonable criticality sorting of meta-actions.

TABLE 4. Description, definition and scoring of importance.

Description	Definition	Scoring
Most important	An extremely small change of meta-motion failure rate will cause an extremely great change of whole machine failure rate.	10
Very important	A very small change of meta-motion failure rate will cause a great change of whole machine failure rate.	9
Important	A smaller change of meta-motion failure rate will cause a greater change of whole machine failure rate.	7、8
Medium importance	A greater change of meta-motion failure rate will cause a greater change of whole machine failure rate.	5、6
Generally important	A great change of meta-motion failure rate will only cause a small change of whole machine failure rate.	3、4
Slightly important	A very great change of meta-motion failure rate will only cause a very small change of whole machine failure rate.	2
Hardly important	The change of meta-motion failure rate will hardly cause the change of whole machine failure rate.	1

TABLE 5. Description, definition and scoring of occurrence degree.

Description	Definition	Scoring
Happen is inevitable	Failure occurs at least once a day or almost every day.	10
Very high frequency	Failure occurs almost once a week.	9
High frequency	Failure occurs at least once a month.	8
Medium frequency	Failure occurs every four months.	6、7
Low frequency	Failure rarely occurs or occurs every six months.	4、5
Very low frequency	Failure rarely occurs or occurs once a year.	2、3
Happen is hardly	Failure has hardly occurred or there is no record about it.	1

1) CORRECTION FACTORS

Importance, occurrence degree, detection degree and maintainability are selected as the correction factors of meta-action criticality sorting in this paper. The correction factors set can be expressed as $\boldsymbol{X} = \{x_1, x_2, x_3, x_4\}$={importance, occurrence degree, detection degree, maintainability}. Expert fuzzy scoring method can be used to evaluate correction factors in the absence of data. The corresponding scoring rules are shown in Table 3.

The fuzzy description, definition and scoring rule for each correction factor in Table 3 are shown in Tables 4 to 7, respectively.

When using fuzzy theory and analytic hierarchy process to build the evaluation matrixes of correction factors, it is necessary to give the fuzzy numbers and their membership functions of expert scoring about correction factors. The corresponding fuzzy numbers of expert scoring in Tables 4 to 7 are shown in Table 8 [27]. The membership functions corresponding to the fuzzy numbers are shown in Fig. 5.

2) CORRECTION FACTORS WEIGHT

The relative weight of each correction factor is generally different. Fuzzy analytic hierarchy process (FAHP) is used to obtain the relative weight of correction factor herein.

TABLE 6. Description, definition and scoring of detection degree.

Description	Definition	Scoring
Extremely low	Existing methods cannot detect the failure.	10
Very low	The failure is difficult to detect and the detection process is not easy to implement.	8、9
Low	Lacking of suitable inspection equipment and inspection procedure, and failures can only be detected manually, and whether they can be detected depends on luck.	6、7
Commonly	Failure needs to be checked many times, and the inspection process needs to be strictly controlled to get the correct conclusion.	5
High	The correct conclusion can be obtained only by detecting the failure once, but the detection process is not automatic.	3、4
Very high	Failure only needs to be detected once to get the correct result, and the detection process is automatic.	2
Extremely high	Machine tool has automatic stop or restricting procedures to avoid failures.	1

TABLE 7. Description, definition and scoring of maintainability.

Description	Definition	Scoring
Extremely high	Meta-action failure is extremely easy to maintain, the meta-action repaired can be restored to its working level before the failure.	1
Very high	Meta-action failure is easy to maintain, the meta-action repaired can be restored to its working level before the failure.	2、3
High	Meta-action failure is difficult to maintain, but the meta-action repaired can be restored to its working level before the failure.	4、5
Commonly	Meta-action failure is more difficult to maintain, but the meta-action repaired can be restored to its working level before the failure.	6、7
Low	Meta-action failure is more difficult to maintain. The meta-action repaired can run, but it cannot be restored to its working level before the failure.	8
Very low	Meta-action failure is very difficult to maintain, the meta-action repaired is difficult to restore to its working level before the failure.	9
Extremely low	A malfunctioning meta-action has no maintenance value, and even if it is repaired, the maintenance result is also difficult to satisfy the users.	10

TABLE 8. Fuzzy numbers of expert scoring.

Expert scoring	1	2	3	4	5
Fuzzy numbers	(1,1,2)	(1,2,3)	(2,3,4)	(3,4,5)	(4,5,6)
Expert scoring	6	7	8	9	10
Fuzzy numbers	(5,6,7)	(6,7,8)	(7,8,9)	(8,9,10)	(9,10,10)

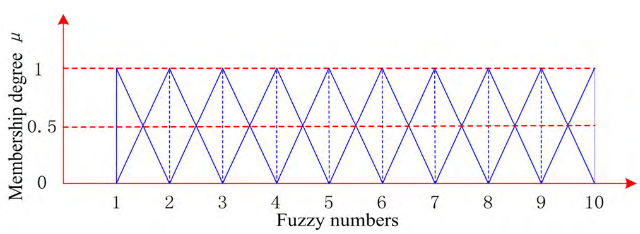

FIGURE 5. Membership function of fuzzy numbers.

a: EXPERT WEIGHT COEFFICIENT

Duce to the differences in professional knowledge and familiarity with every meta-action of CNC machine tool,

TABLE 9. Expert self-evaluation criteria.

Evaluation factor	Description	Scoring
Familiarity $\tilde{e}_{ij}$	Very familiar	0.9
	Familiar	0.7
	Common	0.5
	Unfamiliar	0.3
	Very unfamiliar	0.1
	Intermediate state between the above two descriptions	0.2,0.4,0.60.8

TABLE 10. Scoring criterion of triangular fuzzy number median value.

Importance of factor i relative to j	Scoring
Extremely unimportant	0.1
Very unimportant	0.2
Unimportant	0.3
Slightly unimportant	0.4
Equally important	0.5
Slightly important	0.6
Important	0.7
Very important	0.8
Extremely important	0.9

the evaluation result given by different expert has different influences on the final results. In order to solve this problem, the concept of expert weight coefficient is proposed in this paper. Experts from enterprises evaluate the accuracy of the results given by themselves according to their familiarity with the correction factors. The expert self-evaluation criteria are shown in Table 9.

In Table 9, $\tilde{e}_{ij}$ represents the familiarity self-evaluation value of the i-th expert on the j-th correction factor. The correction factor self-evaluation set given by k experts can be expressed as $\tilde{\boldsymbol{E}} = (\tilde{e}_1, \tilde{e}_2, \ldots, \tilde{e}_i, \ldots, \tilde{e}_k)$, and $\tilde{e}_i = \frac{1}{n}\sum_{j=1}^{n}\tilde{e}_{ij}$. The expert weight coefficient set $\boldsymbol{E}$ can be obtained by standardizing $\tilde{\boldsymbol{E}}$, and the result is shown in formula (3).

$$\begin{cases} \boldsymbol{E} = (e_1, e_2, \ldots, e_i, \ldots, e_k) \\ e_i = \tilde{e}_i / \sum_{i}^{k} \tilde{e}_i \end{cases} \tag{3}$$

While e_i is the weight coefficient of the i-th expert.

b: FUZZY CONSISTENT JUDGMENT MATRIX

Triangular fuzzy number is used to build the fuzzy consistent judgment matrix herein. The median value of triangular fuzzy number should be determined first, then the upper and lower bound value are determined [28]. The scoring criterion of triangular fuzzy number median value can be shown in Table 10.

k experienced experts are invited to give their fuzzy scores on correction factors according to Table 10. $\tilde{a}_{ijp} = (l_{ijp}, m_{ijp}, u_{ijp})$ is used to represent the triangular fuzzy number of factor i relative to j given by the p-th expert. l_{ijp}, m_{jp} and u_{ijp} are the upper, median and lower bound value of $\tilde{a}_{ijp}$, respectively. The fuzzy judgment matrix $\tilde{\boldsymbol{A}}_p$ built by the p-th expert can be given by formula (4).

$$\tilde{\boldsymbol{A}}_p = \begin{bmatrix} \tilde{a}_{11p} & \tilde{a}_{12p} & \ldots & \tilde{a}_{1np} \\ \tilde{a}_{21p} & \tilde{a}_{22p} & \ldots & \tilde{a}_{2np} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{n1p} & \tilde{a}_{n2p} & \ldots & \tilde{a}_{nnp} \end{bmatrix} = \begin{bmatrix} (l_{11p}, m_{11p}, u_{11p}) & (l_{12p}, m_{12p}, u_{12p}) & \ldots & (l_{1np}, m_{1np}, u_{1np}) \\ (l_{21p}, m_{21p}, u_{21p}) & (l_{22p}, m_{22p}, u_{22p}) & \ldots & (l_{2np}, m_{2np}, u_{2np}) \\ \vdots & \vdots & \vdots & \vdots \\ (l_{k1p}, m_{k1p}, u_{k1p}) & (l_{k2p}, m_{k2p}, u_{k2p}) & \ldots & (l_{knp}, m_{knp}, u_{knp}) \end{bmatrix} \tag{4}$$

Formula (4) needs to be transformed several times to ensure that it is a fuzzy consistent matrix [29]. The fuzzy adjustment judgment matrix $\boldsymbol{B}_p$ about it can be obtained by formula (5), firstly.

$$\begin{cases} \boldsymbol{B}_p = \begin{bmatrix} b_{11p} & b_{12p} & \ldots & b_{1np} \\ b_{21p} & b_{22p} & \ldots & b_{2np} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1p} & b_{n2p} & \ldots & b_{nnp} \end{bmatrix} \\ b_{ijp} = \frac{1}{6}(l_{ijp} + 4m_{ijp} + u_{ijp})\left[1 - \frac{u_{ijp} - l_{ijp}}{2(l_{ijp} + m_{ijp} + u_{ijp})}\right] \end{cases} \tag{5}$$

Secondly, the fuzzy complementary judgment matrix $\boldsymbol{A}_p$ about $\boldsymbol{B}_p$ can be obtained by formula (6).

$$\begin{cases} \boldsymbol{A}_p = \begin{bmatrix} a_{11p} & a_{12p} & \ldots & a_{1np} \\ a_{21p} & a_{22p} & \ldots & a_{2np} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1p} & a_{n2p} & \ldots & a_{nnp} \end{bmatrix} \\ a_{ijp} = \frac{1}{2}(1 + b_{ijp} - b_{jip}) \end{cases} \tag{6}$$

Thirdly, the directive matrix $\boldsymbol{C}_p$ of $\boldsymbol{A}_p$ can be obtained by formula (7).

$$\begin{cases} \boldsymbol{C}_p = \begin{bmatrix} c_{11p} & c_{12p} & \ldots & c_{1np} \\ c_{21p} & c_{22p} & \ldots & c_{2np} \\ \vdots & \vdots & \vdots & \vdots \\ c_{n1p} & c_{n2p} & \ldots & c_{nnp} \end{bmatrix} \\ c_{ijp} = \begin{cases} 1 & a_{ijp} > 0.5 \\ 0 \end{cases} \end{cases} \tag{7}$$

Finally, the reachable matrix $\boldsymbol{D}_p$ about $\boldsymbol{A}_p$ can be obtained by formula (7) as shown in formula (8).

$$\boldsymbol{D}_p = \boldsymbol{C}_p \dotplus \boldsymbol{C}_p^2 \dotplus \ldots \dotplus \boldsymbol{C}_p^n \tag{8}$$

While $\dotplus$ represents the "sum" of Boolean operations.

If the elements on the diagonal of $\boldsymbol{D}_p$ are all 0, it can be considered that the consistency of $\boldsymbol{A}_p$ is acceptable. Otherwise, the correction factors must be re-scored.

The fuzzy consistent judgment matrix $\boldsymbol{A}$ containing expert weight can be obtained by formula (3) and $\boldsymbol{A}_p$ as shown in formula (9).

$$\begin{cases} \boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \\ a_{ij} = \sum_{p=1}^{k} e_p a_{ijp} \end{cases} \tag{9}$$

c: CORRECTION FACTORS WEIGHT

The weight ω_i of the i-th correction factor can be given by literature [29] directly as formula (10).

$$\omega_i = \frac{1}{n} - \frac{1}{n-1} + \frac{2}{n(n-1)} \sum_{j=1}^{n} a_{ij} \tag{10}$$

While n is the number of correction factors.

The correction factors weight vector can be expressed as formula (11).

$$\boldsymbol{W} = (\omega_1 \quad \omega_2 \quad \ldots \quad \omega_i \quad \ldots \quad \omega_n) \tag{11}$$

d: CORRECTION FACTORS FUZZY DECISION MATRIX

The same k experts are invited to give their fuzzy scores on the correction factors according to Table 4 to Table 8. $\tilde{x}_{ij}^p = (\tilde{x}_{ijl}^p, \tilde{x}_{ijm}^p, \tilde{x}_{iju}^p)$ is used to represent the influence degree score of the j-th correction factor on the i-th meta-action given by the p-th expert. $\tilde{x}_{ijl}^p$, $\tilde{x}_{ijm}^p$ and $\tilde{x}_{iju}^p$ represent the upper, median and lower bound value of expert score, respectively. The fuzzy decision matrix of correction factors given by the p-th expert can be expressed as formula (12).

$$\begin{aligned} \tilde{\boldsymbol{X}}^p &= \begin{bmatrix} \tilde{x}_{11}^p & \tilde{x}_{12}^p & \cdots & \tilde{x}_{1n}^p \\ \tilde{x}_{21}^p & \tilde{x}_{22}^p & \cdots & \tilde{x}_{2n}^p \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1}^p & \tilde{x}_{m2}^p & \cdots & \tilde{x}_{mn}^p \end{bmatrix} \\ &= \begin{bmatrix} (\tilde{x}_{11l}^p, \tilde{x}_{11m}^p, \tilde{x}_{11u}^p) & (\tilde{x}_{12l}^p, \tilde{x}_{12m}^p, \tilde{x}_{12u}^p) & \cdots & (\tilde{x}_{1nl}^p, \tilde{x}_{1nm}^p, \tilde{x}_{1nu}^p) \\ (\tilde{x}_{21l}^p, \tilde{x}_{21m}^p, \tilde{x}_{21u}^p) & (\tilde{x}_{22l}^p, \tilde{x}_{22m}^p, \tilde{x}_{22u}^p) & \cdots & (\tilde{x}_{2nl}^p, \tilde{x}_{2nm}^p, \tilde{x}_{2nu}^p) \\ \vdots & \vdots & \vdots & \vdots \\ (\tilde{x}_{m1l}^p, \tilde{x}_{m1m}^p, \tilde{x}_{m1u}^p) & (\tilde{x}_{m2l}^p, \tilde{x}_{m2m}^p, \tilde{x}_{m2u}^p) & \cdots & (\tilde{x}_{mnl}^p, \tilde{x}_{mnm}^p, \tilde{x}_{mnu}^p) \end{bmatrix} \end{aligned} \tag{12}$$

The correction factors fuzzy decision matrix $\tilde{\boldsymbol{X}}$ containing expert weight can be obtained by formula (3) and formula (12) as shown in formula (13).

$$\begin{cases} \tilde{\boldsymbol{X}} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \\ \tilde{x}_{ij} = (\tilde{x}_{ijl}, \tilde{x}_{ijm}, \tilde{x}_{iju}) \\ \tilde{x}_{ijl} = \sum_{p=1}^{k} e_p \tilde{x}_{ijl}^p, \tilde{x}_{ijm} = \sum_{p=1}^{k} e_p \tilde{x}_{ijm}^p, \tilde{x}_{iju} \sum_{p=1}^{k} e_p \tilde{x}_{iju}^p) \end{cases} \tag{13}$$

Formula (13) is defuzzified according to literature [30], and the result is shown in formula (14).

$$\begin{cases} \boldsymbol{X} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \\ x_{ij} = (\tilde{x}_{ijl} + \tilde{x}_{ijm} + \tilde{x}_{iju})/3 \end{cases} \tag{14}$$

e: MA CRITICALITY CORRECTION COEFFICIENT VECTOR

The meta-action criticality correction coefficient vector $\tilde{\boldsymbol{P}}$ of CNC machine tool can be obtained by formula (11) and formula (14) as shown in formula (15).

$$\begin{cases} \tilde{\boldsymbol{P}} = (\tilde{p}_1 \quad \tilde{p}_2 \quad \ldots \quad \tilde{p}_m) = \boldsymbol{W}\boldsymbol{X}^T \\ \tilde{p}_i = \omega_1 x_{i1} + \omega_2 x_{i2} +, \ldots, +\omega_n x_{in} \end{cases} \tag{15}$$

The standardized meta-action criticality correction coefficient vector can be expressed as below:

$$\begin{cases} \boldsymbol{P} = (p_1 \quad p_2 \quad \ldots \quad p_m) \\ p_i = \tilde{p}_i / \sum_{i=1}^{m} \tilde{p}_i \end{cases} \tag{16}$$

D. KEY MAU EXTRACTION

The failure criticality of meta-action i can be corrected by the meta-action criticality correction coefficient p_i, which is shown in formula (17).

$$\tilde{C}_{Si} = p_i C_{Si} \tag{17}$$

The corrected meta-action criticality and criticality matrix diagram are used to re-order the meta-action criticality. Then the key meta-action and key meta-action unit of CNC machine tool can be extracted by the extraction criteria.

IV. MODELING AND ANALYSIS

A. MODEL SIMPLIFICATION AND MODELING

Key meta-action unit has a great influence on the reliability and dynamic characteristics of machine tool, so it should be analyzed emphatically. In order to reduce the difficulty of modeling, the structure of meta-action unit should be simplified according to the actual situation.

Mathematical model is the premise of mechanical performance analysis and reliability analysis. FEM is the method often used in mathematical modeling, so it is used to build the mechanical model of key meta-action unit. The general steps of FEM are as follows. Firstly, the appropriate unit is select to divide the mesh according to the model characteristics. Secondly, the kinetic energy and potential energy of each unit are calculated. Thirdly, the dynamic model of each unit is obtained by Lagrange second equation. Finally, the dynamic model of each unit is integrated into the dynamic model of key meta-action unit by coordinate transformation matrix and coordinate coordination matrix.

TABLE 11. Meta-action failure mode criticality.

(λ_i, C_{ij}, C_{si} /× 10^{-4})

MA	Failure mode	Severity	λ_i	α_{ij}	β_{ij}	C_{ij}	C_{si}
Worm rotation	Worm cannot rotate	III	2.500	0.286	0.7	0.250	M01 II -level: 0.715 M02 III-level: 0.786
	Worm mis-rotation	II		0.143	0.4	0.143	
	Worm rotates inflexibly	III		0.143	0.4	0.143	
	Worm rotates unsteadily	II		0.286	0.8	0.286	
	Worm rotation is not in place or over range	III		0.143	0.4	0.143	
Gear shaft rotation	Gear shaft cannot rotate	III	2.857	0.125	0.6	0.214	M03 II -level: 0.821 M04 III-level: 0.500
	Gear shaft mis-rotation	II		0.250	0.4	0.286	
	Gear shaft rotates inflexibly	III		0.125	0.4	0.143	
	Gear shaft rotates unsteadily	II		0.375	0.5	0.536	
	Gear shaft rotation is not in place or over range	III		0.125	0.4	0.143	
Rotary table rotation	Rotary table cannot rotate	III	2.143	0.167	0.6	0.215	M05 II -level: 0.571 M06 III-level: 0.465
	Rotary table mis-rotation	II		0.332	0.4	0.285	
	Rotary table rotates inflexibly	III		0.167	0.5	0.179	
	Rotary table rotates unsteadily	II		0.167	0.8	0.286	
	Rotary table rotation is not in place or over range	III		0.167	0.2	0.072	

B. ANALYSIS

Modal analysis is an important way to explore the failure cause and failure mechanism. The modal parameters are the inherent characteristics of system, which are independent of the external load. Meanwhile, damping has little effect on the natural frequency and mode shape of system, so the natural frequency and mode shape can be calculated by the undamped free vibration equation of system as shown in formula (18) [31].

$$\boldsymbol{M}\ddot{\boldsymbol{U}} + \boldsymbol{K}\boldsymbol{U} = \boldsymbol{0} \tag{18}$$

While $\boldsymbol{M}$ and $\boldsymbol{K}$ respectively represent the mass matrix and stiffness matrix of system; $\boldsymbol{U}$ and $\ddot{\boldsymbol{U}}$ respectively represent the generalized displacement and generalized acceleration of system.

Free vibration can be considered as the superposition of some simple harmonic vibrations, so the solution of formula (18) can be expressed as formula (19).

$$\boldsymbol{U} = \boldsymbol{\phi} e^{j\omega t} \tag{19}$$

While ω is the natural frequency of the simple harmonic vibration system; ϕ is the column vector of the node displacement amplitude.

Substituting formula (19) into formula (18) and eliminating $e^{j\omega t}$, then formula (20) can be obtained.

$$(\boldsymbol{K} - \omega^2 \boldsymbol{M})\boldsymbol{\phi} = \boldsymbol{0} \tag{20}$$

The i-th natural frequency ω_i and eigenvector θ_i of system can be obtained by formula (20).

Theory and practice have proved that the participation degree of each mode in system vibration responses is not the same, and the participation degree is independent of the external excitation. In the free vibration system under any external excitation, the contribution of low-order modes to the system is greater than that of high-order modes. Therefore, only the first four modes of key meta-action unit are calculated in this paper.

TABLE 12. Results of expert scoring.

Experts	Correction factors x_1	x_2	x_3	x_4	Mean
q_1	0.8	0.7	0.5	0.7	0.675
q_2	0.6	0.7	0.8	0.5	0.650
q_3	0.7	0.9	0.6	0.7	0.725
q_4	0.5	0.7	0.7	0.9	0.700

Through modal analysis, we can find out the fundamental reasons affecting system reliability. It is also convenient for us to formulate the corresponding improvement measures for these failure reasons. The improved measures after verification are applied to actual production, which lays a foundation for improving the reliability of machine tool.

V. APPLICATION

A NC rotary table of a CNC machine tool made in China is taken as the research object in this paper. The key meta-action about it is extracted and the corresponding modal analysis and reliability analysis are carried out.

A. MA DECOMPOSITION

The indexing motion of NC rotary table is composed of four motions, which are the up-and-down motion of NC rotary table, the rotary motion of NC rotary table, the loosening and tightening motion of pull claw and the up-and-down motion of ejector pins. Firstly, NC rotary table achieves the up-and-down motion under the driving of hydraulic cylinder. Secondly, servo motor drives worm to rotate by coupling.

TABLE 13. Correction factors fuzzy scoring.

Correction factors	q_1				q_2			
	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4
x_1	(0.50,0.50,0.50)	(0.45,0.55,0.65)	(0.55,0.65,0.75)	(0.65,0.75,0.85)	(0.50,0.50,0.50)	(0.45,0.60,0.75)	(0.50,0.65,0.80)	(0.55,0.70,0.85)
x_2	(0.35,0.45,0.55)	(0.50,0.50,0.50)	(0.50,0.60,0.70)	(0.55,0.65,0.75)	(0.25,0.40,0.55)	(0.50,0.50,0.50)	(0.40,0.55,0.70)	(0.45,0.60,0.75)
x_3	(0.25,0.35,0.45)	(0.30,0.40,0.50)	(0.50,0.50,0.50)	(0.50,0.60,0.70)	(0.20,0.35,0.50)	(0.30,0.45,0.60)	(0.50,0.50,0.50)	(0.40,0.55,0.70)
x_4	(0.15,0.25,0.35)	(0.25,0.35,0.45)	(0.30,0.40,0.50)	(0.50,0.50,0.50)	(0.15,0.30,0.45)	(0.25,0.40,0.55)	(0.30,0.45,0.60)	(0.50,0.50,0.50)
Correction factors	q_3				q_4			
	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4
x_1	(0.50,0.50,0.50)	(0.50,0.65,0.70)	(0.65,0.70,0.75)	(0.75,0.80,0.85)	(0.50,0.50,0.50)	(0.45,0.55,0.65)	(0.50,0.60,0.70)	(0.60,0.70,0.80)
x_2	(0.30,0.35,0.40)	(0.50,0.50,0.50)	(0.55,0.60,0.65)	(0.60,0.65,0.70)	(0.35,0.45,0.55)	(0.50,0.50,0.50)	(0.45,0.55,0.65)	(0.50,0.60,0.70)
x_3	(0.25,0.30,0.35)	(0.35,0.40,0.45)	(0.50,0.50,0.50)	(0.50,0.55,0.60)	(0.30,0.40,0.50)	(0.35,0.45,0.55)	(0.50,0.50,0.50)	(0.45,0.55,0.65)
x_4	(0.15,0.20,0.25)	(0.30,0.35,0.40)	(0.40,0.45,0.50)	(0.50,0.50,0.50)	(0.20,0.30,0.40)	(0.30,0.40,0.50)	(0.35,0.45,0.55)	(0.50,0.50,0.50)

Then the worm drives worm wheel to rotate by mutual meshing. Then the worm wheel drives gear shaft to rotate by the flat key. Then the gear shaft drives upper end-tooth tray fixedly connected with revolving body to rotate by mutual meshing, which achieves the rotary motion of NC rotary table. Thirdly, when NC rotary table rotates to the specified position, the pull claw will move downward under the pressure of oil or upward under the thrust of spring, which achieve the loosening and tightening motion of pull claw. Finally, ejector pins will rise under the thrust of spring or descend under the weight of objects after the loosening and tightening motion of pull claw is finished, which achieve the up-and-down motion of ejector pins. The four motions cooperate with each other, and then the indexing motion of NC rotary table is realized.

Based on above analysis, the FMA decomposition process of NC rotary table can be shown in Fig. 6.

B. KMA EXTRACTION

1) MA FAILURE CRITICALITY CALCULATION

Formula (1), formula (2) and Table 2 are used to calculate the meta-action single failure mode criticality and meta-action failure criticality. The results are shown in Table 11.

2) MA CRITICALITY CORRECTION COEFFICIENT VECTOR

a: EXPERT WEIGHT COEFFICIENT

Four experts from design, manufacturing, assembly and after-sales departments in a machine tool manufacturing enterprise are invited to give their scores according to Table 9. Assuming that expert set is $\boldsymbol{Q} = \{q_1, q_2, q_3, q_4\}$={design department expert, manufacturing department expert, assembly department expert, after-sales department expert}. The scoring results are shown in Table 12.

The standardized expert weight coefficient set can be obtained by formula (3) and Table 12 as below:

$$\boldsymbol{E} = (e_1, e_2, e_3, e_4) = (0.245, 0.236, 0.264, 0.255) \quad (21)$$

b: CORRECTION FACTORS WEIGHT VECTOR

The same experts are invited to make a fuzzy scoring on the relative importance of correction factors according to Table 10. The results are shown in Table 13.

TABLE 14. Influence degree fuzzy scoring of correction factors on MA.

MA	q_1				q_2			
	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4
MA_1	(7,8,9)	(5,6,7)	(4,5,6)	(7,8,9)	(8,9,10)	(4,5,6)	(5,6,7)	(6,7,8)
MA_2	(6,7,8)	(4,5,6)	(5,6,7)	(5,6,7)	(6,7,8)	(3,4,5)	(4,5,6)	(5,6,7)
MA_3	(6,7,8)	(3,4,5)	(4,5,6)	(4,5,6)	(6,7,8)	(3,4,5)	(3,4,5)	(4,5,6)
MA	q_3				q_4			
	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4
MA_1	(8,9,10)	(6,7,8)	(4,5,6)	(5,6,7)	(8,9,10)	(5,6,7)	(4,5,6)	(6,7,8)
MA_2	(6,7,8)	(3,4,5)	(4,5,6)	(5,6,7)	(6,7,8)	(4,5,6)	(4,5,6)	(5,6,7)
MA_3	(7,8,9)	(4,5,6)	(3,4,5)	(3,4,5)	(7,8,9)	(3,4,5)	(3,4,5)	(4,5,6)

The reachable matrix of correction factors can be obtained by substituting the data in Table 13 into formulas (4) to (8) as shown in below.

$$\boldsymbol{D}_p = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (p = 1, 2, 3, 4)$$

It can be seen from $\boldsymbol{D}_p$ that $\boldsymbol{A}_p$ has a satisfactory consistency. The weight vector of correction factors can be calculated from formulas (9) to (11), and the result is shown in formula (22).

$$\boldsymbol{W} = (0.3288, 0.2695, 0.2227, 0.1789) \quad (22)$$

c: CORRECTION FACTORS FUZZY DECISION MATRIX

MAC2 is used as an example to extract the key meta-action of NC rotary table. Assuming that meta-action set is $\boldsymbol{MA} = \{MA_1, MA_2, MA_3\}$={worm rotation, gear shaft rotation, rotary table rotation}. The same experts are invited to make a fuzzy scoring for correction factors according to Tables 4 to 8, and the results are shown in Table 14.

The defuzzified correction factors fuzzy decision matrix can be obtained by substituting the data in Table 14 into formulas (12) to (14) as below:

$$\boldsymbol{X} = \begin{bmatrix} 8.755 & 6.028 & 5.236 & 6.981 \\ 7.000 & 4.500 & 5.245 & 6.000 \\ 7.519 & 4.264 & 4.245 & 4.736 \end{bmatrix} \quad (23)$$

The standardized criticality correction coefficient vector of meta-action can be obtained by substituting formula (22)

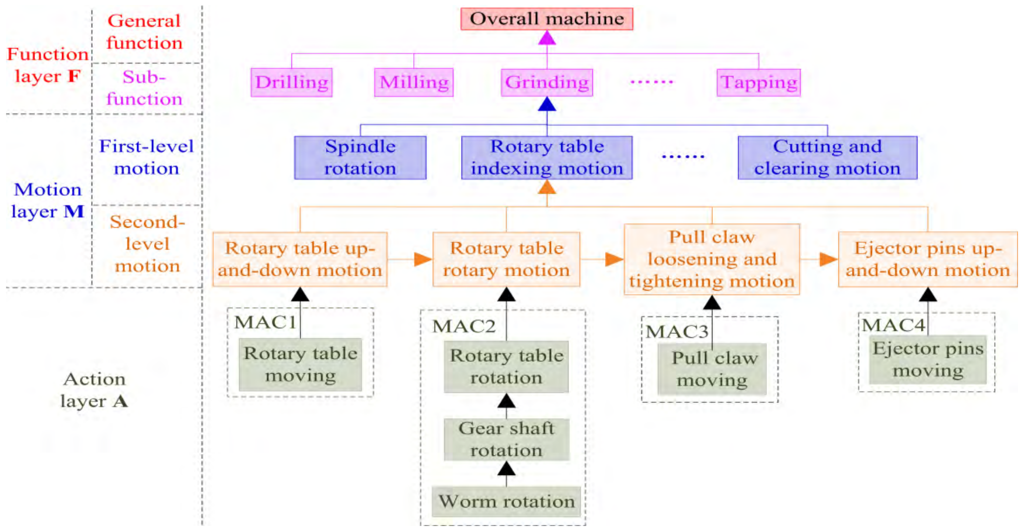

FIGURE 6. FMA decomposition for NC rotary table.

TABLE 15. Revised meta-action failure mode criticality.

MA	$\tilde{C}_{si}$ / $\times 10^{-4}$
Worm rotation	M01 II -level: 0.273 M02 III-level: 0.301
Gear shaft rotation	M03 II -level: 0.261 M04 III-level: 0.159
Rotary table rotation	M05 II -level: 0.171 M06 III-level: 0.139

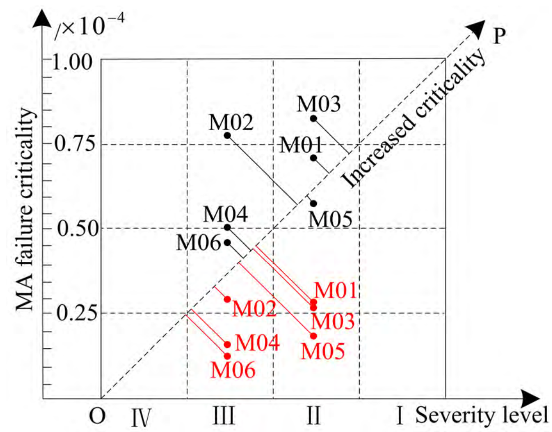

FIGURE 7. MA criticality matrix diagram.

and formula (23) into formula (15) and formula (16) as the following formula.

$$\boldsymbol{P} = (0.3825 \quad 0.3182 \quad 0.2993) \tag{24}$$

3) MA FAILURE CRITICALITY ANALYSIS

The results in Table 11 are corrected by formula (17) and formula (24) as shown in Table 15.

Taking criticality of meta-action failure as ordinate and severity intermediate value as abscissa, the criticality matrix diagram can be obtained according to Fig. 4, Table 14 and Table 15 as follows.

In Fig. 7, black dots represent the meta-action criticality before criticality correction coefficient vector is introduced, and red dots represent the meta-action criticality after criticality correction coefficient vector is introduced.

4) KMA EXTRACTION

It can be seen from Fig. 7 that the criticality order of meta-action before the criticality correction coefficient vector is introduced is M03>M01>M05>M02>M04>M06, and the meta-action criticality order after the criticality correction coefficient vector is introduced is M01>M03>M05>M02>M04>M06. From the results, we can see that an obvious change has taken place. The worm rotation can be considered as the key meta-action of NC rotary table according to the key meta-action extraction criterion. So the worm rotation meta-action unit is the key meta-action unit of NC rotary table. The conclusion is consistent with the actual situation obtained by enterprise, which proves the correctness of key meta-action extraction method presented in this paper.

C. DYNAMIC MODELING

1) MODEL SIMPLIFICATION

Worm rotation meta-action unit is mainly composed of power input part (such as servo motor), middleware (such as coupling), power take-off part (such as worm), fastener (such as screw) and strutting piece (such as gear box and bearing cover). The structure diagram about it is shown in Fig. 8.

For a meta-action unit, power input part, middleware and power take-off part are of the greatest concern to us. Therefore, the following simplifications are made in this paper

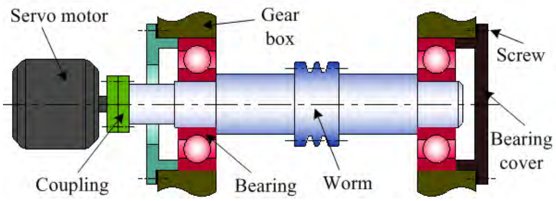

FIGURE 8. Structure diagram of worm rotation meta-action unit.

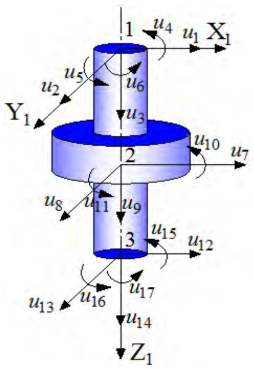

FIGURE 9. Motor unit finite element model.

when build the mathematical model of worm rotation meta-action unit. Firstly, the worm rotation meta-action unit is simplified to a component consisting mainly of servo motor and worm. Coupling is treated as a concentrated mass. Secondly, angular contact ball bearings and cylindrical roller bearings are simplified to compression spring mass units only having radial stiffness. Thirdly, the stiffness of servo motor shaft and worm are treated as constant. Finally, the rotor of servo motor is considered to have the same density as motor shaft, and it is treated as an additional distribution mass of the motor shaft.

When building the mathematical model of worm rotation meta-action unit, the influence of shear deformation in strain energy is not taken into account and the same to the influence of lateral displacement on tension compression deformation. The elasticity of shaft unit is considered mainly in the vibration analysis. The rigid motion and elastic motion of the motor shaft unit can be obtained by the torsional vibration of motor shaft relative to motor rotor, transverse vibration and axial vibration of motor shaft [32].

2) MOTOR UNIT FINITE ELEMENT MODEL

The schematic diagram of motor unit finite element model is shown in Fig. 9.

In Fig. 9, $X_1Y_1Z_1$ is the coordinate system of motor unit. At the same time, motor is treated as 1 unit, and three nodes are set on the axis of the motor shaft. u_i $(i = 1, 2, \ldots, 17)$ is used to represent the displacement of each node. The generalized displacement of motor unit can be expressed as below:

$$\boldsymbol{u}_1 = [u_1 \quad u_2 \ldots u_{17}]^T$$

The displacement of any point on the axis of motor unit can be expressed as formula (25).

$$\begin{cases} W_{X_1}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 1, 4, 7, 10, 12, 15 \\ W_{Y_1}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 2, 5, 8, 11, 13, 16 \\ W_{Z_1}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 3, 9, 14 \\ V_{Z_1}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 6, 17 \end{cases} \tag{25}$$

While $W_{X_1}(x,t)$, $W_{Y_1}(x,t)$, and $W_{Z_1}(x,t)$ are respectively the displacement of node x, which is located on the axis of motor unit, along X_1, Y_1 and Z_1 direction; $V_{Z_1}(x,t)$ is the twist angle displacement of shaft section around Z_1 axis at node x which is located on the axis of the motor unit; $\phi_i(x)$ is the shape-function corresponding to $u_i(x)$.

The kinetic energy of motor unit can be calculated by formula (26).

$$\begin{aligned} \boldsymbol{T}_1 = &\frac{1}{2}\int_0^{l_2}[m_1(x) + m_{10}\delta(l_{11})][\dot{W}_{X_1}(x,t)]^2dx \\ &+ \frac{1}{2}\int_0^{l_2}[m_1(x) + m_{10}\delta(l_{11})][\dot{W}_{Y_1}(x,t)]^2dx \\ &+ \frac{1}{2}\int_0^{l_2}[m_1(x) + m_{10}\delta(l_{11})][\dot{W}_{Z_1}(x,t)]^2dx \\ &+ \frac{1}{2}\int_0^{l_2}[j_1(x) + j_{10}\delta(l_{11})][\dot{V}_{Z_1}(x,t)]^2dx \end{aligned} \tag{26}$$

While l_1 is the length of motor shaft; l_{11} is the distance from node 1 to the rotor upper end-face; $m_1(x)$ and $j_1(x)$ are the mass distribution function and moment of inertia distribution function of motor shaft; m_{10} and j_{10} are respectively the mass and moment of inertia of motor rotor; $\delta(l_{11})$ is the centroid position function of motor rotor; $\dot{W}_{X_1}(x,t)$, $\dot{W}_{Y_1}(x,t)$, $\dot{W}_{Z_1}(x,t)$ and $\dot{V}_{Z_1}(x,t)$ represent the absolute velocities of node x located on the axis of motor unit.

The elastic potential energy of motor unit can be obtained by formula (27).

$$\begin{aligned} \boldsymbol{N}_1 = &\frac{1}{2}\int_0^{l} E_1A_1(x)\left[\frac{\partial W_{X_1}^2(x,t)}{\partial x^2}\right]^2 dx \\ &+ \frac{1}{2}\int_0^{l} E_1I_1(x)\left[\frac{\partial W_{Y_1}^2(x,t)}{\partial x^2}\right]^2 dx \\ &+ \frac{1}{2}\int_0^{l} EI_1(x)\left[\frac{\partial W_{Z_1}^2(x,t)}{\partial x^2}\right]^2 dx \\ &+ \frac{1}{2}\int_0^{l} G_1I_{1p}(x)\left[\frac{\partial V_{Z_1}^2(x,t)}{\partial x^2}\right]^2 dx \end{aligned} \tag{27}$$

While E_1, G_1, $I_1(x)$, $I_{1p}(x)$ and $A_1(x)$ are respectively the elastic modulus, shear elastic modulus, inertia moment distribution function of anti-flexural section, inertial moment distribution function of anti-torsional section and cross-sectional area distribution function of motor shaft.

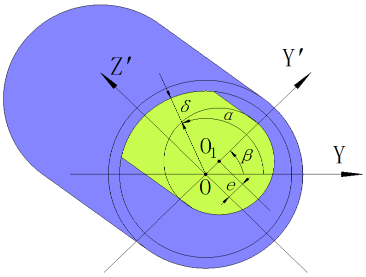

FIGURE 10. **Motor rotor vibration eccentricity.**

Motor unit is inevitably affected by electromagnetic field in operation. The electromagnetic parameters of electromagnetic field interact with the mechanical parameters of motor shaft to form electromechanical coupling. Motor rotor will vibrate under the electromechanical coupling. The schematic diagram of motor rotor vibration eccentricity is shown in Fig. 10.

While O is the geometric center of motor stator; O_1 is the geometric center of motor rotor; e is the eccentric distance from the rotor center to the stator center; α is the angle between air gap length and Y axis; β is the angle between the position that air gap between rotor and stator is the smallest and Y axis; $\sigma = k_u\delta_0$, k_u is saturation, δ_0 is the size of uniform magnetic field air gap of motor.

The air gap magnetic field energy of motor can be obtained by literature [33], then it is expanded, and the first five items about it are extracted as the following.

$$\begin{aligned} W = &\frac{R_g L\Lambda_0}{2}\{[1+\frac{u_7^2+u_8^2}{2\sigma^2}+\frac{3(u_7^2+u_8^2)^2}{8\sigma^4}] \\ &+[\frac{u_7}{\sigma}+\frac{3}{4\sigma^3}(u_7^3+u_7u_8^2)]\cos\alpha \\ &+[\frac{u_8}{\sigma}+\frac{3}{4\sigma^3}(u_8^3+u_8u_7^2)]\sin\alpha \\ &+(\frac{u_8^2-u_7^2}{2\sigma^2}+\frac{u_7^4-u_8^4}{2\sigma^4})\cos 2\alpha \\ &+(\frac{u_7u_8}{\sigma^2}+\frac{u_7^3u_8+u_7u_8^3}{\sigma^4})\sin 2\alpha+\frac{1}{4\sigma^3}(u_7^3-3u_7u_8^2)\cos 3\alpha \\ &+\frac{1}{4\sigma^3}(3u_7^2u_8-u_8^3)\sin 3\alpha+\frac{1}{8\sigma^4}(u_7^4-6u_7^2u_8^2+u_8^4)\cos 4\alpha \\ &+\frac{1}{2\sigma^4}(u_7^3u_8-u_7u_8^3)\sin 4\alpha]\cdot[F_j\cos(\omega t+\theta+\varphi+\frac{\pi}{2}-p\alpha) \\ &+F_s\cos(\omega t+p\alpha)]^2\}d\alpha \end{aligned} \tag{28}$$

While R_g is the inner circle radius of motor stator; L is the effective length of motor rotor; Λ_0 is the uniform air gap permeability; ω is the synchronous speed of motor; θ is the internal power angle of motor; φ is the power factor angle of motor; p is the number of pole pairs of motor magnetic field; F_j and F_s are respectively the amplitude of rotor magnetic potential fundamental and stator magnetic potential fundamental.

The component force of magnetic pull force in directions u_7 and u_8 can be expressed as formula (29).

$$\begin{cases} f_x = \dfrac{\partial W}{\partial u_7} = \dfrac{R_g L\Lambda_0}{2}\displaystyle\int_0^{2\pi}\dfrac{d\Lambda(\alpha,z,t)}{du_7} \\ \qquad \times[F_j\cos(\omega t+\theta+\varphi+\dfrac{\pi}{2}-p\alpha) \\ \qquad +F_s\cos(\omega t-p\alpha)]^2 d\alpha \\ f_y = \dfrac{\partial W}{\partial u_8} = \dfrac{R_g L\Lambda_0}{2}\displaystyle\int_0^{2\pi}\dfrac{d\Lambda(\alpha,z,t)}{du_8} \\ \qquad \times[F_j\cos(\omega t+\theta+\varphi+\dfrac{\pi}{2}-p\alpha) \\ \qquad +F_s\cos(\omega t+p\alpha)]^2 d\alpha \end{cases} \tag{29}$$

After a series of calculations such as derivation, expansion, integration and simplification for formula (29), the following formula is obtained.

$$\begin{cases} f_x = \dfrac{\lambda_1}{\sigma}u_7+\dfrac{3}{2\sigma^3}(u_7^3+u_7u_8^2)+\dfrac{u_7}{2\sigma}(\lambda_2\cos 2\omega t \\ \quad +\lambda_3\sin 2\omega t)+\dfrac{u_{14}}{2\sigma}(\lambda_2\sin 2\omega t-\lambda_3\cos 2\omega t) \\ \quad +\dfrac{u_7^3}{\sigma^3}(\lambda_2\cos 2\omega t+\lambda_3\sin 2\omega t)-\dfrac{u_8^3}{\sigma^3}(\lambda_2\sin 2\omega t \\ \quad -\lambda_3\cos 2\omega t)+\dfrac{3}{4\sigma^3}(u_7^2u_8+u_8^3)(\lambda_2\sin 2\omega t \\ \quad -\lambda_3\cos 2\omega t) \\ f_y = \dfrac{\lambda_1}{\sigma}u_8+\dfrac{3}{2\sigma^3}(u_7^2u_8+u_8^3)+\dfrac{u_{13}}{2\sigma}(\lambda_2\sin 2\omega t \\ \quad -\lambda_3\cos 2\omega t)-\dfrac{u_{14}}{2\sigma}(\lambda_2\cos 2\omega t+\lambda_3\cos 2\omega t) \\ \quad -\dfrac{u_7^3}{\sigma^3}(\lambda_2\sin 2\omega t-\lambda_2\cos 2\omega t)-\dfrac{u_7^3}{\sigma^3}(\lambda_2\cos 2\omega t \\ \quad +\lambda_3\sin 2\omega t)+\dfrac{3}{2\sigma^3}(u_7+u_7u_8^2)(\lambda_2\sin 2\omega t \\ \quad -\lambda_3\cos 2\omega t) \\ \lambda_1 = \dfrac{\pi R_g L\Lambda_0 K}{2\sigma}[F_s^2+F_j^2-2F_sF_j\sin(\theta+\varphi)] \\ \lambda_2 = \dfrac{\pi R_g L\Lambda_0 K}{2\sigma}[F_s^2-F_j^2\cos(2\theta+2\varphi)-2F_sF_j\sin(\theta+\varphi)] \\ \lambda_3 = \dfrac{\pi R_g L\Lambda_0 K}{2\sigma}[F_j^2\sin(2\theta+2\varphi)-2F_sF_j\cos(\theta+\varphi)] \end{cases} \tag{30}$$

Substituting formula (26), formula (27) and formula (30) into Lagrange second equation and using the viscous damping theory to approximately estimate the effect of damping on the system [34], the dynamic equation of motor unit can be obtained as formula (31).

$$\begin{aligned} \boldsymbol{m}_1\ddot{\boldsymbol{u}}_1+\boldsymbol{c}_1\dot{\boldsymbol{u}}_1+\boldsymbol{k}_1\boldsymbol{u}_1 = &\boldsymbol{f}_1+\boldsymbol{q}_1+\boldsymbol{k}_{11}\boldsymbol{u}_1\boldsymbol{u}_1^T\boldsymbol{k}_{12}\boldsymbol{u}_1 \\ &+\boldsymbol{k}_{13}\boldsymbol{u}_1\boldsymbol{u}_1^T\boldsymbol{k}_{14}\boldsymbol{u}_1-\boldsymbol{m}_1\ddot{\boldsymbol{u}}_{1r} \end{aligned} \tag{31}$$

While $\boldsymbol{m}_1$ is the mass matrix of motor unit; $\boldsymbol{c}_1$ is the damping matrix of motor unit; $\boldsymbol{k}_1$ is the stiffness matrix of motor unit; $\boldsymbol{f}_1$ is the excitation of motor unit, and $f_1 = \sqrt{f_x^2+f_y^2}$; $\boldsymbol{q}_1$ is the column vector of the force applied to the motor unit by the worm unit; $\boldsymbol{k}_{11}$, $\boldsymbol{k}_{12}$, $\boldsymbol{k}_{13}$ and $\boldsymbol{k}_{14}$ are both the stiffness matrixes related to the electromagnetic parameters of the motor; $\ddot{\boldsymbol{u}}_{1r}$ is the rigid body acceleration column vector of motor unit.

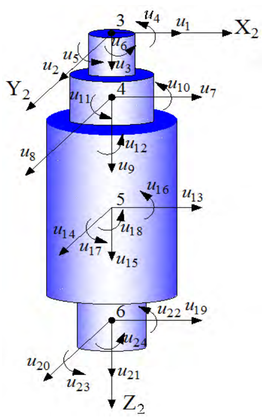

FIGURE 11. Worm unit finite element model.

3) WORM UNIT FINITE ELEMENT MODEL

Worm is divided into 3 units, and four nodes are set on its axis. The schematic diagram of worm unit finite element model is shown in Fig. 11.

In Fig. 11, $X_2Y_2Z_2$ is the coordinate system of worm unit. u_i $(i = 1, 2, \ldots, 24)$ represents the displacement of each node. The generalized displacement of worm unit can be expressed as the following formula.

$$\boldsymbol{u}_2 = [u_1 \quad u_2 \quad \ldots \quad u_{24}]^T$$

The displacement of any point on the axis of worm unit can be expressed as formula (32).

$$\begin{cases} W_{X_2}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 1, 4, 7, 10, 13, 16, 19, 22 \\ W_{Y_2}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 2, 5, 8, 11, 14, 17, 20, 23 \\ W_{Z_2}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 3, 9, 15, 21 \\ V_{Z_2}(x,t) = \sum_i \phi_i(x)u_i(t) & i = 6, 12, 18, 24 \end{cases} \tag{32}$$

While $W_{X_2}(x, t)$, $W_{Y_2}(x, t)$, and $W_{Z_2}(x, t)$ are respectively the displacement of node x, which is located on the axis of worm unit, along X_2, Y_2 and Z_2 axis direction; $V_{Z_2}(x, t)$ is the twist angle displacement of shaft section around Z_2 axis at node x which is located on the axis of worm unit; $\phi_i(x)$ is the shape-function corresponding to $u_i(x)$.

The kinetic energy of worm unit can be obtained by formula (33).

$$\begin{aligned} \boldsymbol{T}_2 = &\frac{1}{2}\int_0^{l_2} m_2(x)[\dot{W}_{X_2}(x,t)]^2 dx \\ &+ \frac{1}{2}\int_0^{l_2} m_2(x)[\dot{W}_{Y_2}(x,t)]^2 dx \\ &+ \frac{1}{2}\int_0^{l_2} m_2(x)[\dot{W}_{Z_2}(x,t)]^2 dx \\ &+ \frac{1}{2}\int_0^{l_2} j_2(x)[\dot{V}_{Z_2}(x,t)]^2 dx \end{aligned} \tag{33}$$

While l_2 is the length of worm; $m_2(x)$ and $j_2(x)$ are the mass distribution function and moment of inertia distribution function of worm; $\dot{W}_{X_2}(x, t)$, $\dot{W}_{Y_2}(x, t)$, $\dot{W}_{Z_2}(x, t)$ and $\dot{V}_{Z_2}(x, t)$ are respectively the absolute velocities of node x which is located on the axis of worm unit.

The elastic potential energy of worm unit can be calculated by formula (34).

$$\begin{aligned} \boldsymbol{N}_2 = &\frac{1}{2}\int_0^{l} E_2A_2(x)\left[\frac{\partial W_{X_2}^2(x,t)}{\partial x^2}\right]^2 dx \\ &+ \frac{1}{2}\int_0^{l} E_2I_2(x)\left[\frac{\partial W_{Y_2}^2(x,t)}{\partial x^2}\right]^2 dx \\ &+ \frac{1}{2}\int_0^{l} E_2I_2(x)\left[\frac{\partial W_{Z_2}^2(x,t)}{\partial x^2}\right]^2 dx \\ &+ \frac{1}{2}\int_0^{l} G_2I_{2p}(x)\left[\frac{\partial V_{Z_2}^2(x,t)}{\partial x^2}\right]^2 dx \end{aligned} \tag{34}$$

While E_2, G_2, $I_2(x)$, $I_{2p}(x)$ and $A_2(x)$ are respectively the elastic modulus, shear elastic modulus, inertia moment distribution function of anti-flexural section, inertial moment distribution function of anti-torsional section and cross-sectional area distribution function of worm.

Substituting formula (33) and formula (34) into Lagrange second equation and using the viscous damping theory to approximately estimate the effect of damping on the system [34], the dynamic equation of worm unit can be obtained as formula (35).

$$\boldsymbol{m}_2\ddot{\boldsymbol{u}}_2 + \boldsymbol{c}_2\dot{\boldsymbol{u}}_2 + \boldsymbol{k}_2\boldsymbol{u}_2 = \boldsymbol{f}_2 + \boldsymbol{q}_2 - \boldsymbol{m}_2\ddot{\boldsymbol{u}}_{2r} \tag{35}$$

While $\boldsymbol{m}_2, \boldsymbol{c}_2, \boldsymbol{k}_2, \boldsymbol{u}_2, \dot{\boldsymbol{u}}_2$ and $\ddot{\boldsymbol{u}}_{2r}$ are the mass matrix, damping matrix, stiffness matrix, generalized displacement, generalized velocity and generalized rigid body acceleration of worm unit, respectively; $\boldsymbol{f}_2$ is the excitation of worm unit; $\boldsymbol{q}_2$ is the column vector of the force applied to the worm unit by motor unit.

4) WORM ROTATION MAU DYNAMIC EQUATION

$\boldsymbol{R}_1$ and $\boldsymbol{B}_1$ are respectively used to represent the coordinate transformation matrix and coordinate coordination matrix of motor unit. $\boldsymbol{R}_2$ and $\boldsymbol{B}_2$ are respectively used to represent the coordinate transformation matrix and coordinate coordination matrix of worm unit. $\boldsymbol{U}$, $\dot{\boldsymbol{U}}$ and $\ddot{\boldsymbol{U}}_r$ are respectively used to represent the generalized coordinate vector, generalized velocity vector and generalized rigid body acceleration vector of each unit in global coordinate system. The generalized coordinate vector $\boldsymbol{U}$ of the system can be expressed as below.

$$\boldsymbol{U} = [\,u_1 \quad u_2 \quad \cdots \quad u_i \quad \cdots \quad u_{35}\,]^T$$

The dynamic equation of worm rotation meta-action unit in global coordinate system can be expressed as below.

$$\begin{aligned} \boldsymbol{M}\ddot{\boldsymbol{U}} + \boldsymbol{C}\dot{\boldsymbol{U}} + \boldsymbol{K}\boldsymbol{U} = \boldsymbol{F} + \boldsymbol{K}_{11}\boldsymbol{U}\boldsymbol{U}^T\boldsymbol{K}_{12}\boldsymbol{U} \\ + \boldsymbol{K}_{13}\boldsymbol{U}\boldsymbol{U}^T\boldsymbol{K}_{14}\boldsymbol{U} - \boldsymbol{M}\ddot{\boldsymbol{U}}_r \end{aligned} \tag{36}$$

While $\boldsymbol{M} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{m}_1\boldsymbol{B}_1\boldsymbol{R}_1 + \boldsymbol{B}_2^T\boldsymbol{R}_2^T\boldsymbol{m}_2\boldsymbol{B}_2\boldsymbol{R}_2$, $\boldsymbol{C} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{c}_1\boldsymbol{B}_1\boldsymbol{R}_1 + \boldsymbol{B}_2^T\boldsymbol{R}_2^T\boldsymbol{c}_2\boldsymbol{B}_2\boldsymbol{R}_2$, $\boldsymbol{K} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{k}_1\boldsymbol{B}_1\boldsymbol{R}_1 +$

TABLE 16. Worm rotation meta-action unit natural frequencies.

Order	1	2	3	4
a [Hz]	52.61	86.67	428.29	652.27
b [Hz]	13.45	33.98	52.82	106.86

$\boldsymbol{B}_2^T\boldsymbol{R}_2^T\boldsymbol{k}_2\boldsymbol{B}_2\boldsymbol{R}_2$ are the mass matrix, damping matrix and stiffness matrix of the system; $\boldsymbol{F} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{f}_1 + \boldsymbol{B}_2^T\boldsymbol{R}_2^T\boldsymbol{f}_2$ is the excitation of the system; $\boldsymbol{K}_{11} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{k}_{11}\boldsymbol{B}_1\boldsymbol{R}_1$, $\boldsymbol{K}_{12} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{k}_{12}\boldsymbol{B}_1\boldsymbol{R}_1$, $\boldsymbol{K}_{13} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{k}_{13}\boldsymbol{B}_1\boldsymbol{R}_1$ and $\boldsymbol{K}_{14} = \boldsymbol{B}_1^T\boldsymbol{R}_1^T\boldsymbol{k}_{14}\boldsymbol{B}_1\boldsymbol{R}_1$ are the stiffness matrices related to the electromagnetic parameters of the motor, which are the electromechanical coupling terms.

D. MODAL ANALYSIS

Substituting formula (36) into formulas (18) to (20), the first four order natural frequencies of worm rotation meta-action unit considering the electromechanical coupling or not can be obtained by MATLAB. The results are shown in Table 16.

In Table 16, ***a*** represents the natural frequencies considering electromechanical coupling, ***b*** represents the natural frequencies without considering electromechanical coupling. It can be seen from Table 16 that electromechanical coupling has an important influence on the natural frequencies of system. The values of system natural frequency considering electromechanical coupling are larger than those without considering electromechanical coupling. When electromechanical coupling is considered, the first-order natural frequency of system is $\omega_{1a} = 52.61$Hz, and the corresponding first-order critical speed is $n_{1a} = 60 \times \omega_{1a} = 3156.6r/min$. On the contrary, the first-order natural frequency of system is $\omega_{1b} = 13.45$Hz, and the corresponding first-order critical speed is $n_{1b} = 60 \times \omega_{1b} = 807r/min$. The normal working speed of the worm rotation meta-action required in this paper is 1980r/min, which is greater than the first-order critical speed of system without considering electromechanical coupling and less than the first-order critical speed of system considering electromechanical coupling. Therefore, if the influence of electromechanical coupling is not considered in design stage, it will lead to the wrong conclusion that the meta-action will resonate before the required working speed is reached. In order to make the meta-action avoid the resonance zone effectively, the measures such as the redesign for the structure of the worm rotation meta-action unit or the reselection for the corresponding purchased components will inevitably be implemented. However, the fact is that the resonance does not occur before the worm rotation meta-action reaches its normal working speed. Therefore, the design of meta-action unit model without considering the influence of electromechanical coupling will lead to the deviation of calculation results, which will waste the design time of enterprises and increase their production costs.

For a meta-action unit, the motion state of its power take-off part is often the most concerned by people. So the motor and coupling are treated as lumped mass, the bearings are simplified as compression spring mass units which only have radial stiffness, and the strutting piece is simplified as force and displacement constraints during the simulation. The simplified worm rotation meta-action unit is simulated by ABAQUS, and the results are shown in Fig. 12.

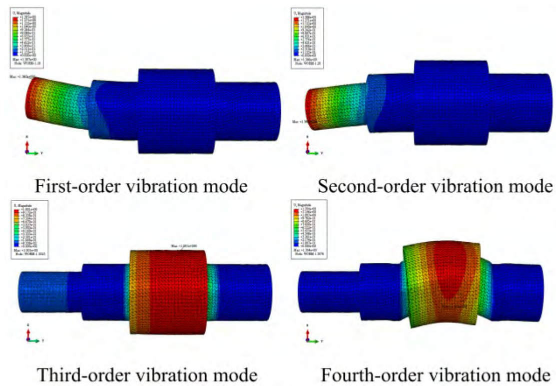

FIGURE 12. Worm rotation meta-action unit vibration modes.

TABLE 17. Deformation of worm rotation meta-action unit.

Order	1	2	3	4
Deformation [mm]	1.387	1.386	1.001	1.304

Vibration theory believes that the energy in vibration process is mainly concentrated in the first two orders. It can be seen from Fig. 12 that the phenomenon occurred in the first-order mode and second-order mode of worm rotation meta-action unit are worm bending deformation. So the worm bending deformation is the main failure of worm rotation meta-action unit during its operation. The bending deformation of worm will cause the failure modes of worm rotation meta-action such as inflexible operation, vibration, stuck and so on, which will reduce the operational performance of worm rotation meta-action and even cause the loss of its function. Once the worm rotation meta-action fails, the failure will be transmitted according to the arrow direction in Fig. 6. This will affect the performance and function of NC rotary table and ultimately reduce the reliability of CNC machine tool.

The maximum deformation of the first four modes of worm rotation meta-action unit can be obtained by ABAQUS as shown in Table 17.

According to the main modes (the first two modes) of system, it can be known from the mechanics knowledge that the deformation of the worm can be reduced by increasing appropriately the span between the angular contact ball bearings and cylindrical roller bearings. At the same time, this method can also reduce the vibration amplitude of worm rotation meta-action and improve the stability of its operation. This will reduce the failure rate of NC rotary table and improve the reliability of CNC machine tool.

According to the above analysis, installation positions of the bearings in worm rotation meta-action unit are adjusted appropriately. The maximum deformation of the first four modes of the improved worm rotation meta-action unit can be obtained as shown in Table 18.

TABLE 18. Deformation of improved worm rotation meta-action unit.

Order	1	2	3	4
Deformation [mm]	1.095	1.095	1.000	1.034

Comparing table 17 and table 18, we can see that the maximum deformation of the first two modes of worm rotation meta-action unit has been reduced, which verifies the effectiveness of the improvement measures proposed in this paper.

VI. CONCLUSION

In view of the shortcomings of current reliability and modal analysis methods for machine tool, key meta-action unit is proposed as the research object, and the influence of electromechanical coupling on reliability is also considered when the analytical model is built. Meanwhile, the latest research results about meta-action and FMA method are presented, and the concepts of meta-action failure mode and meta-action chain are also proposed. A NC rotary table made in China is taken as an example, the FMA decomposition about it is carried out to get all the meta-actions. The key meta-action unit of NC rotary table is obtained by the proposed method, and a finite element model considering electromechanical coupling is also built. Then the model is simulated, analyzed and validated. The corresponding measures to improve the operation stability of the meta-action are proposed, which lay a foundation for improving the reliability of CNC machine tool.

Meta-action unit is the smallest motion unit which can reflect the reliability and dynamic performance of machine tool. It is more reasonable to take a meta-action unit as the analysis object. At the same time, selecting the key meta-action unit of CNC machine tool as the research object can effectively reduce the blindness of the selection of analysis object when enterprises improve the performance of machine tool. In this paper, reliability analysis and finite element modeling are combined, failure analysis and dynamic analysis are also combined, which have the characteristics of interdisciplinary intersection.

The research results are beneficial to the selection and redesign of key meta-action units of machine tool products. The research results are also beneficial to the failure analysis, reliability analysis and mechanical analysis based on machine tool meta-action. These lay a foundation for the further optimization of machine tool dynamic performance based on the meta-action. The methods proposed in this paper are also applied to other types of machine tool.

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