Chapter

Reliability Technology Based on Meta-Action for CNC Machine Tool

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Abstract

Computer numerical control (CNC) machines are a category of machining tools that are computer driven and controlled, and are as such, complicated in nature and function. Hence, analyzing and controlling a CNC machine's overall reliability may be difficult. The traditional approach is to decompose the major system into its subcomponents or parts. This, however, is regarded as not being an accurate method for a CNC machine tool, since it encompasses a dynamic working process. This chapter proposes a meta-action unit (MU) as the basic analysis and control unit, the resulting combined motion effect of which is believed to optimize the CNC's overall function and performance by improving each meta-action's reliability. An overview of reliability technology based on meta-action is introduced.

Keywords: reliability, meta-action, CNC machine tool

1. Introduction

Along with social development, the reliability of computer numerical control (CNC) machine tools is becoming more and more important in the market [1]. However, it seems that reliability analysis becomes increasingly difficult, not least due to its complex structure. In order to improve the reliability of CNC machine tools, many scholars have carried out extensive research, including reliability prediction, allocation, analysis, test, and evaluation. There are a series of mature quality technique tools, such as failure mode and effects analysis (FMEA) and fault tree analysis (FTA), to name but a few. Yet, most of these tools are based on the reliability technology of electronic products. The reliability block diagram and the mathematical modeling of the parts are established straightforwardly. In this field, the electronic components, such as resistors and capacitors, do not interact with each other. When assigning a reliability index, the reliability index of the whole machine is allocated to each component according to the reliability block diagram. Then, an FMEA analysis is performed so as to identify all possible failure modes according to historical data and tests [2, 3]. At the end, the FTA analysis of each failure mode is executed in order to determine all bottom events [4]. As such, the reliability of the entire machine is predicted by the component level reliability block diagram.

In reliability research, reliability data is fundamental. The data pertaining to CNC machine tool reliability are not enough, suggesting that the analysis results and accuracy are unsatisfactory [5]. In order to obtain reliability analysis technology suitable for CNC machine tools, various kinds of CNC machine tools were analyzed and summarized. Then, the most basic structure to determine the reliability of CNC machine tool—meta-action was established. In this chapter, this method is standardized.

The FMA decomposition method is described in detail, which is to obtain meta-action. The definition of meta-action and its parts are discussed. The conceptual, structural, and assembly models of meta-action are defined. Identifying similarities of various CNC machine tools may prove difficult, as is their respective analysis. The specific movement and function of each meta-action unit is different, hence, establishing a standardized meta-action model may equally be difficult. According to the meta-action decomposition analysis method, the most important motion unit of CNC machine tool is found, which is affecting its reliability in most of the cases.

This chapter introduces the basic methodology. A number of industrial applications are also presented. The method applies in reliability modeling, allocation, evaluation, and fault diagnosis. Afterward, the research on reliability test and design based on meta-action would be performed. This includes setting up a reliability test bench and performing a meta-action reliability test used in design. All reliability studies may use this method and a complete reliability research system will form. Likewise, this method can be used in other quality characteristics analysis, such as precision, availability, and stability. Thus, further research aimed in this very specific area is deemed necessary.

Indeed, Karyagina proposed that the CNC machine tool manufacturers should pay more attention to the fault information feedback and reliability analysis of after-sales products and to establish a quality and a reliability assurance system [6]. Su and Xu performed research on the theory and methods of dynamic reliability modeling for complex electromechanical products [7]. Zhang and Wang focused on reliability allocation technology of CNC machine tools based on task [8].

Building on past experiences, when analyzing the reliability of such complex systems, the approach would be to break it down into small systems or basic units, and then analyze the basic units instead. There are a number of ways to further divide the machine tool. Xin and Xu took the machining process as the basic unit in precision analysis [9]. Zhang et al. considered the part as the basic unit in the assembly process [10]. Each decomposition method has its own clear object, but few can analyze a system with much function and quality coupling synthetically.

2. Findings

The difference between a CNC machine tool and an electronic product is that the function of the CNC machine tool is realized in terms of the relative motion between components. The latter are internally driven by a large number of meta-actions. Therefore, for a CNC machine tool, as long as the meta-actions break down, the movement function and performance of the components cannot be realized normally. Thus, action should be taken at the basic unit of design, analysis, test, and control [11]. The correctness of each action should be guaranteed to ensure the entire machine's function. All parts that realize an action may be treated as a whole. The method based on action simplifies the analysis process and refines its results. It can be used not only in reliability, but also in the design and manufacture of the CNC machine tool [12]. A complete new theoretical system of CNC machine tool design and manufacture based on meta-action is proposed.

Reliability is the product's ability to perform its specified functions under the stated conditions for a given period of time [13] and is concerned whether the function and movement can be realized. However, the traditional decomposition methods, assembly unit-component-parts (ACP), function-behavior-structure (FBS), and components-suite-parts (CSP), are based on product structure (or parts), which cannot reflect the motion characteristics of a CNC machine tool. Therefore, these methods are not entirely suitable for reliability analyses of dynamic systems.

A CNC machine may perform a number of functions such as drilling and milling throughout its entire service life. Basically, the function is realized by some movements of mechanisms, such as the rotational movement of a spindle. Finally, the movement is gradually achieved by the transmission of basic meta-actions. That is, the function of the CNC machine tool is accomplished by the movement, which in turn is completed by different actions. The latter defines the reliability of the product.

The main reasons that traditional methods are not applicable to CNC machine tool are described as follows:

1. CNC machine tools are basically unable to carry out accurate reliability prediction analysis, as they lack failure-specific probability data. Collecting the data requires much time and cost. In order to obtain more data, many scholars expand the data by means of some mathematical methods. Jia et al. proposed a method of increasing reliability data of CNC machine tool based on artificial neural network theory and algorithm [14]. The radial basis function (RBF) neural network is used to simulate the reliability data, which enlarges the latter's sample size [15]. This method can expand the data; however, the data is not precise.

2. The function and performance of CNC machine tools mainly rely on the interaction between components. It is necessary to analyze these parts as a whole [16].

3. The components of a CNC machine tool are very complex. A component may contain thousands of parts, and the establishment of a fault tree is very large. Zhai used fuzzy methods to solve the minimum cut-set. The large complex fault tree is decomposed into relatively independent sub-trees [17]. However, the basic problem is not resolved.

4. The failure mode of a CNC machine tool is higher than that of an electronic product and as such, the failure reasons may be extensive. Thus, it is difficult to predict all the potential failure modes in FMEA analysis [18].

5. Because of the complexity and the cross fusion of components, the reliability allocation method of electronic products cannot be used directly [19].

The meta-action decomposition method is proposed in this chapter. As such, the CNC machine tool is decomposed into several MUs, which are composed of several parts.

3. Analysis

In this chapter, the meta-action method is described in detail, including the FMA decomposition method and meta-action structure. Some applications of this method

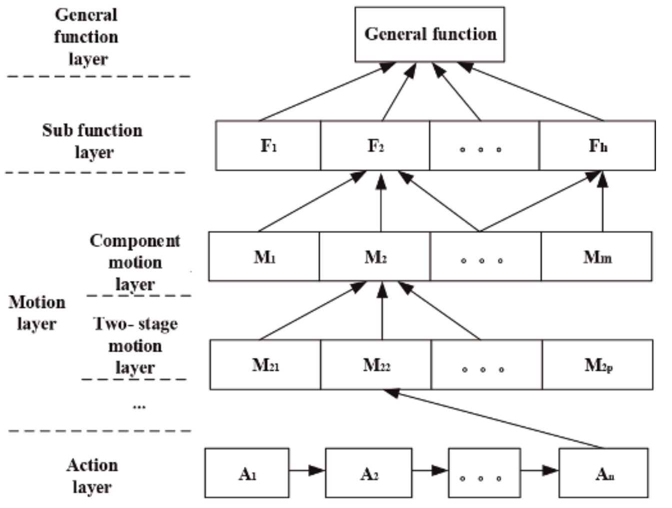

Figure 1.
FMA-structured decomposition.

are represented as well. Also, the use of meta-action reliability technology is described in this section, to provide references for increasing CNC machine tools' degree of reliability. The applications are introduced in three aspects: reliability modeling, design, and manufacturing.

3.1 FMA decomposition method

The "FMA" structured decomposition is used to decompose the CNC machine tool to the meta-action level and carry out the reliability analysis at the MU level. One may conduct the "FMA"-structured decomposition as shown in **Figure 1**. The concrete steps of the meta-action decomposition method are described as follows:

1. Analyze all functions of the CNC machine tool by means of its design project description or instruction manual.

2. According to the structure of the CNC machine tool, study the pattern to realize the function and determine the movements facilitating certain functions

3. Analyze the transfer route from the power part to the actuator(s) and obtain the meta-actions.

4. Depict the FMA tree including functions, movements, and meta-actions based on the above three steps

5. Determine the elements to realize the meta-action and describe the MUs

    - Function layer: it is the design function of the CNC machine tool at the level of design, i.e., milling, grinding, drilling, and turning functions.

    - Motion layer: in order to ensure the normal implementation of a function, the required motion combination level is the motion layer. For example, in order to realize the function of "drilling" in a machining center, it is necessary to co-ordinate the movement of spindle rotation, the indexing of NC turntable, X-Y-Z axes, which form the motion layer

- Action layer: in order to ensure the normal completion of the movement, the level of actions combination is the action layer. The actions in the layer are all meta-actions, and there is no inclusion relationship.

According to the path of action transmission, the actions can be divided into first-order action, second-order action, …, and N-level action. For example, the movement of the worm and gear drive is divided into two meta-movements. The worm rotation is a first-order action, and the worm gear rotation is a second-order action.

3.2 Meta-action and meta-action unit

3.2.1 Meta-action

The function of a CNC machine tool is accomplished by motion, which in turn is usually done by a transmission system. The latter can be decomposed into the most basic motion unit. Therefore, meta-action may be defined the smallest motion in mechanical products.

The meta-action of CNC machine tool can be usually divided into moving meta-action and rotating meta-action. The former realizes the most basic moving functions, such as the linear movement of piston in the cylinder, the linear movement of a nut along the axis of a screw, the movement of a moving guide rail on the static guide rail, etc.

The latter accomplishes the most basic rotating functions, such as a pair of gear transmission that may be divided into two gear rotating meta-actions. A pair of worm and gear transmission can be decomposed into worm rotating meta-action and worm wheel rotating meta-action.

In design and manufacture, the performance of a CNC machine tool can be controlled only by managing the performance of meta-action.

3.2.2 Meta-action unit

In order to realize the movement of components, the following four elements must be present:

- power input parts,
- transmission parts,
- supporting parts,
- motion output parts.

For example, in order to carry out the rotational motion function of the spindle, it is necessary to have a motor coupling, a pulley, or a gear as the power input, an intermediate drive shaft and a gear as the transmission parts, a supporting part (such as a spindle box) for mounting the transmission parts, and a spindle body as the motion output. These parts form an assembly that facilitates the rotation movement function of the main shaft.

In view of the above, one might define the MU as the unified whole of all parts, which can ensure the normal operation of the meta-action according to the structural relations. The MU must have the following basic elements: power input, power output, middleware, support, and fastener. The specific definition of each basic element is shown in **Table 1**.

3.2.3 The basic model of MU

1. The conceptual model of MU

In order to describe the concept of MU, a conceptual MU model is established, which is shown in **Figure 2**.

2. The structural model of a MU

The structural model describes the MU from the aspect of mechanical structure. In general, two types of MUs units are moving units and rotating units. **Figure 3** is

Composed element	Definition	Example
Power input parts	In MU, the parts that receive or provide a power source or adjacent to the motion or power input of the previous MU	In worm and worm gear drive, the motor is the input of the element action unit, which provides the power input for the element action unit
Power output parts	The last part of a MU that outputs motion or power is the main part of the MU and it completes the specified meta-action	In worm-worm gear transmission, the worm is the output of the element action unit in which it is located, and motion and power are transmitted to the input of the next element's action unit
Middleware	A part (part combination) that occurs between a "power input" and a "power output" and plays a major role in transmitting motion and power, and has no relative motion with the input and output parts	In worm and worm gear transmission, the coupling transmits the motion and the power output by the motor to the output of the unit - worm
Fastener	In a MU, a part that is fixed, loosen-proof, and sealed, or is used to connect two or more parts without relative motion	Such as screws, pins and end covers, spring washers, sealing rings, sealing sleeves, sealing gaskets, etc.
Supporting parts	A part in a MU that provides assembly references or supporting functions for other parts	Such as bearing, piston cylinder, sleeve, machine tool base and box

Table 1.
The definitions of MU basic elements.

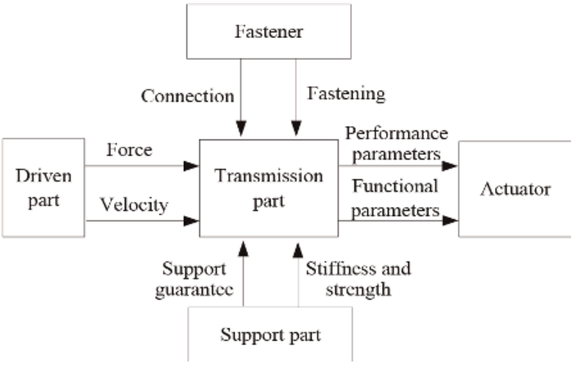

Figure 2.
The conceptual MU model.

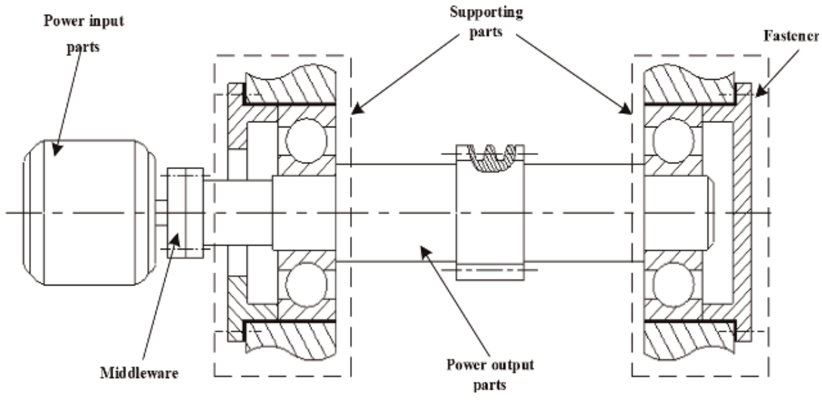

Figure 3.
Worm rotating MU.

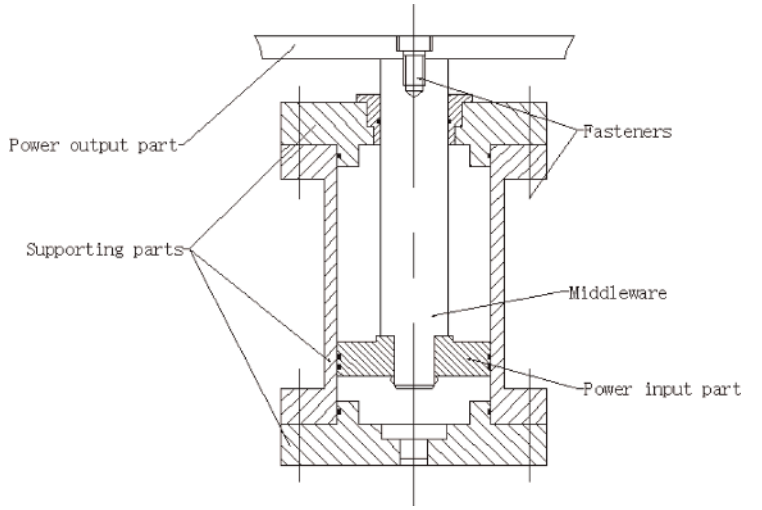

Figure 4.
Pallet moving MU.

the structural model of typical rotating units. **Figure 4** is the structural model of typical moving units.

3. The assembly model of MU

The assembly model of a MU describes the assembly process of a MU. Therefore, it is necessary to establish their standard assembly process according to the structural model of two types of MU, and draw the assembly model diagram according to the standard assembly process. **Figure 5** shows an assembly model of a MU.

3.3 Applications

3.3.1 Reliability mathematical modeling based on MU

As the smallest action unit in enabling a CNC machine tool's function, MU's reliability affects the whole system [20]. Therefore, the technology incorporated in the MU should be studied and the reliability mathematical model of the MU should be established first.

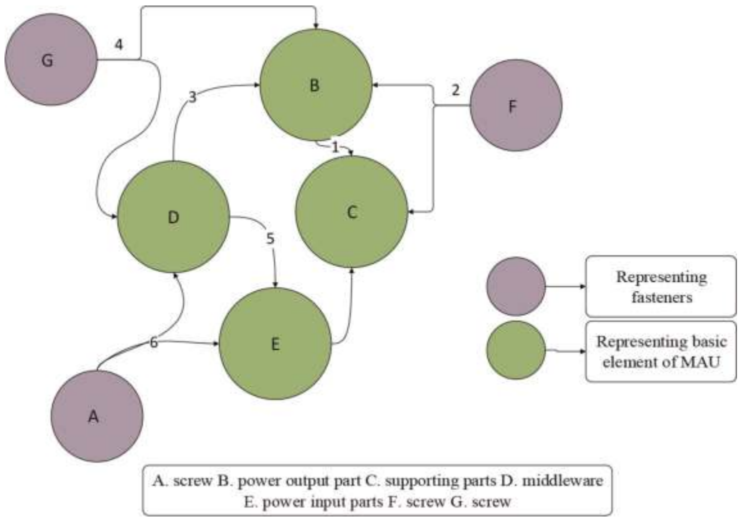

Figure 5.
The assembly model of a MU.

MU's reliability means the ability of the MU to remain functional. It can be also characterized by the degree of reliability. The reliability degree of the MU means the probability that the MU will perform its required function under given conditions for a stated time interval [21], namely, the probability that MU output characteristic parameters are within acceptable ranges in specified time periods. This is shown in Eq. (1).

$$R = P[Y_{\min} \le Y(t) \le Y_{\max}] \tag{1}$$

where, $Y(t)$ means the output quality characteristic parameters (such as precision, accuracy life, performance stability, etc.), $[Y_{\min}, Y_{\max}]$ defines the ranges of MU's output quality characteristic parameters under design requirements.

Taking the motion precision of MU, for example, and assuming that motion error values of MU follow the normal distribution, then the reliability of the MU can be described as below:

$$R = P(e_{min} \le E \le e_{max}) = P(E \le e_{max}) - P(E \le e_{min}) = \Phi\left(\frac{e_{max} - \mu}{\sigma}\right) - \Phi\left(\frac{e_{min} - \mu}{\sigma}\right)$$

In a practical situation, the CNC machine tool needs to accomplish multiple different missions by different MUs, so the system's mission reliability is actually a dynamic combination of each MU's reliability, shown in **Figure 6**.

The calculation of the machine system's mission reliability is shown in Eq. (2).

$$R^W = \sum_{i=1}^{n} \alpha_i R^{A_i} \tag{2}$$

where, R^W means the reliability of the wth mission, α_i means the weight that the ith MU relative to the wth mission, R^{A_i} means the reliability of the ith MU.

3.3.2 Reliability design for CNC machine tool based on MU

Reliability design is a basic guarantee of the CNC machine tools' reliability. As everyone knows, design of the machine tool is a difficult system engineering

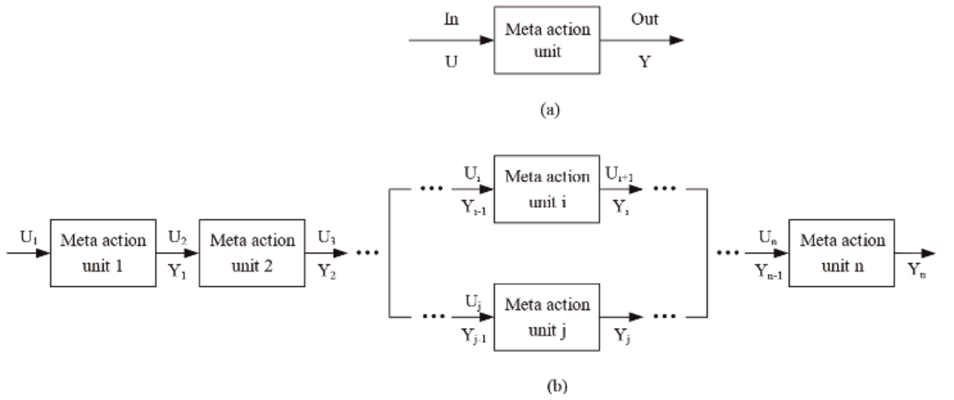

Figure 6.
Mission reliability model of MU. (a) Single meta-action unit and (b) machine system based on meta-action unit.

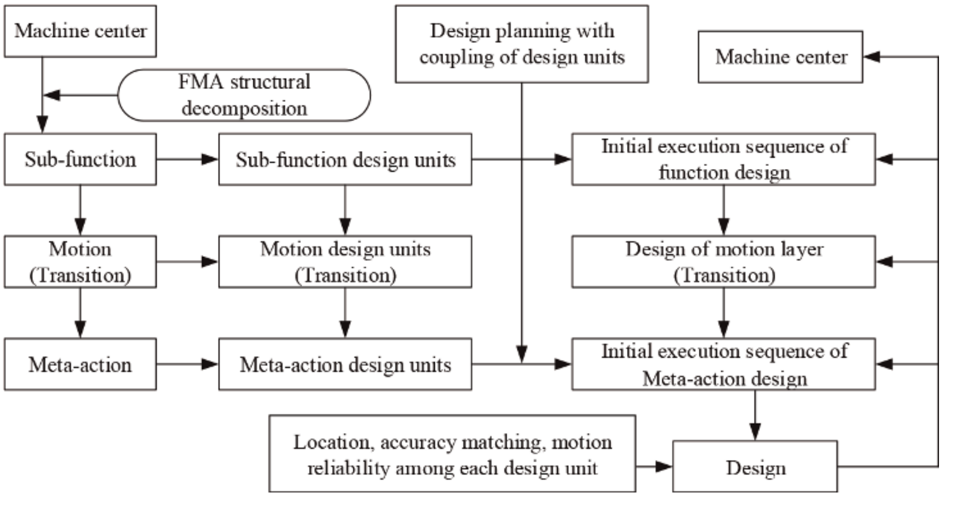

Figure 7.
Design process planning driven by FMA structural decomposition.

problem. To simplify the design, the reliability design technology by using FMA has been studied.

3.3.2.1 Design process planning for machine center driven by FMA structural decomposition

The design process of the machine center is optimized by using the FMA structural decomposition methodology [22]. There is a large amount of information coupling among each design unit; the basic planning of the design process is obtained based on the consideration of each unit's coupling, as shown in **Figure 7**, which can speed-up the design and the development of machining centers.

Firstly, the machine center is decomposed into sub-function design units, motion design units, and meta-action design units by FMA structural decomposition.

Secondly, the initial design sequence (IDS) of the function layer is obtained by considering the coupling among the design units of the sub-function layer. Next, the IDS of the meta-action layer is determined in the light of a sub-function, by taking its motion layer as a transition layer. The last step is to design the mechanical structures following an ascending order, i.e., from bottom to top (from the meta-action layer to the entire machine).

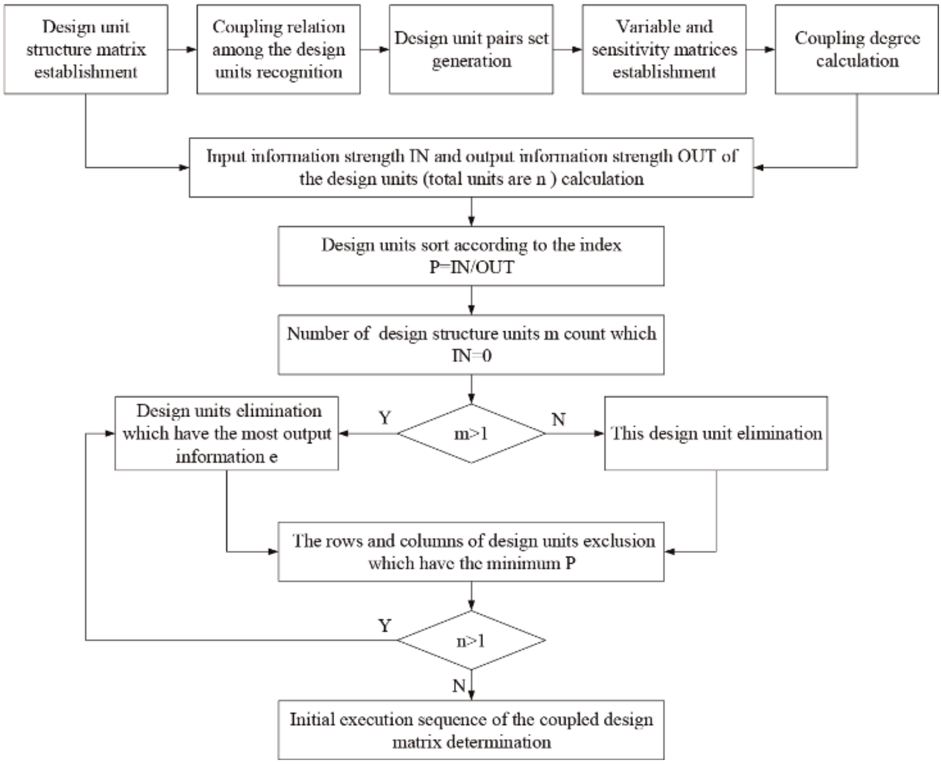

Figure 8.
Execution steps of the coupling strength calculation and coupling splitting.

After the design process planning, the coupling strengths among the design units are calculated by using variability and sensitivity indices based on the information coupling among them (i.e., the design units). Then, the splitting method is been used for the coupling design structure matrix to optimize the IDS of each design unit. **Figure 8** illustrates the procedure.

The variable stands for the degree of information change transmitted from the top design structure units to the bottom design structure units. Sensitivity means the degree of the bottom design units' output information change caused by the top design units' output information change.

3.3.2.2 Research on the evaluation of mechanical structure similarity and reliability prediction

To overcome the problem of failure data shortage because of the low yield and in order to expand the failure data, Zhang et al. [23] decomposed the CNC machine tools by FMA, and referred the failure data of similar MUs. Because of the high failure rate in the CNC machine tools, the NC rotary table is taken as an example.

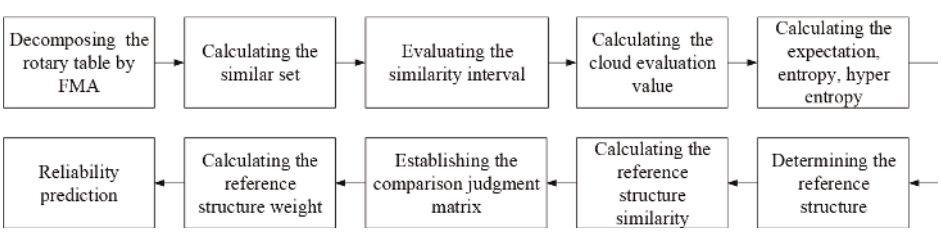

Figure 9.
Procedure of reliability prediction based on meta-action units and structure similarity.

Firstly, the NC rotary table is decomposed into the meta-action layer and possible similar unit sets of each MU are obtained. Secondly, similar MUs are determined according to the similarity of possible similar units calculated by using interval number normal cloud model. Lastly, the failure data according to the similarity among units is modified, resulting in the reliability prediction, as shown in **Figure 9**.

3.3.2.3 FTA and FMEA for meta-action unit

FTA and FMEA for meta-action unit (MU-FTA and MU-FMEA) are more suitable for the CNC machine tools that showcase the main body of mechanical structure rather than the traditional FTA and FMEA.

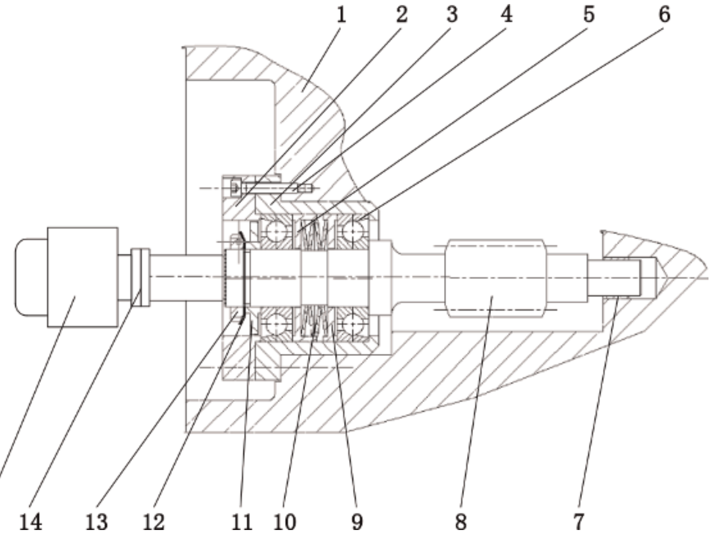

Figure 10.
Worm rotation meta-action unit: (1) slippery seat; (2) bearing cover; (3) bearing seat; (4) screw; (5) spacer sleeve; (6) bearing; (7) bushing; (8) worm; (9) spacer sleeve; (10) disk spring; (11) spacer sleeve; (12) tab washer; (13) round nut; (14) coupling; and (15) servo motor.

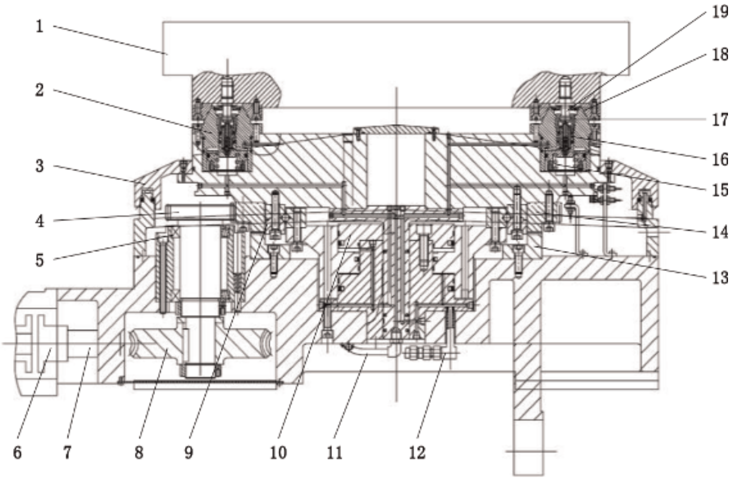

Figure 11.
End-toothed disc indexing table schematic drawing: (1) pallet; (2) male tapper; (3) sealed shell; (4) gear shaft; (5) gear shaft bearing; (6) motor; (7) worm; (8) worm gear; (9) axisymmetric body bearing; (10) lift cylinder; (11) locked cylinder oil circuit; (12) lift cylinder oil circuit; (13) lower tooth disc; (14) upper tooth disc; (15) large spring; (16) pull stud; (17) claw; (18) generating cone; and (19) positioning nail.

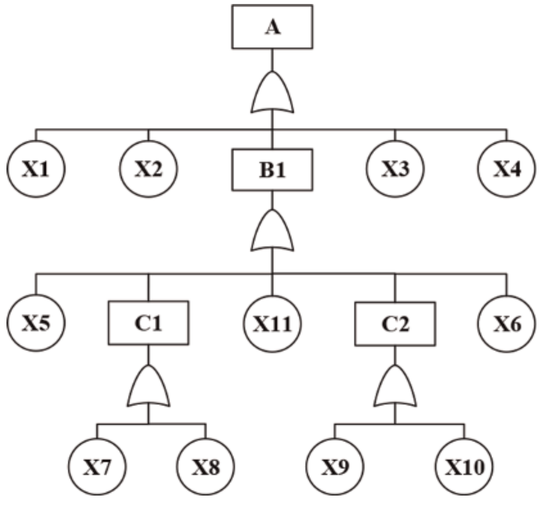

Figure 12.
FTA of worm's vibration.

Label	Event definitions	Label	Event definitions
A	Worm vibration	X5	Interference between bearing and shaft is too large
B1	Bearing vibration	X6	Fatigue failure of disc springs
C1	Bad lubrication of bearings	X7	Unreasonable grease injection
C2	Insufficient bearing preload	X8	Unclean grease
X1	Bad assembling of coupling	X9	Loosening round nut loosening
X2	Breaking liner	X10	Aging of shim gaskets
X3	Teeth bonding	X11	Bearing preload is too large
X4	Teeth pitting		

Table 2.
FTA event definition of worm vibration.

Taking the worm rotation meta-action (shown in **Figure 10**) and the end-toothed disc indexing table (shown in **Figure 11**) as examples, the MU-FTA and MU-FMEA are shown below [24]. Therefore, MU-FTA and MU-FMEA are shown in **Figure 12** and **Table 3**, and the specific contents of the fault tree are shown in **Table 2**.

3.3.3 Manufacturing technology of CNC machine tool by using FMA

Manufacturing technology is important to guarantee the reliability of CNC machine tools. Assembly, the last step of manufacture, also inadvertently affects the reliability of CNC machine tools. The research on CNC machine tools' assembly reliability by using FMA can be categorized into the following two areas:

- assembly error analysis;
- assembly reliability modeling.

3.3.3.1 Assembly error modeling technology by using FMA

The main methodologies of assembly error modeling by using FMA are assembly error transfer link graph [25] and assembly error propagation state space model [26].

Meta-action	Mode	Failure mode	Failure cause	Failure effects		Detection	Improvement measures
				Local effects	Final effects		
Worm rotation	Rotation	No action of worm rotation	Servo motor damaged	Loss worm's and gear shaft's function	Hindering the parts processing	Instruments	Maintaining or replacing the motors, couplings, bearings. Improving assembly process of bearings and couplings. Strengthening the assembly quality inspection. Inspecting the state of bearings regularly
			Coupling broken				
			Bearing jammed				
		Worm vibration	Bearing vibration	Worm and gear shaft vibration	Hindering the parts processing	Instruments	Maintaining or replacing the couplings, nuts. Improving protection and sealing structures. Changing the lubricating mode or type. Strengthening the assembly accuracy control of bearings. Improving assembly process of the bearings. Strengthening the assembly quality inspection measures. Inspecting the state of nuts and bearings regularly
			Bad assembly of bearings				
			Bearing cannot keep correct position				
			Nut loosening				
			Entry of foreign bodies				
			Bad lubrication				
			Worm root broken				
			Teeth pitting, wear or gluing				
			Wear, pitting, and gluing of upper gear disc surfaces				
			Bad assembly of large bearings				
			Bad lubrication of large bearing				
			Screw loosening				

Table 3.
MU-FMEA (partial).

1. Assembly error transfer link graph.

The assembly errors of the MU can be categorized into five aspects, namely:

- geometric position error;
- geometrical shape error;
- assembly position error;

- assembly torque (deformation) error; and
- measuring error of the parts.

The transfer and accumulation processes are shown in the assembly error transfer link graph (**Figure 18**) by using the error propagation link. The graph is a basic encapsulation unit that represents the error propagation and accumulation rules in assembly parts or between assembly parts. The function models of each part from the meta-action assembly units (MU) are presented by the circles, whereas the error propagation rules (they consist of one or several functional relations) between the function models for the parts before assembling (input) and after assembling (output) are presented by rectangles. The linkages between the function models and the rules are presented by arrows. The positive direction of the arrows is directed from the error references to the functions, shown in **Figure 13**.

For the first to the fifth error, g_{ij} means the *j*th function model in the part $i(i \geq 1, j \geq 0)$, d_k are the error models of the first to the fifth error, thus, the first to fifth error model $(0 \leq k \leq 5)$ of the part $i(i \geq 1, j \geq 0)$, E_{imk} means the *k*th error between part i and m.

There are two kinds of error propagation relation between two parts: coupling and nesting, as shown by **Figure 14**.

The complex assembly error propagation relation network (i.e., link network) is generated by the coupling and nesting of the assembly error transfer link diagram for multiple parts, shown in **Figure 15**.

At last, the link network of error propagation is transformed into the structural link matrix to predict the error propagation of MUs or the entire machine.

The link matrix is made of three aspects:

- linkage,
- error propagation model, and
- error sources.

The above are presented in **Table 4**. This methodology is used to define and describe on one hand the error source among the parts, and on the other, the error source relations during the assembly process.

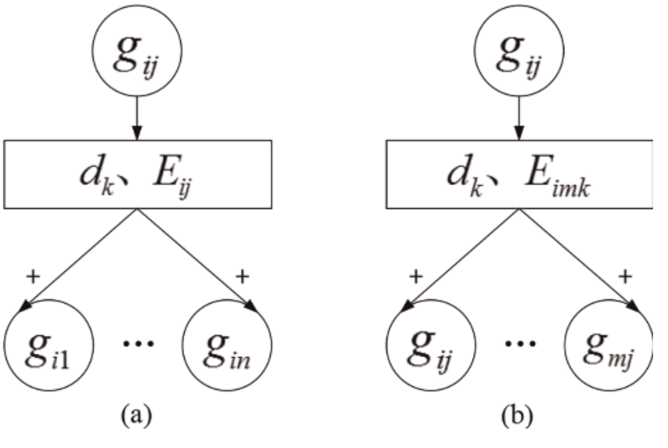

Figure 13.
Link of error propagation. (a) 1st error flow; (b) 2nd error flow.

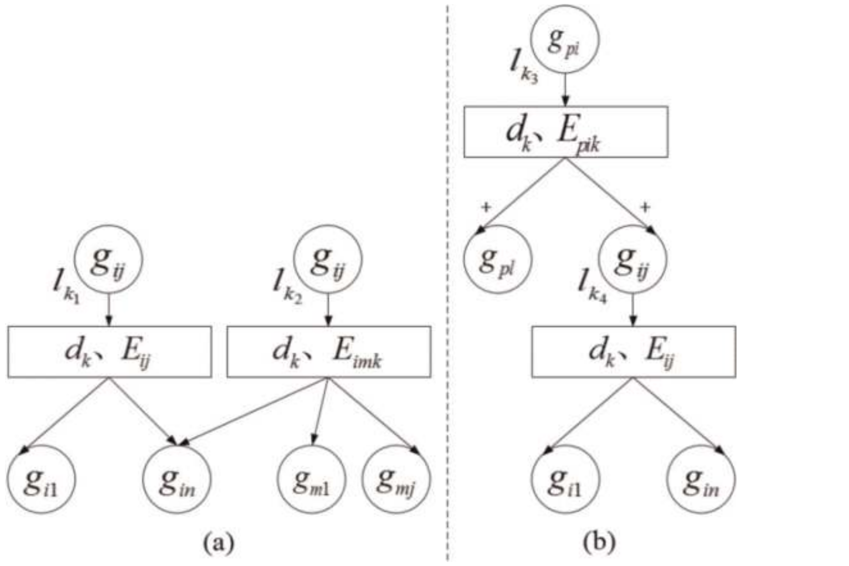

Figure 14.
Link coupling and nesting of error propagation. (a) Coupling between l_{k_1} and l_{k_2} (b) nesting between l_{k_1} and l_{k_2}.

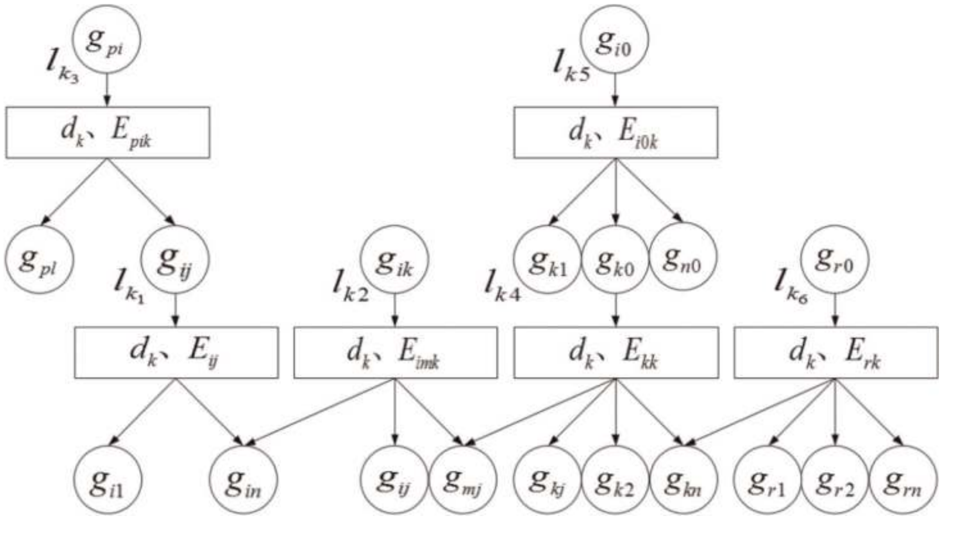

Figure 15.
Link network of the assembly error propagation (NBL).

	A					**B**			**C**							**D**			
	g_{pi}	g_{pl}	g_{ij}	g_{i1}	g_{in}	g_{ik}	g_{ij}	g_{mj}	g_{i0}	g_{kj}	g_{k0}	g_{n0}	g_{k1}	g_{k2}	g_{kn}	g_{r0}	g_{r1}	g_{r2}	g_{rn}
l_{k_1}				k	k														
l_{k_2}					k	k	k	k											
l_{k_3}	k	k	k																
l_{k_4}								k			k		k	k	k				
l_{k_5}									k	k	k	k							
l_{k_6}															k	k	k	k	k

Table 4.
Matrix of error propagation link (MBL).

The link matrix is constructed according to the two-level composite matrix architecture. In this table, the row elements represent the links, the elements in the first level column stand for the assembly parts or components, the second level column elements signify the parts contained in the components, and the center cells are identified by the error source type $k(0 \leq k \leq 5)$. However, if there is no error propagation or if there are no effects in assembly quality and accuracy during the error propagation, the cells should be empty.

2. State space model of assembly error propagation

The hierarchy diagram of assembly errors propagation is established by decomposing the error propagation process hierarchically based on the error propagation carriers that function assembly units, motion assembly units and MUs, is depicted in **Figure 16**.

The small displacement torsor is introduced on the basis of a hierarchy diagram, while the errors between actual geometric characteristics and ideal geometric characteristics are represented by the error vector $R = [a, b, c, \alpha, \beta, \gamma]^T$, where a, b, c and α, β, γ mean the translation errors and rotation errors along the three axes, respectively. The relative poses among assembly units are determined by their position and pose parameters, and the feature matrix is established according to the pose parameters among sub-coordinate systems, shown in Eq. (3).

$$A_k = \begin{bmatrix} 1 & -\Delta\gamma & \Delta\beta & \Delta a + x \\ \Delta\gamma & 1 & -\Delta\alpha & \Delta b + y \\ -\Delta\beta & \Delta\alpha & 1 & \Delta c + z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

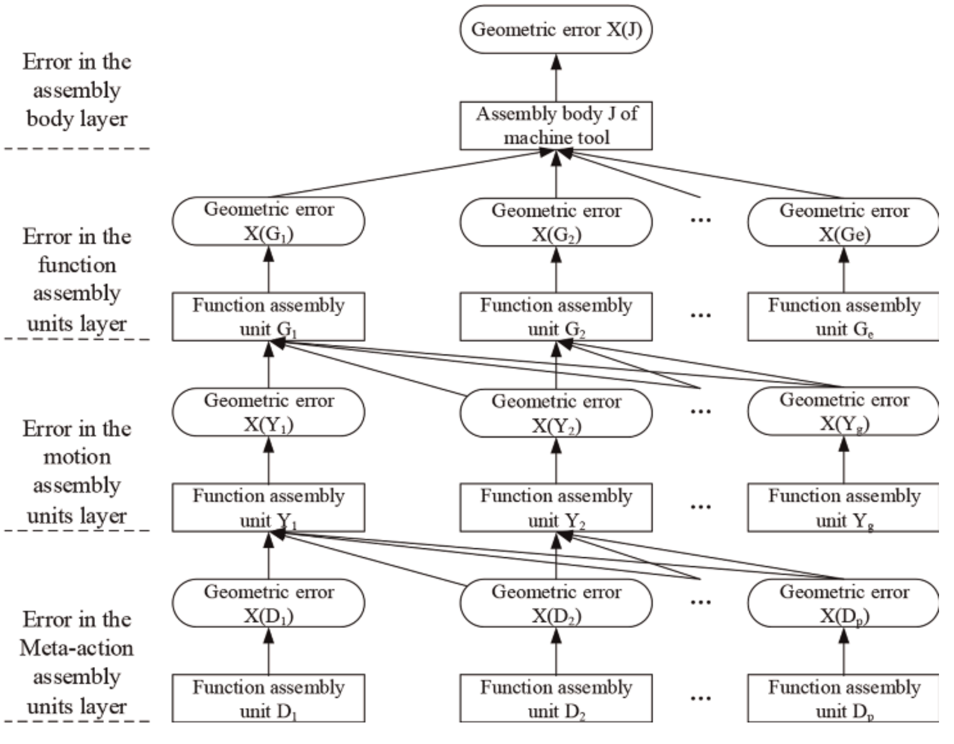

Figure 16.
Hierarchy diagram of assembly errors propagation.

Suppose the geometric characteristics of motion assembly units are affected by single factor of the MUs, thus, by sorting the MUs that affect the hth geometric error of the gth motion unit according to the assembly sequence number, shown in **Figure 17**.

According to the assembly process, after finishing the assembly of kth MU, the assembly error outputs are represented by the small displacement screw $X_{gh}(k)$ as below:

$$X_{gh}(k) = \begin{bmatrix} d_k \\ \delta_k \end{bmatrix} = \begin{bmatrix} a_k & b_k & c_k & \alpha_k & \beta_k & \gamma_k \end{bmatrix}^T$$

where, $k = 1, 2, \ldots, i, i$ is the total number of the MUs that affect the hth geometric error of the gth motion unit, d_k is the translation component of geometric error, and δ_k is the rotation component of geometric error.

The errors introduced by the dynamic uncertain factors of assembly force and measurement, etc., are considered in the actual assembly process and are shown in Eq. (4).

$$\begin{cases} X_{gh}(k) = A_{gh}(k)X_{gh}(k-1) + B_{gh}(k)\mu_{gh}(k) + v_{gh}(k) \\ T_{gh}(k) = C_{gh}(k)X_{gh}(k) + \xi_{gh}(k) \end{cases} \tag{4}$$

where, $A_{gh}(k)$ is the transformation matrix of the geometric error vector among characteristic co-ordinate systems, $B_{gh}(k)$ is the error input matrix that reflects the affection of new input geometric characteristic error on assembly units, and $\mu_{gh}(k)$ is the geometric error vector introduced by the assembly of the kth MU.

The error vector consists of the errors generated by the assembly, grinding and repairing of the MUs; and $v_{gh}(k)$ is the assembly error introduced by the assembly force, $\xi_{gh}(k)$ is the measurement noise obeying the normal distribution with a mean value of 0. However, it is worth noting that there is no error input if this station

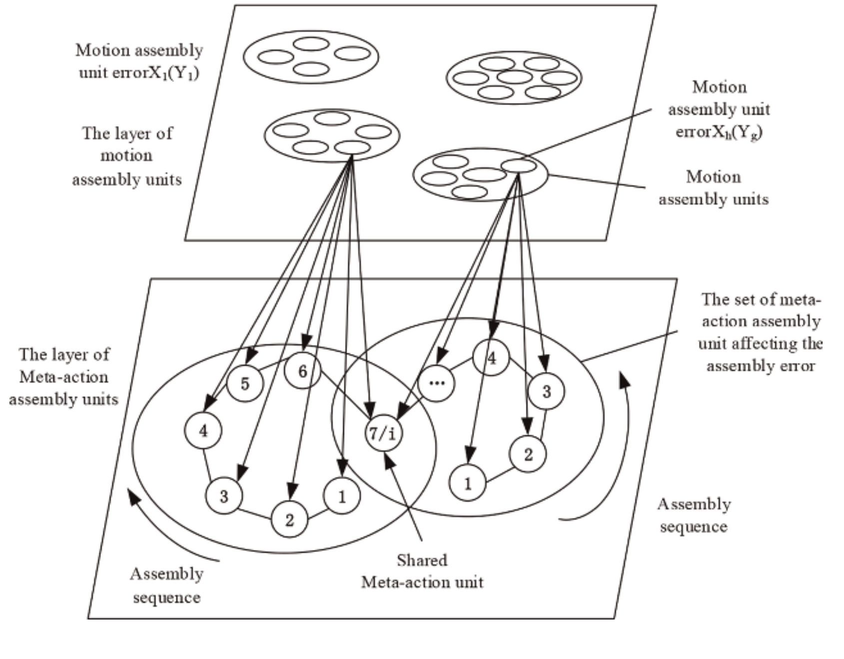

Figure 17.
Assembly process from meta-action assembly units to motion assembly units.

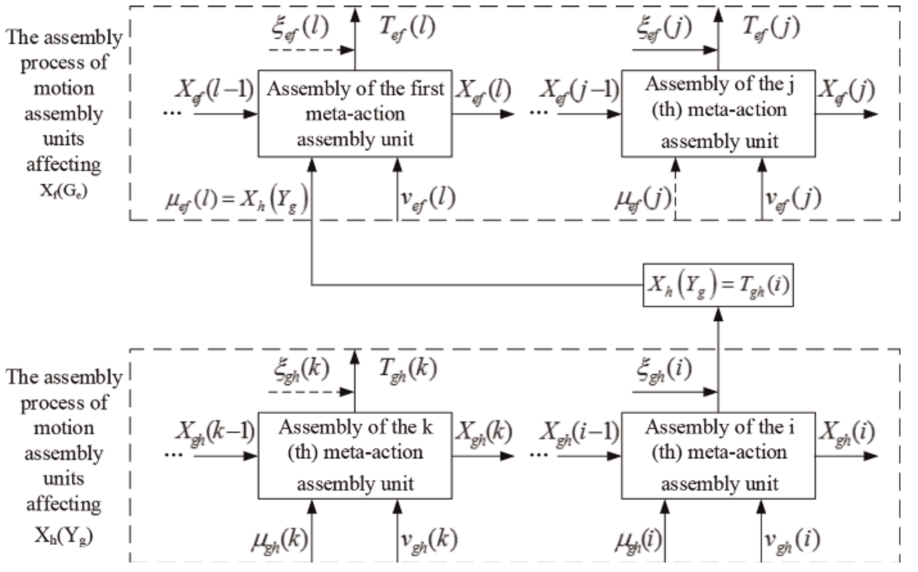

Figure 18.
The state space model of assembly error propagation.

does not need to be measured. $C_{gh}(k)$ is the output matrix and $T_{gh}(k)$ is the geometric error obtained by measuring.

The state space model of assembly error propagation is shown in **Figure 18**.

The definition of the motion assembly units' final output error is the geometric error $T_{gh}(i)$ measured after finishing the assembly of the final assembly unit i, i.e., $X_h(Y_g) = T_{gh}(i)$. Therefore, the state space models of assembly error propagating from motion assembly units to function assembly units, from function assembly units to the whole machine assembly are deduced for the same reason, shown in Eqs. (5) and (6).

$$\begin{cases} X_{ef}(k) = A_{ef}(k)X_{ef}(k-1) + B_{ef}(k)\mu_{ef}(k) + v_{ef}(k) \\ T_{ef}(k) = C_{ef}(k)X_{ef}(k) + \xi_{ef}(k) \end{cases} \tag{5}$$

$$\begin{cases} X_z(k) = A_z(k)X_z(k-1) + B_z(k)\mu_z(k) + v_z(k) \\ T_z(k) = C_z(k)X_z(k) + \xi_z(k) \end{cases} \tag{6}$$

The geometric error $X(G_e) = \{X_1(G_e), X_2(G_e), \ldots, X_f(G_e)\}$ of the function assembly unit e, referred as synthesis error of function assembly unit e, is obtained by introducing the error of assembly units into the state space model layer-by-layer is shown below:

$$\begin{aligned} &E(G_e) = F\big(X_1(G_e), X_2(G_e), \ldots, X_f(G_e)\big) = \\ &F(X_1(Y_1), X_2(Y_1)\ldots X_1(Y_2), X_2(Y_2)\ldots X_1(Y_n), X_2(Y_n)\ldots) = \\ &F(X_1(D_1), X_2(D_1)\ldots X_1(D_2), X_2(D_2)\ldots X_1(D_n), X_2(D_n)\ldots) \end{aligned}$$

3.3.3.2 Assembly reliability modeling based on the MUs

A large number of attempts had been made in the assembly reliability modeling of MUs, and their respective modeling methodology by the modular fault tree proposed by Li et al. [27].

The FTA is accomplished on the target product first, and decomposes the fault tree into the layer of MUs, then performs the analysis and calculation by regarding

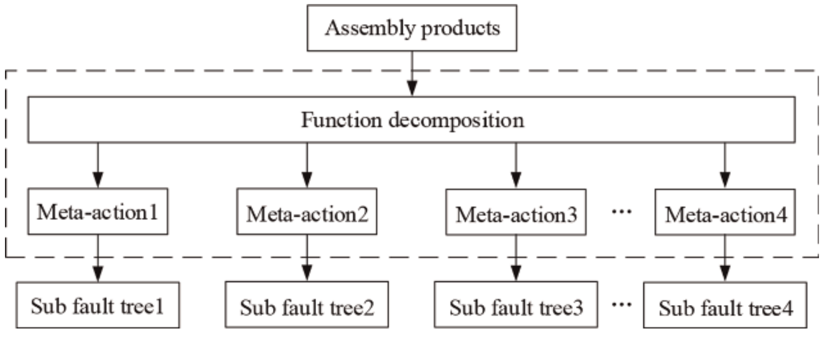

Figure 19.
Modularization fault tree model based on the function decomposition.

the meta-action fault tree after function decomposition as separate independent modules (**Figure 19**).

The function implementation is the key performance of the assembly quality; the performances of the assembly units are characterized by using the quadruples based on the modularization fault model, as $F = (S, P, T, Q)$, where:

- S symbolizes the set of assembly units' performance,
- P stands for the set of assembly units' performance attribute,
- P_m means the performance evaluation index of the assembly units, and the indices constitute the set of the assembly units' performance attribute,
- T characterizes the set of all action obtained by the function decomposition,
- T_{ij} denotes the cell of T, and $T_{i(j+1)}$ is used to represent the subordinate functional action of T_{ij} because of the inclusion relationship among the functional actions, and
- Q signifies the mapping function from the functional action to assembly performance, $Q_a : T \to P$.

On the basis of the modularization fault tree, the assembly reliability modularization fault tree is simplified by sorting basic events. Then, the fault tree is transformed into a binary decision diagram (BDD) by using ITE structural analysis methodology. Finally, transforming the meta-action sub-fault tree into a BDD, researching the assembly reliability of meta-action assembly units by combining the BDD with a mapping function, and obtaining the mapping function Q_a of meta-action assembly reliability are shown in Eq. (7).

$$Q_a : M \times F \tag{7}$$

where M means the mapping matrix of different performance attributes' weight for meta-actions and F indicates performance index evaluation results of the MUs' reliability.

3.3.4 Other reliability application based on meta-action

In addition to the application of reliability modeling, reliability design, and assembly reliability analysis for CNC machine tool based on MU, FMA methodology has also been used in failure classification [24], system motion reliability analysis [28], maintenance decision [29], to name but a few.

4. Discussion

Reliability modeling by FMA is more suitable than other decomposition methodologies because of its motion characteristics and the complicated structure of CNC machine tools. As one of the quality characteristics (i.e., precision, reliability, precision retaining ability, availability stability, and other minor characteristics), reliability is affected by other characteristics, so it is more accurate to establish the reliability model of CNC machine tools by FMA.

Reliability design is a basic assurance of a CNC machine tools' reliability. With the increasing complexity of CNC machine tools, their design became more challenging, as it was associated with poor efficiency, multiple iterations, and long design cycles. The entire machine was decomposed into MUs to ensure accomplishing the function by means of simple rotations and movements. As such, the design of the entire machine is turned into the design of MUs, and the design process of the CNC machines is hence simplified.

Otherwise, practice has shown that the traditional similar product method, which seeks for similar structure at the whole machine level, in conjunction with FMA can expand the failure data more accurately, thereby reaching more precise conclusions. As such, an FMA decomposition can simplify the CNC machine tools by making the analysis more efficient and avoiding duplicate results. Otherwise, since traditional FTA and FMEA are carried out on the basis of the parts, MU-FTA and MU-FMEA can reduce the number of agreed levels and reduce the workload.

As far as the assembly technology is concerned, it would cause data explosion and increase the difficulty of analysis from the research of assembly-specific technology based on the parts. In the entire machine layer, the assembly technology research will be affected by the coupling relationship between the parts, which increases the disassembly difficulty of the assembly process. To reduce the difficulty of reliability assembly work, the common approach is to simplify the products by decomposition. FMA decomposition is more suitable for the assembly reliability study than other decomposition methodology, because of the quality characteristic similarity between the complete machine and the units.

5. Conclusions and further work

Performed research showed that meta-action methodology is adaptive and scientifically correct for the reliability analysis of the product. In this chapter, the meta-action methodology is introduced. To obtain the meta-action, the FMA decomposition process and its rules were presented. The meta-action and their corresponding units were defined and the constituent parts of the meta-action unit were shown. Some applications were introduced, such as reliability model, allocation, assessing, and fault diagnosing.

Meta-action methodology, as a new kind of structural decomposition theory, is more suitable for quality and reliability analysis of mechanical systems than traditional methods. It is an important tool to accomplish the reliability related work for CNC machine tools and even electromechanical products.

It is the authors' view that it will be more widely used in the future based on its constant deep study. In view of the above, research on reliability based on meta-action should be further facilitated and performed. A systematic research method of reliability based on meta-action method can be built, which would promote the reliability level of CNC machine tool holistically. This basically includes the following three aspects:

- reliability design technology from bottom to top by regarding the meta-actions as the smallest units, since the meta-actions are decomposed from functions;
- fault mode classification by meta-action, because the fault modes of meta-action units are relatively fixed and have certain regularity; and
- fault mechanism study by meta-action, as the FMA has the function of simplifying the CNC machine tools.

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