Chapter

Research on Key Quality Characteristics of Electromechanical Product Based on Meta-Action Unit

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Abstract

Electromechanical products have many quality characteristics, representing their quality. In addition, there are long-existed quality problems of electromechanical products, such as poor accuracy, short precision life, large fluctuations in performance, frequently failing, and so on. Based on meta-action unit (MU) for electromechanical products, this book chapter proposes a key quality characteristic control method, which provides theoretical and technical support for essentially guaranteeing the complete machine's quality. The formation mechanisms of MU's four key quality characteristics (precision, precision life, performance stability, and reliability) are studied. Moreover, we introduce an overview of key quality characteristic control methods based on MU. The complex large system research method of "decomposition-analysis-synthesis" is adopted to study these key science problems.

Keywords: key quality characteristics, electromechanical product, meta-action unit

1. Introduction

The construction of industrial modernization cannot be separated from the electromechanical integration [1]. Electromechanical products play an extremely important role in the current society. The technical level of electromechanical products determines the development level of the national economy and also directly reflects the country's manufacturing capacity, scientific and technological strength, economic strength, international competitiveness, and other comprehensive national strengths [2]. Poor quality of electromechanical products will not only bring economic losses to enterprises but also seriously affect the international market competitiveness of products and, more seriously, the overall image and economic strength of the country. Therefore, accelerating the development of electromechanical products and improving the quality of products are of vital significance for the national economic construction, national defense security, and social stability.

There are many quality indexes of electromechanical products. Among them, the four indexes (precision, precision life, performance stability, and reliability) are the most concerned by users, which together constitute the key quality characteristics of electromechanical products and decisively affect the market competitiveness of electromechanical products. Therefore, in order to occupy a place in the competitive high-end market, we must first improve the level of these key quality characteristics [3]. Therefore, carrying out a research into the electromechanical product quality control technology, especially, the quality of its key features, is extremely important. However, it is very difficult to control the quality of complex electromechanical products, not only for its complex structure but also for its working process, a dynamic process composed of many motions. The commonly used structural decomposition methods are mostly the static research based on the quality characteristics of parts in the design process. At the same time, there is a lot of uncertainty and coupling in the process of motion, which makes the dynamic quality characteristics greatly different from the static ones. In view of these problems, this paper puts forward the research idea of quality characteristic control technology of electromechanical product based on MU [4].

2. Literature review

There are many quality characteristics of electromechanical products, but its key characteristics mainly include precision, precision life, performance stability, and reliability, which comprehensively reflect the availability of the product. At present, the analysis of precision is quite common for the stages of design, manufacture, and operation of electromechanical products, but the research of precision life, performance stability, and reliability is few.

The precision of electromechanical products includes geometric accuracy, motion accuracy, transmission accuracy, position accuracy, etc., among which geometric accuracy is the basis and guarantee of other precisions. There are many studies on the precision of electromechanical products. Enterprises pay more attention to the precision of electromechanical products, especially for machine tools. Sata et al. put forward a method to improve machining accuracy of machining center through computer control compensation earlier [5]. Ceglarek et al. used the state space model to model the stream of variation (SOV) of the multi-stage manufacturing system, described the errors of process parameters and product quality characteristics with the vector tolerance, and applied it in automobile body-in-white assembly and automobile engine cylinder head machining [6]. Zeyuan et al. carried out simulation and experimental research on geometric error detection, identification, and compensation of translational axis of NC machine tools by two geometric error-modeling methods [7]. Li et al. summarized the characteristics of the existing error compensation methods and discussed the future development direction of improving the spatial positioning accuracy of five-axis CNC machine tools [8]. Yongwei et al. proposed a method for predicting the motion accuracy of CNC machine tools based on the time-series deep learning network [9].

The research on precision life mainly focuses on the working stage of electromechanical products, and the research object mainly focuses on the precision life of servo feed system (such as screw pair, etc.). Min et al. carried out a simulation test of the precision retaining ability degradation of the ball screw pair to achieve a fast prediction of the life of the ball screw pair [10]. Liping et al. conducted a gray prediction of the rotary precision life of the spindle of CNC lathe [11]. Linlin studied the precision retaining ability of servo feed system of CNC machine tool and its test method [12]. Hu et al. proposed a vibration aging process parameter selection method based on modal analysis and harmonious response analysis to improve the precision life of large basic parts of CNC machine tools in view of the nonstandard phenomenon of vibration aging process in domestic manufacturing enterprises [13].

Shijun et al. analyzed the influence of axial load on friction torque of ball screw pair through experiments and pointed out that the pre-tightening force plays a leading role in the fluctuation of friction torque of ball screw pair [14].

The research on performance stability mainly focuses on the research of performance index and parameter design. Saitou et al. summarized the development history of structural design and optimization of mechanical products and optimized the parameters to achieve the purpose of improving the stability of its performance [15]. Ta et al. studied the influence of friction on sliding stability of multibody systems [16]. Caro et al. improved the robust design method based on the sensitive area and proposed the comprehensive robust design method of mechanism deviation [17]. The size of the mechanism was calculated according to the performance robustness index, and the optimal deviation of the mechanism was calculated using the comprehensive deviation method. Gao et al. analyzed the robustness and robustness estimation of the product quality features [18]. They established a mathematical model based on minimum sensitivity region estimation (MSRE) for the robust optimization of the product quality features. Hui et al. constructed a dual-inertia feed system model based on the sensitivity of the closed-loop transfer function and analyzed the influence of the change of feed system stiffness on the stability of motion accuracy [19].

The research on reliability mainly focuses on reliability design, assembly reliability control, and fault diagnosis technology. Based on the shortcomings of traditional stress-strength interference model, Zhang et al. modeled the reliability from a dynamic perspective [20]. Pinghua et al. studied the assembly reliability control technology of electromechanical products based on fault modeling of motion unit to improve the reliability of assembly process [21]. Genbao et al. proposed the assembly process and technology driven by reliability and used the dynamic Bayesian method to model and control the assembly process [22]. Assaf and Dugan proposed a diagnostic method for large systems using monitors and sensors for reliability analysis by optimizing the diagnostic decision tree (DDTs) [23]. Yu et al. proposed a fault maintenance strategy for field equipment of assembly system [24]. And according to the differences in reliability design of different types of equipment, a comprehensive maintenance mode was introduced to ensure the reliability of automatic docking assembly of large aircraft parts. Qinghu et al. carried out a systematic analysis and prediction modeling research on the main failure mechanism and failure evolution rule of key components of the power transmission system [25].

Quality characteristic control is a comprehensive technical control activity based on decoupling or prediction of quality characteristic, including analysis of quality characteristic at each granularity and adjustment of influencing factors. Moreover, according to quality fluctuation, quality characteristic is under control. Haifeng studied the coupling mapping relation of quality characteristics of complex electromechanical products [26]. Then, combined with axiomatic design principle, they proposed the idea of decoupling design of quality characteristics of complex electromechanical products and presented the decoupling control model in the process of quality characteristic mapping of complex electromechanical products. Xianghua proposed a multiscale collaborative and intelligent quality control method for key parts of air separation equipment including the air compressor, the turbine expander, and the whole machine and conducted an in-depth research on coupling mapping and collaborative control of quality characteristics of large-scale air separation equipment from the whole machine to each part at all scales [27]. Nada studied the quality prediction in the design process of manufacturing system, constructed a basic framework on the basis of the manufacturing system configuration parameters to evaluate the quality of the products, and constructed a comprehensive evaluation model of system configuration based on quality by analytic hierarchy process (AHP), which can transform the structural parameters of manufacturing system into configuration capability indexes and then predict and control them [28]. Xianlin conducted an in-depth research on the quality characteristic prevention and control key technologies such as the quality characteristic evolution mechanism, coupling and decoupling control, timing data prediction, immune diagnosis, and control in the manufacturing process of electromechanical products [29]. In order to solve the coupling problem in quality characteristic predictive control, Zhentao established a quality characteristic predictive decoupling model based on predictive control theory [30]. Yang et al. established and solved the predictive control model based on particle swarm optimization algorithm and support vector machine on the basis of analyzing the characteristics of multiprocess and multistage product quality prediction control and realized the global optimization of multistage product quality prediction and related process parameters [31].

3. Findings

Through the analysis of the above research status, it can be seen that the following main problems exist in the quality characteristic control of electromechanical products at present.

Traditional quality control is mainly based on the quality control of parts, precisely, the precision, However, the combination with the function of parts is far from the expectance. Particularly, general electromechanical products exist for the realization of a certain motion function, and the overall functional failure of the product is caused by the inability to realize the basic motion function. Therefore, quality control should be placed in the basic level of motion, as long as the basic motion function is normal and the overall function of the product is guaranteed. Starting from the quality control of MUs, the quality control of the whole machine is realized through the quality control of the unit level. This control mode is more simple and effective, which does not need to simplify the model and is conducive to the accomplishment of refined quality control.

In terms of the key quality characteristic control technology, there are many researches on the pure precision but few achievements on the precision life, performance stability, reliability, and their coupling control. In fact, the quality gap of electromechanical products at present mainly lies in the aspects of precision life, performance stability, and reliability, among which reliability is the biggest bottleneck of electromechanical products. How to improve the precision life, performance stability, and reliability of electromechanical products as soon as possible is an urgent problem to be solved in the manufacturing industry.

4. Formation mechanisms of MU’s four key quality characteristics

Meta-action unit (MU) is a kind of basic action unit of electromechanical products decomposed in accordance with failure model analysis (FMA) structural decomposition method. It has the specific function of independently completing the specified movement or operation. Compared with other decomposition units, MU is more suitable for quality and reliability analysis. However, the complex quality characteristics are reflected not only in the MU’s motion accuracy but also in its precision life, performance stability, reliability, and other aspects. So it is necessary to conduct an in-depth study on the formation mechanism of each quality characteristic.

The quality characteristics of electromechanical products are very numerous, generally including 12 aspects, i.e., functional compliance, performance stability, application reliability, precision retaining ability, technology primacy, cost economy, esthetic appearance, maintenance convenience, and service timeliness, character uniqueness, security assurance, perception satisfaction, etc., which lead to the resultant diversity of MU's quality characteristics. During the research process, the key quality characteristics need to be extracted from the perspective of the user's requirements and the fault distribution. At the same time, as the smallest motion unit decomposed from electromechanical products, most of MUs' quality characteristics are dynamic; therefore, it is necessary to conduct an in-depth study on their formation mechanism and extract the characteristic indicators of each key quality characteristic from the perspective of motion. Moreover, to expand the amount of the sample data, the corresponding models are established and applied to the similarity determination of MUs.

4.1 Formation mechanism of the MU motion accuracy

Accuracy is the degree to which actual geometric parameters conform to ideal ones, and their deviation values are often defined as errors. The accuracy of electromechanical products generally includes geometric accuracy, motion accuracy, transmission accuracy, and positioning accuracy [32]. For MUs, the accuracy refers to the motion accuracy of the output part that implements the meta-action. Moreover, the movement accuracy of the unit actuator is also affected by the manufacture and assembly errors of other parts in the unit (support, transmission, and fasteners). For example, as the actuator of the rack moves the MU, the translation accuracy of the rack is the only measure indicator. In the actual situation, there are many kinds of error sources that affect the motion accuracy of the MU actuators. Actually, the formation process of the accuracy is also the transmission process of the errors.

4.1.1 The MU motion accuracy

For translation and rotation MU, the motion accuracy of the actuator also includes translation and rotation accuracy. The corresponding translation accuracy indicators of the actuator mainly include positioning accuracy, repeat positioning accuracy, reverse error, moving straightness (trajectory), moving parallelism (trajectory), and resolution (minimum translation increment). The rotation accuracy indicators include positioning accuracy, repeat positioning accuracy, indexing accuracy, reverse error, rotation face fluctuation (radial and end faces), and rotation fluctuation (axial).

The motion accuracy of the unit actuator is also affected by the geometric and assembly accuracy of the various parts in the unit. The geometric accuracy of the part includes the geometric position and shape accuracy, expressed as static errors such as size, position, and shape. According to ISO230-1:1996 and GB/T1800.1-2009 "Limit and fit Part 1: The basis of tolerance, deviation and fit," the size and position error of the MU actuator refers to the defects in the design, manufacture, and assembly process, which cause the MU actuator (output member) deviating from the ideal size and position. It mainly includes distance dimension error, diameter dimension error, angular dimension error, parallelism, coaxiality, verticality, position, symmetry, and round and full runout. The geometric shape error of the MU actuator refers to the deviation between the actual and ideal shape after machining, which is set as a machining range of the normal distribution and mainly includes straightness, flatness, roundness, cylindricity, line profile, and surface profile.

4.1.2 Error model of the MU motion accuracy

4.1.2.1 Topology structure description of electromechanical product

The electromechanical product is a kind of multibody system, a complete abstract and effective description of general complicated mechanical system, which is the optimal mode of analyzing and researching complicated mechanical system [33–35]. The multibody kinematic theory is used to establish the synthetic space motion error model of the MU actuator in this chapter.

An MU is regarded as a body, and there is only a single degree-of-freedom relative motion with the constraint type of translation or rotation. The motion of electromechanical products, open or closed loop, aims to accomplish a corresponding function. Because closed-loop motion can be converted as open with specific constraint, the topological structure for general electromechanical products is expressed as follows (**Figure 1**). The inertial reference system and MU are regarded as different bodies. Then the bodies are numbered in turn along the direction away, according to the natural growth sequence, from one branch to another (each branch accomplishing its corresponding function).

The low-order body array is used to describe the topological structure of the multibody system [36], which can be obtained by the following calculation formula (1). The optional body B_k is any typical body in the system, and the sequence number of its n-th lower-order body is defined as

$$L^n(k) = j \tag{1}$$

where L is the low-order body operator and body B_k is the n-th high-order body of body B_j (**Table 1**). $L^n(k) = L\left(L^{n-1}(k)\right)$, $L^0(k) = k$, and $L^n(k) = 0$. Moreover, when body B_j is the adjacent lower-order body of body B_k, $L(k) = j$.

4.1.2.2 Motion error characteristic matrix of adjacent MUs

According to the MU motion of the electromechanical product in the actual working process, the description method of multibody system error is used to study

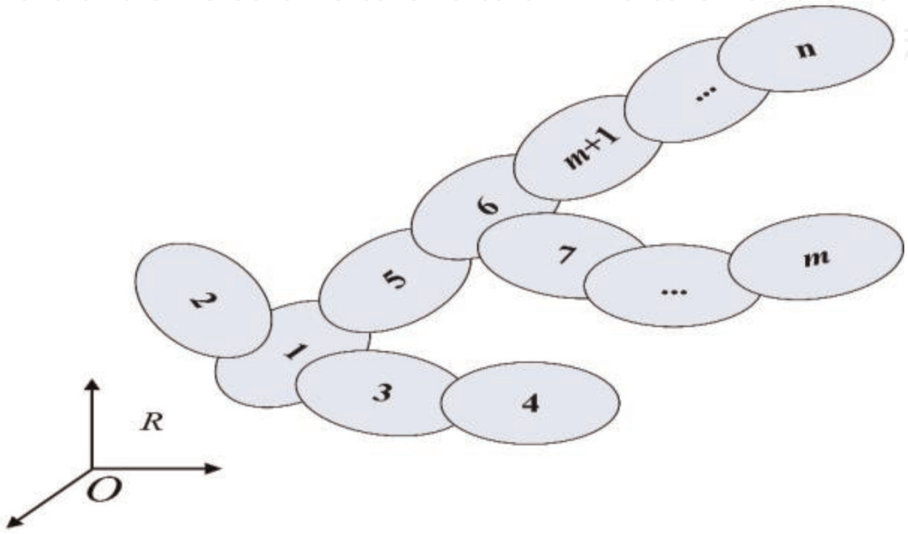

Figure 1.
The topological structure diagram of electromechanical products based on MUs.

k	1	2	3	4	5	6	7	$\cdots$	m	$m+1$	$\cdots$	n
$L^0(k)$	1	2	3	4	5	6	7	$\cdots$	m	$m+1$	$\cdots$	n
$L^1(k)$	0	1	1	3	1	5	6	$\cdots$	$m-1$	6	$\cdots$	$n-1$
$L^2(k)$	0	0	0	1	0	1	5	$\cdots$	$m-2$	5	$\cdots$	$n-2$
$L^3(k)$	0	0	0	0	0	0	1	$\cdots$	$m-3$	1	$\cdots$	$n-3$
$L^m(k)$	0	0	0	0	0	0	0	0	0	0	0	0
$L^n(k)$	0	0	0	0	0	0	0	0	0	0	0	0

Table 1.
The low-order bodies of electromechanical products based on MU.

the motion error of the MU actuator (**Figure 2**). P_k, P_k^I, and P_k^E are the actual position vector, the ideal position vector, and the position error vector of the origin Q_k of the body B_k motion reference coordinate system in its low-order body B_j, respectively; and D_k, D_k^I, and D_k^E are the actual displacement vector, the ideal displacement vector, and the displacement error vector of the origin O_k of body B_k reference coordinate system.

From the kinematic point of view, the errors of MU actuators are divided into two categories. One is the errors that happened in the motion reference coordinate of MU (body B_k), described with the position (static) error vector P_k^E and the position error feature (transformation) matrix T_{jk}^{PE}. Another is the motion process error (translation or rotation) of the MU (body B_k) relative to the actual motion reference coordinate, described with the translation (motion) error vector D_k^E (linear or angular displacement) and the motion error feature (transformation) matrix T_{jk}^{DE}.

4.1.2.2.1 Motion error characteristic matrix from translation MU to translation MU

When the MU (body B_k) translates x_{jk}^D, y_{jk}^D, and z_{jk}^D along the X-axis, Y-axis, and Z-axis relative to its adjacent MU (lower-order body B_j), its actuator's translation

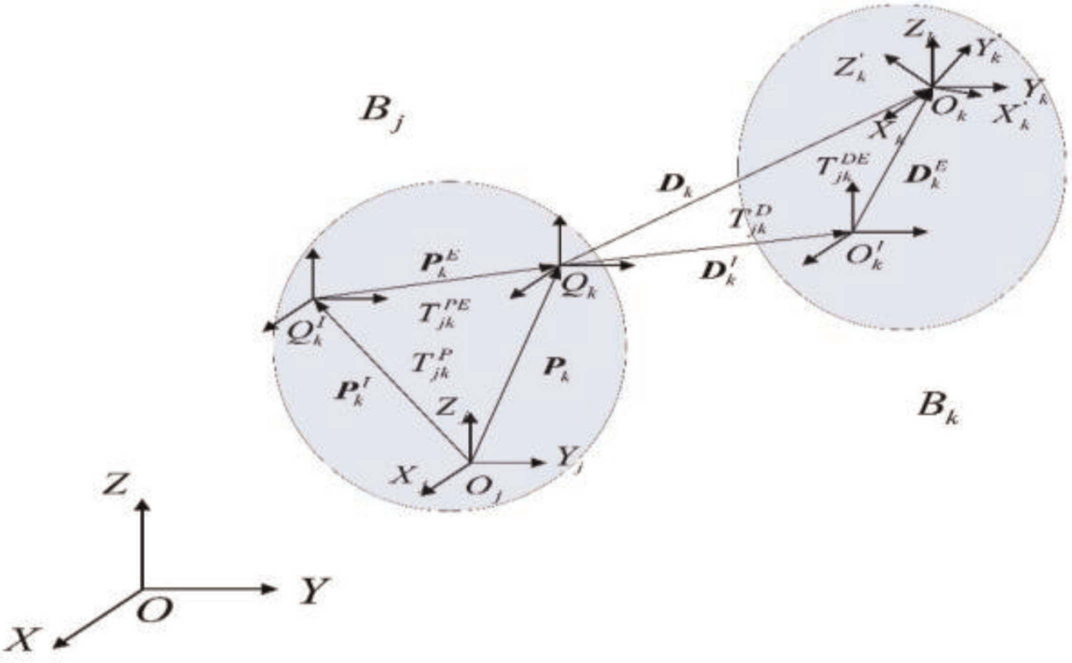

Figure 2.
The relative motion sketch of adjacent MUs.

matrices and translation error feature matrices can be expressed, respectively, as follows:

$$T_{\text{jk}}^{D}(x)=\begin{bmatrix}1&0&0&x_{\text{jk}}^{D}\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix},T_{\text{jk}}^{\text{DE}}(\Delta\text{x})=\begin{bmatrix}1&0&0&\Delta x_{\text{jk}}^{\text{DE}}\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

$$T_{\text{jk}}^{D}(y)=\begin{bmatrix}1&0&0&0\\0&1&0&y_{\text{jk}}^{D}\\0&0&1&0\\0&0&0&1\end{bmatrix},T_{\text{jk}}^{\text{DE}}(\Delta\text{y})=\begin{bmatrix}1&0&0&0\\0&1&0&\Delta y_{\text{jk}}^{\text{DE}}\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

$$T_{\text{jk}}^{D}(z)=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&z_{\text{jk}}^{D}\\0&0&0&1\end{bmatrix},T_{\text{jk}}^{\text{DE}}(\Delta\text{z})=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&\Delta z_{\text{jk}}^{\text{DE}}\\0&0&0&1\end{bmatrix}$$

4.1.2.2.2 Motion error characteristic matrix from rotation MU to rotation MU

When the MU (body B_k) rotates α_{jk}^{D}, β_{jk}^{D}, and γ_{jk}^{D} (the Euler angle or the Karl single angle of the coordinate system k relative to the coordinate system j) along the X-axis, Y-axis, and Z-axis relative to its adjacent MU (lower-order body B_j), its actuator's rotation matrices and rotation error feature matrices can be expressed, respectively, as follows:

$$T_{\text{jk}}^{D}(\alpha)=\begin{bmatrix}1&0&0&0\\0&\cos\alpha_{\text{jk}}^{D}&-\sin\alpha_{\text{jk}}^{D}&0\\0&\sin\alpha_{\text{jk}}^{D}&\cos\alpha_{\text{jk}}^{D}&0\\0&0&0&1\end{bmatrix},T_{\text{jk}}^{\text{DE}}(\Delta\alpha)=\begin{bmatrix}1&0&0&0\\0&\cos\Delta\alpha_{\text{jk}}^{\text{DE}}&-\sin\Delta\alpha_{\text{jk}}^{\text{DE}}&0\\0&\sin\Delta\alpha_{\text{jk}}^{\text{DE}}&\cos\Delta\alpha_{\text{jk}}^{\text{DE}}&0\\0&0&0&1\end{bmatrix}$$

$$T_{\text{jk}}^{D}(\beta)=\begin{bmatrix}\cos\beta_{\text{jk}}^{D}&0&\sin\beta_{\text{jk}}^{D}&0\\0&1&0&0\\-\sin\beta_{\text{jk}}^{D}&0&\cos\beta_{\text{jk}}^{D}&0\\0&0&0&1\end{bmatrix},T_{\text{jk}}^{\text{DE}}(\Delta\beta)=\begin{bmatrix}\cos\Delta\beta_{\text{jk}}^{D}&0&\sin\Delta\beta_{\text{jk}}^{D}&0\\0&1&0&0\\-\sin\Delta\beta_{\text{jk}}^{D}&0&\cos\Delta\beta_{\text{jk}}^{D}&0\\0&0&0&1\end{bmatrix}$$

$$T_{\text{jk}}^{D}(\gamma)=\begin{bmatrix}\cos\gamma_{\text{jk}}^{D}&-\sin\gamma_{\text{jk}}^{D}&0&0\\\sin\gamma_{\text{jk}}^{D}&\cos\gamma_{\text{jk}}^{D}&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix},T_{\text{jk}}^{\text{DE}}(\Delta\gamma)=\begin{bmatrix}\cos\Delta\gamma_{\text{jk}}^{D}&-\sin\Delta\gamma_{\text{jk}}^{D}&0&0\\\sin\Delta\gamma_{\text{jk}}^{D}&\cos\Delta\gamma_{\text{jk}}^{D}&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

Motion error characteristic matrix of synthetic motion at the MU (body B_k) translates first and then rotates relative to its adjacent MU (low-order body B_j). The specific motion order is translating x_{jk}^{D}, y_{jk}^{D}, and z_{jk}^{D} along the X-axis, Y-axis, and

Z-axis and rotating α_{jk}^{D} along the X-axis, β_{jk}^{D} along the Y-axis, and γ_{jk}^{D} along the Z-axis, and the ideal motion feature matrix of the unit actuator can be expressed as

$$T_{jk}^{D}=T_{jk}^{D}(x)T_{jk}^{D}(y)T_{jk}^{D}(z)T_{jk}^{D}(\alpha)T_{jk}^{D}(\beta)T_{jk}^{D}(\gamma) \tag{2}$$

The motion error feature matrix of the unit actuator is expressed as

$$T_{jk}^{DE}=T_{jk}^{DE}(\Delta x)T_{jk}^{DE}(\Delta y)T_{jk}^{DE}(\Delta z)T_{jk}^{DE}(\Delta\alpha)T_{jk}^{DE}(\Delta\beta)T_{jk}^{DE}(\Delta\gamma) \tag{3}$$

The position and position error feature matrix are expressed as

$$T_{jk}^{P}=T_{jk}^{P}(x)T_{jk}^{P}(y)T_{jk}^{P}(z)T_{jk}^{P}(\alpha)T_{jk}^{P}(\beta)T_{jk}^{P}(\gamma) \tag{4}$$

$$T_{jk}^{PE}=T_{jk}^{PE}(\Delta x)T_{jk}^{PE}(\Delta y)T_{jk}^{PE}(\Delta z)T_{jk}^{PE}(\Delta\alpha)T_{jk}^{PE}(\Delta\beta)T_{jk}^{PE}(\Delta\gamma) \tag{5}$$

4.1.2.3 Actual characteristic matrix of MUs

According to the geometric description method above, the actual feature (transformation) matrix of the MU actuator in the multibody system is obtained as

$$T_{jk}=T_{jk}^{P}T_{jk}^{PE}T_{jk}^{D}T_{jk}^{DE} \tag{6}$$

where T_{jk}, T_{jk}^{P}, T_{jk}^{PE}, T_{jk}^{D}, and T_{jk}^{DE} are the actual position, the ideal position, the static error, the ideal motion, and the motion error feature matrix of the MU actuator, respectively.

4.1.2.4 Integrated space motion errors of MUs

Set the homogeneous coordinates of the MU (body B_j) on any point W in subcoordinate system $O_j-X_jY_jZ_j$ as

$$W_j=\begin{bmatrix} w_{xj} & w_{yj} & w_{zj} & 1\end{bmatrix}^T \tag{7}$$

Thus, the ideal homogeneous coordinates of the point W in subcoordinate system $O_j-X_jY_jZ_j$ is obtained as

$$W_k^I=\left[\prod_{u=n,L^n(k)=0}^{u=1} T^P_{L^u(k)L^{u-1}(k)}T^D_{L^u(k)L^{u-1}(k)}\right]^{-1}\left[\prod_{t=n,L^n(j)=0}^{t=1} T^P_{L^t(j)L^{t-1}(j)}T^D_{L^t(j)L^{t-1}(j)}\right]W_j \tag{8}$$

The actual homogeneous coordinates of the point W in subcoordinate system $O_j-X_jY_jZ_j$ is

$$W_k=\left[w_{xk}w_{yk}w_{zk}1\right]^T\left[\prod_{u=n,L^n(k)=0}^{u=1} T_{L^u(k)L^{u-1}(k)}\right]^{-1}\left[\prod_{t=n,L^n(j)=0}^{t=1} T_{L^t(j)L^{t-1}(j)}\right] \tag{9}$$

In the process of MU working (actuator moving), the error between ideal and actual motion position of point W is expressed as

$$
\begin{aligned}
E &= \left(e_x^P\ e_y^P\ e_z^P\ 0\right)^T = W_k^I - W_k \\
&= \left[\prod_{u=n,L^n(k)=0}^{u=1} T^P_{L^u(k)L^{u-1}(k)}T^D_{L^u(k)L^{u-1}(k)}\right]^{-1}\left[\prod_{t=n,L^n(j)=0}^{t=1} T^P_{L^u(j)L^{u-1}(j)}T^D_{L^u(j)L^{u-1}(j)}\right]W_j \\
&\quad - \left[\prod_{u=n,L^n(k)=0}^{u=1} T_{L^u(k)L^{u-1}(k)}\right]^{-1}\left[\prod_{t=n,L^n(j)=0}^{t=1} T_{L^u(j)L^{u-1}(j)}\right]W_j
\end{aligned}
\tag{10}
$$

Equation (10) is the comprehensive spatial motion error model of MU actuators for general electromechanical products.

4.2 Formation mechanism of the MU precision life

In the process of electromechanical product working, MUs are influenced by various changing indicators, e.g., increase in ambient temperature, wear on part surface, and change of load or force. These indicators cause the variation of the MU accuracy [37, 38].

The general formation process of MU accuracy faults is shown in **Figure 3**. After MU moving for a period of time, its accuracy variation reaches the designed accuracy variation limit (Y_{max} or Y_{min}). Its specific variation law $f(t)$ is as follows.

4.2.1 Initial stage

MU is working at an expectation accuracy a_0 (producing accuracy). For a specific MU, because of the influence of its initial state and working condition, a_0 has a certain dispersion, following the distribution law $f(a)$.

4.2.2 Stable stage

After MU working stably for a period of time T_a, the influence reaches enough degree to cause the variation of MU accuracy. Because of the considerable degree of

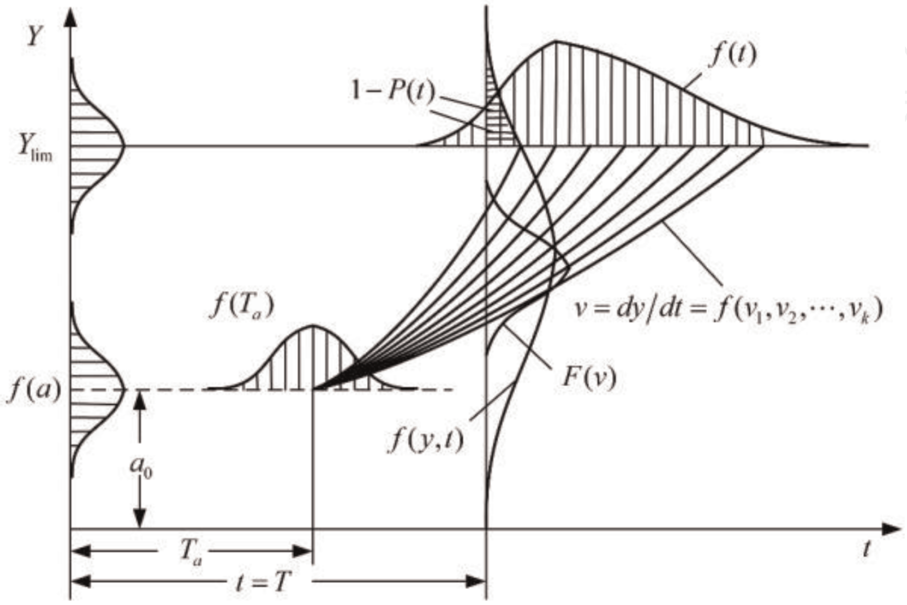

Figure 3.
The general forming process of the MU accuracy failure.

randomness of the uncertainty influencing factors, the stable operating time T_a obeys a random distribution $f(T_a)$.

4.2.3 Degradation stage

MU accuracy reaches Y_{lim} at a speed v, and faults happen, where v is a random factor obeying distribution law $F(v)$, so operating time without faults T is also a random factor obeying $f(t)$.

During the moving process, MU is affected by various factors, e.g., friction, environment, and changing working conditions. Its accuracy variation rate v can be regarded as a normal distribution:

$$f(v) = \frac{1}{\sigma_v\sqrt{2\pi}} e^{-\frac{(v-\bar{v})^2}{2\sigma_v^2}} \tag{11}$$

where $f(v)$ is the probability density function of accuracy variation, $\bar{v}$ represents the average rate of accuracy variation process, and σ_v is the mean square error of rate accuracy variation.

For a specific MU, if its initial accuracy is a known value a_0, obeying a random distribution and its stable accuracy stage is finished, that is, $T_a = 0$, and then its accuracy variation is obtained as (e.g., linear correlation)

$$Y = a_0 + vt \tag{12}$$

As is shown in **Figure 3**, before accuracy reaching the limitation, $Y = Y_{lim}$, its operating time without failure is the precision life (accuracy retention time), which is the function of speed v:

$$T = \frac{Y0_{lim}}{v} \tag{13}$$

Finally, its accuracy reliability is expressed as

$$R = P(t \le T) = P(v \le \left|\frac{Y0_{lim}}{t} \| \right| \frac{Y0_{lim}}{t} \| \left| \right) = \Phi(\left| \frac{Y0_{lim}}{t \cdot \sigma_v} \| \frac{\bar{v}}{\sigma_v} \frac{\bar{v}}{\sigma_v} \right| \Big| \tag{14}$$

4.3 Formation mechanism of the MU performance stability

The performance stability of MUs refers to the ability of maintaining the performance of the MU or the variation range of output quality characteristic (dynamic characteristic) minimal with the uncertainty factor while satisfying various constraints. It means that the output value Y fluctuates around the input-output linear relationship and the smaller the fluctuation, the better the stability.

4.3.1 Performance stability evaluation of MUs

4.3.1.1 The dynamic tracking errors and steady errors

The performances of MUs are real-time and dynamic, and its output quality characteristic fluctuates with input parameters. That is, there is a corresponding objective value for each input signal. At the same time, the fluctuation needs to be as small as possible. This characteristic is defined as a dynamic characteristic.

The dynamic state in the process of MU motion is divided into transient and stead. Dynamic tracking errors mean the deviation between the actual value $y(t)$ and expected value y_{Ideal} of the MU quality characteristic indicator of each transient state. Steady errors refer to the fluctuation amplitude Δ of the deviation between the actual value $y(t > T)$ and expected value y_{Ideal} of the MU quality characteristic under steady state after moving for a time T. To guarantee enough high-performance stability, there are two premises for them:

$$\begin{cases} \delta_{max} = \left|y(t) - y_{Ideal}\right|_{max} \le \delta_{Ideal} \\ \Delta_{max} = \left|y(t{>}T) - y_{Ideal}\right|_{max} - \left|y(t{>}T) - y_{Ideal}\right|_{min} \le \delta_{Ideal} \end{cases} \tag{15}$$

4.3.1.2 The signal/noise ratio

The indicator of signal/noise ratio (SNR) [39] (Eq. 16) proposed by Prof. Taguchi is applied to evaluate the MU dynamic performance stability in this section. Generally, the greater the SNR value, the better the stability, which indicates that the noise is low even if the signal is strong:

$$\eta = \frac{P_S}{P_N} \tag{16}$$

where P_S and P_N represent the power of signal and noise, respectively.

For the dynamic characteristic, the objective value m is not a constant but a variable determined according to the variation of signal M output characteristic $y = \alpha + M\beta + \varepsilon$ (**Figure 4**), where ε reflects the degree of interference. Moreover, the variation of output characteristic is set as a normal distribution $N(0,\delta^2)$.

As is shown in **Figure 4**, the SNR of dynamic characteristic y is defined as

$$\eta = \frac{\beta^2}{\sigma^2} \tag{17}$$

where β^2 is the measure of signal sensitivity, and δ^2 is the fluctuation rate (deviation) of amplitude, which is used to evaluate the stability of MU.

For a specific MU quality indicator q_1, the greater the signal/noise ratio η_1, the more stable the quality indicator. Its weight (the contribution rate of this quality indicator to quality instability) is expressed as

$$\lambda_l = \frac{1}{\eta_l * \sum_{j=1}^{m} \frac{1}{\eta_j}} \tag{18}$$

4.3.2 Clearance formation mechanism of MUs

The clearance is one of the main factors causing noise of MU and influencing the performance stability of complete machine [40]. However, in real engineering

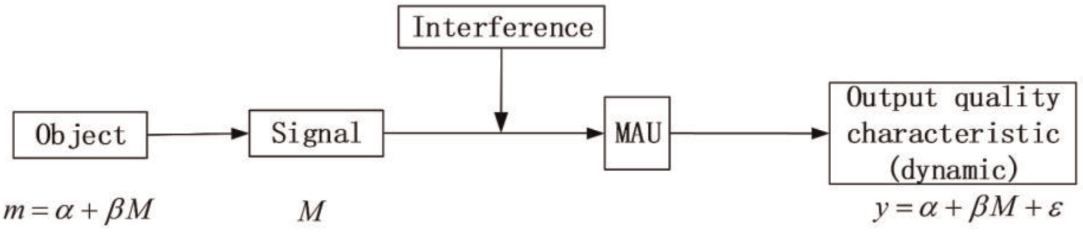

Figure 4.
The sketch of dynamic characteristic.

application, the MU clearance is inevitable. It happens in the inner composition parts of MUs, e.g., the clearance between the large piston and the inner wall of the mandrel in the piston moving unit and the meshing clearance between the rack translating unit and the gear rotating unit (**Figure 5**).

The clearance between MUs includes the static clearance of geometric size and the dynamic clearance under a moving state. As is shown in **Figure 5**, they are mainly caused by three aspects:

1. A regular clearance reserved due to the motion fit design of the MU.
2. The uncertainty factors in the MU design and manufacturing process. The error will be caused to form clearance.
3. The uncertainty factors in the process of operating, e.g., vibration, friction, wear, etc., cause the irregular clearance.

4.4 Formation mechanism of the MU reliability

The MU reliability refers to the ability to accomplish specific machine motion precisely, timely, and coordinately under a specified time and condition and maintain all quality characteristics within the allowable range. Its quantification indicator, the probability, is known as reliability.

4.4.1 Reliability indicators of MUs

4.4.1.1 The MU reliability

The MU reliability refers to the probability of output quality characteristic parameters being in the allowable range at a specified time (period). Suppose that output characteristic parameter, e.g., accuracy, precision life, performance stability, etc., is random variable *Y(t)*. According to the design requirement, output quality characteristic parameter is controlled within the range of $[Y_{min}, Y_{max}]$. The MU reliability is defined as the probability P that happens:

$$R = P[Ymax_{min}] \tag{19}$$

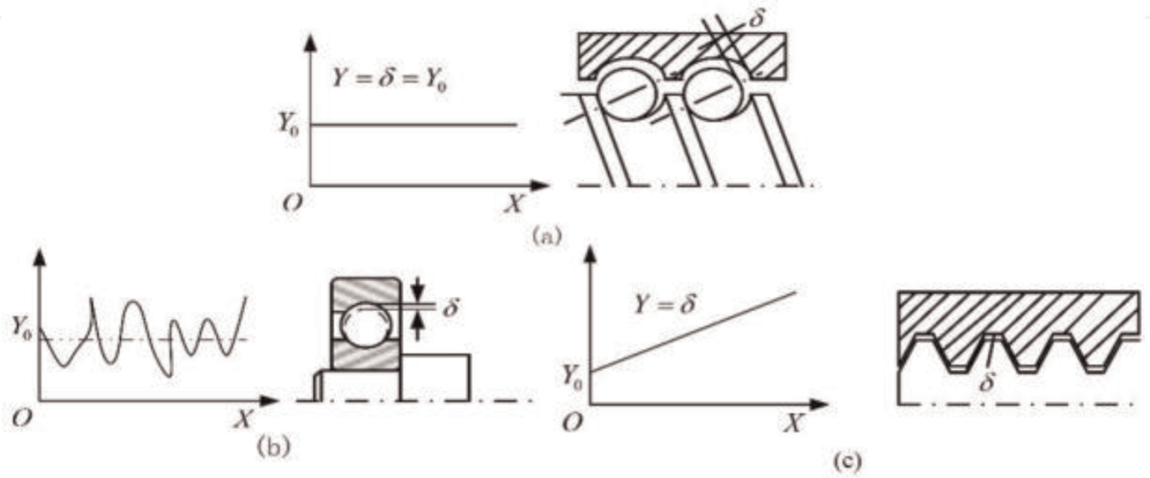

Figure 5.
Clearances between MUs resulting from (a) assembly, (b) design, and (c) wear.

Its corresponding failure probability F is expressed as

$$F = 1 - R = 1 - P[Ymax_{min}] \tag{20}$$

Taking the motion accuracy (motion error) of the MU as an example, its motion accuracy reliability is the probability of its motion output error within the maximum allowable error range:

$$R = P[emax_{min}] \tag{21}$$

For a specific MU, its error obeys a normal distribution, and its reliability is derived as

$$\begin{aligned} R &= P(e_{min} \le E \le e_{max}) \\ &= P(E \le e_{max}) - P(E \le e_{min}) \\ &= \Phi\left(\frac{e_{max} - \mu}{\sigma}\right) - \Phi\left(\frac{e_{min} - \mu}{\sigma}\right) \end{aligned} \tag{22}$$

4.4.1.2 The mission reliability of complete machine system

Because multiple different missions of the upper motion units are accomplished by the input and output of multiple MUs, from the perspective of the mission reliability, the mission reliability of the complete machine system of electromechanical products is an organic combination of the MU motion reliability (**Figure 6**), which is expressed as follows:

$$R^W = \sum_{i=1}^{n} \alpha_i R^{A_i} \tag{23}$$

4.4.2 Failure mechanism of MUs

The MU failure analysis mainly includes three aspects: the failure stress, the failure mechanism, and the failure mode. To highlight the key points, we mainly analyze them from the perspective of the motion function.

4.4.2.1 The failure stress

The failure stress is the physical condition causing the MU failure, mainly including the working and environment stress. The working stress refers to the

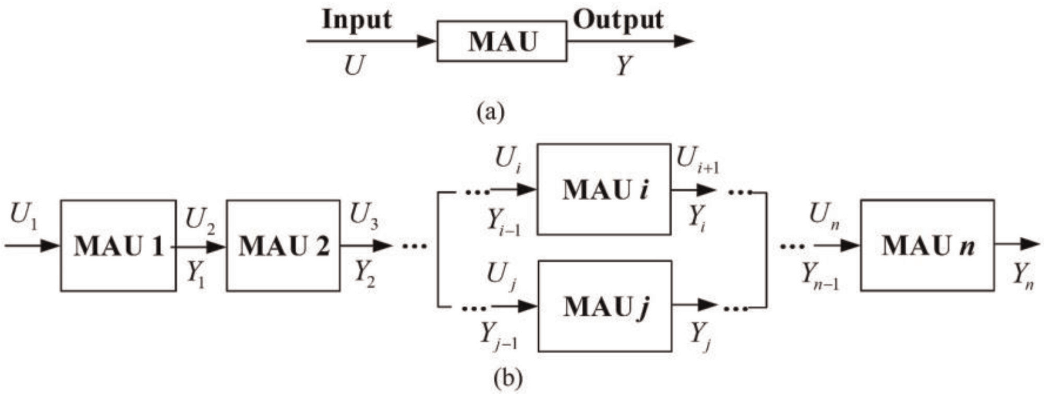

Figure 6.
The mission reliability model of (a) MU and (b) complete machine system.

necessary stress to motivate MU to achieve a basic motion function, e.g., pressure, thrust, bending torque, etc.; the environment stress refers to MU's external working environment conditions and its interaction between the internal parts, e.g., temperature, humidity, dust, noise, vibration, friction, impact force, etc.

Taking the end-toothed disk indexing turntable function unit as an example, we analyzed the failure stress of each decomposition MU (**Table 2**).

4.4.2.2 The failure mechanism

The MU quality uncertainty includes gradual and emergent uncertainty; furthermore, corresponding failures are gradual and emergent. When they happen, their certain performance parameter reaches or exceeds the threshold, caused by the MU uncertainty. If an MU performance parameter changes at the beginning of working process without a stable stage, the failure that happened is defined as a gradual failure. If the MU performance parameter suddenly reaches or exceeds the threshold in an instant with an infinite speed, the failure that happened is defined as an emergent failure. The gradual failure is also called as wear failure, mainly including:

A. Functional abnormality due to the MU wear deformation, e.g., worm gear MU rotation difficulty, loose, vibration, large clearance, etc.; B. function

Function unit	Motion unit	MU	Failure stress
End-toothed disk indexing turntable	Turntable ascending and descending	Piston moving	Hydraulic oil (hydraulic pressure, cleanliness), turntable weight, concentricity, cylindricity, burrs, clearances, assembly stress
		End-toothed disk moving up and down	Weight of the turntable and tool, cutting force and load
	Turntable rotating	Motor rotating	Temperature, cutting fluid
		Worm rotating	Temperature, load, wear, axial thrust, cyclic load stress, vibration, concentricity
		Worm gear rotating	Temperature, load, wear, shear stress
		Gear shaft rotating	Load torque, fatigue, radial load
		Upper tooth rotating	Load torque, wear
		Revolving body rotating	Cutting liquid, load
	Pallet clamping and loosening	Spring pin moving	Vibration, precision
		Spring shrinking	Load, fatigue
		Piston moving	Hydraulic oil (hydraulic pressure, cleanliness), load, concentricity, cylindricity, burrs, clearance, assembly stress
		Pull rod moving	Pull stress, vibration
		Pull claw moving up and down	Pull stress, assembly stress, fatigue, vibration, precision

Table 2.
The failure stress analysis of end-toothed disk indexing turntable function unit.

Failure reason	Failure mechanism	Cause analysis
Wear	Wear generally happens in the relative motion part of MUs. The friction factor increases gradually in the initial wear stage, accompanied by heat, which eventually causes melting	The influence factors include mainly the materials in contact with each other, the surface contact pressure, the wear rate, and the lubricating oil
Fatigue	The MU undergoes a wavelike stress during the movement, and its effect accumulates continuously and develops into a damage after a certain number of iterations	Internal force caused by vibration, rotation, intermittent motion, etc. External force due to roughness of the external contact surface
Vibration	Different degree vibrations happen during the MU motion. Some of them cause failure of the MU and are defined as "failure" vibration	Vibrations determined by the MU structural characteristics, such as meshing vibration of gears, etc.
Yielding	Deformation exceeds the elasticity limit of the material to produce unrecoverable plastic deformation	Under long time stress or stress much higher than the elasticity limit, plastic deformation is produced
Impact	When the MU structure material property is brittle, with an excessive impact load, the visible deformation, e.g., extension or bending, is caused under one shot, especially at the stress concentration	This kind of damage suddenly is caused with a large loss, which is mainly determined by the material basic properties. The reasons include the choice of materials, the stress concentration structure, the imperfect function of the buffer mechanism, etc.

Table 3.
Formation mechanisms of typical MU failures.

abnormality due to the deformation or fracture caused by fatigue, e.g., gear tooth fracture of gear rotation MU; C. deformation and fracture due to corrosion; D. deformation due to yielding; E. deformation, cracking, and fracture due to deterioration of the polymer; F. obstacles caused by wear-induced debris; G. abnormal rotation and heat caused by deterioration of oil; H. abnormal movement due to the incorporation of rust, peeling paint, and peeling plating.

The formation mechanisms of the typical MU failures are shown in **Table 3**.

5. Key quality characteristic control methods based on the MU

On the basis of studying the key quality characteristics of MUs and the coupling relationship of the complete machine quality characteristics, it is necessary to unitize and aggregate the MUs' quality characteristic according to the "decomposition-analysis-synthesis" analysis method of the large system control theory [41]. The whole machine quality prediction method is studied from bottom to top, the quality characteristic state space model is constructed, and the predictive control algorithm is derived to achieve the comprehensive prediction and control of the complete machine quality characteristics.

5.1 Multiple generalized operator model of complex large systems

The whole working process of electromechanical products is achieved and accomplished via various orderly units. Therefore, the whole control process of the complete machine quality characteristic system can be decomposed into several quality control sub-processes of units and regarded as a linear system. To better

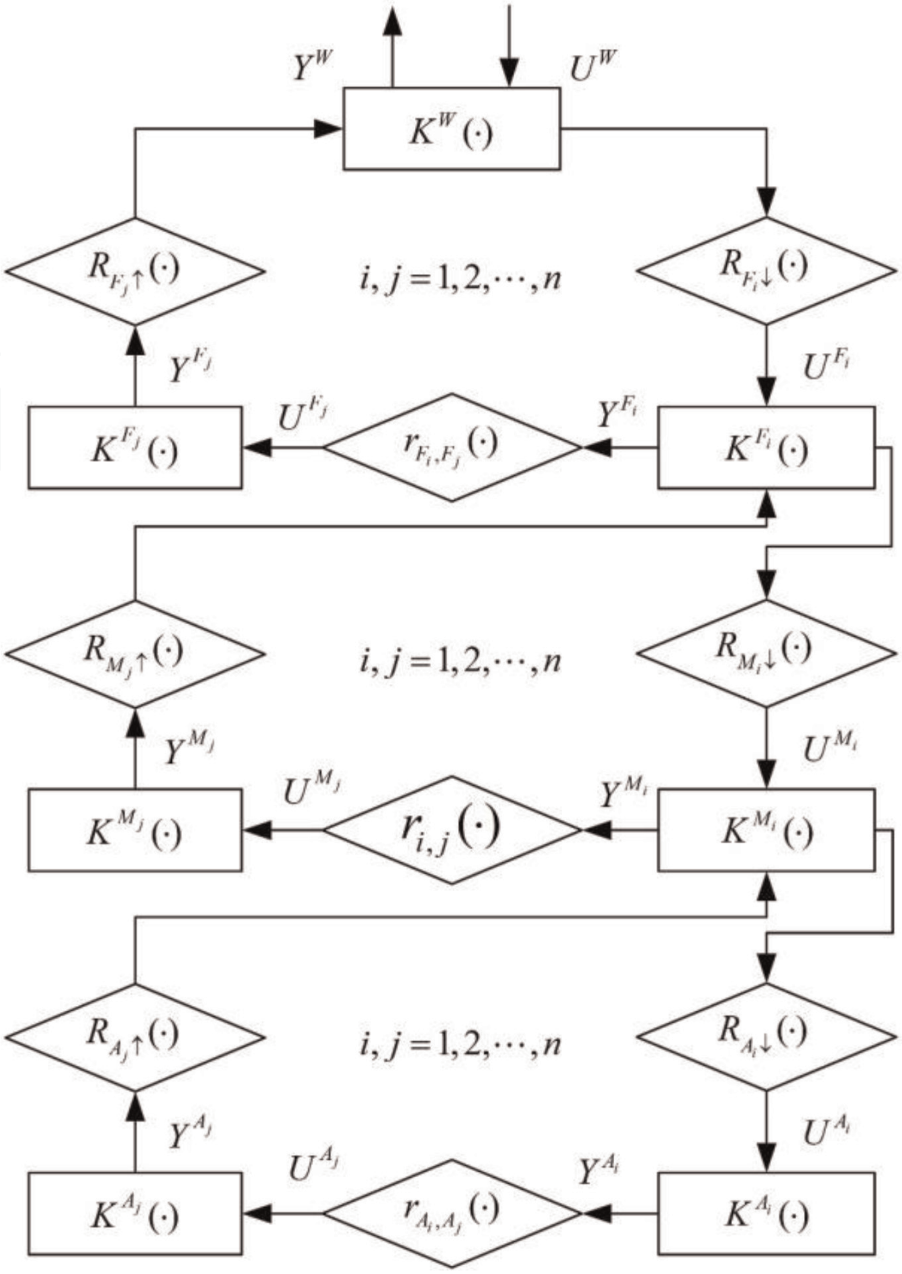

Figure 7.
The multilayer generalized operator model of complete machine.

understand the decomposition and aggregation relationship between the quality characteristics of the upper and lower units, corresponding to the quality characteristic coupling relationship model based on the FMA tree, the multiple generalized operator model of the complete machine large system [42] is established combining generalized operator model of complete machine system and the generalized operator relationship model of units (**Figure** 7).

The power input of the complete machine system is decomposed into the units' output, which is transmitted through the same layer and then aggregated to the complete system.

5.1.1 Generalized operator model of units

1. The first-layer generalized operator model of the complete machine system can be expressed as

$$Y^W \doteq K^W(\cdot)U^W \tag{24}$$

where U^W and Y^W are the total input and output of the complete machine system, respectively, and $K^W(\cdot)$ is the macro generalized operator of coarse granularity.

2. The second-layer generalized operator model of the function units can be expressed as

$$Y^{F_i} \doteq K^{F_i}(\cdot)U^{F_i}, Y^{F_j} \doteq K^{F_j}(\cdot)U^{F_j}, i, j = 1, 2, \cdots, n \tag{25}$$

where U^{F_i} and Y^{F_i} are the input and output of function unit F_i, respectively, and $K^{F_i}(\cdot)$ is its generalized operator.

3. The third-layer generalized operator model of the motion units can be expressed as

$$Y^{M_i} \doteq K^{M_i}(\cdot)U^{M_i}, Y^{M_j} \doteq K^{M_j}(\cdot)U^{M_j}, i, j = 1, 2, \cdots, n \tag{26}$$

where U^{M_i} and Y^{M_i} are the input and output of motion unit M_i respectively, and $K^{M_i}(\cdot)$is its generalized operator.

4. The fourth generalized operator model of the MUs can be expressed as

$$Y^{A_i} \doteq K^{A_i}(\cdot)U^{A_i}, Y^{A_j} \doteq K^{A_j}(\cdot)U^{A_j}, i, j = 1, 2, \cdots, n \tag{27}$$

where U^{A_i} and Y^{A_i} are the input and output of MU A_i and $K^{A_i}(\cdot)$ is its generalized operator.

5.1.2 Relationship model of generalized operators

5.1.2.1 Relationship model of vertical generalized operators

a. According to the function and mission of the unit, the total input of the complete machine system is distributed down to the corresponding unit of the next layer to form its input. Therefore, the input between units from different layers is the effective allocation of the complete machine system input, and the downward vertical relationship model can be expressed as

$$\begin{cases} U^{F_i} \doteq R_{F_i\downarrow}(\cdot)U^W, i = 1, 2, \cdots, n \\ U^{M_i} \doteq R_{M_i\downarrow}(\cdot)U^{F_i}, i = 1, 2, \cdots, n \\ U^{A_i} \doteq R_{A_i\downarrow}(\cdot)U^{M_i}, i = 1, 2, \cdots, n \end{cases} \tag{28}$$

where $R_\downarrow(\cdot)$ is the downward vertical relationship operator.

b. The output (quality characteristics) of the unit is aggregated to the complete machine system to form its total output (quality characteristics). Therefore, Y^W is the order integration of the unit output, and the upward vertical relationship model can be expressed as

$$\begin{cases} Y^W \doteq R_{F_j\uparrow}(\cdot)Y^{F_j}, j = 1, 2, \cdots, n \\ Y^{F_i} \doteq R_{M_j\uparrow}(\cdot)Y^{M_j}, j = 1, 2, \cdots, n \\ Y^{M_i} \doteq R_{A_j\uparrow}(\cdot)Y^{A_j}, j = 1, 2, \cdots, n \end{cases} \tag{29}$$

where $R_\uparrow(\cdot)$ is the upward vertical relationship operator.

5.1.2.2 Relationship model of horizontal generalized operators

$$\begin{cases} U^{F_j} \doteq r_{F_i,F_j}(\cdot)Y^{F_i}, i,j=1,2,\cdots,n \\ U^{M_j} \doteq r_{M_i,M_j}(\cdot)Y^{M_i}, i,j=1,2,\cdots,n \\ U^{A_j} \doteq r_{A_i,A_j}(\cdot)Y^{A_i}, i,j=1,2,\cdots,n \end{cases} \tag{30}$$

where $r_{A_i,A_j}(\cdot)$ is the horizontal relationship operator of MU A_i and A_j.

5.2 Multilayer state space model of quality characteristics

According to the quality characteristic mapping model based on the FMA tree, the large system of the complete electromechanical product is decomposed into several units. To predict and control the quality characteristics of different hierarchical units, the corresponding granularity required is different. The structural features of the multilayer state space model system, decomposition-analysis-synthesis, can combine the microscopic quality characteristics of each unit and the macroscopic large system to control the quality characteristics more accurately. Therefore, referring to the multigeneralized operator model of the large-scale system, the multilayer state space model of the quality characteristic of the complete machine is established step by step as follows [43, 44].

5.2.1 Decomposition

According to the qualitative model, the quantitative equations of multilayer state space model of the complete machine quality characteristics are set as follows:

$$M_I : \begin{cases} x_I^W = A_I^W x_I^W + B_I^W u_I^W \\ y_I^W = C_I^W x_I^W + D_I^W u_I^W \end{cases} M_{\mathrm{II}}^{F_i} : \begin{cases} \dot{x}_{\mathrm{II}}^{F_i} = A_{\mathrm{II}}^{F_i} x_{\mathrm{II}}^{F_i} + B_{\mathrm{II}}^{F_i} u_{\mathrm{II}}^{F_i} \\ y_{\mathrm{II}}^{F_i} = C_{\mathrm{II}}^{F_i} x_{\mathrm{II}}^{F_i} + D_{\mathrm{II}}^{F_i} u_{\mathrm{II}}^{F_i} \end{cases}$$

$$M_{\mathrm{II}}^{F_j} : \begin{cases} \dot{x}_{\mathrm{II}}^{F_j} = A_{\mathrm{II}}^{F_j} x_{\mathrm{II}}^{F_j} + B_{\mathrm{II}}^{F_j} u_{\mathrm{II}}^{F_j} \\ y_{\mathrm{II}}^{F_j} = C_{\mathrm{II}}^{F_j} x_{\mathrm{II}}^{F_j} + D_{\mathrm{II}}^{F_j} u_{\mathrm{II}}^{F_j} \end{cases} M_{\mathrm{III}}^{M_i} : \begin{cases} \dot{x}_{\mathrm{III}}^{M_i} = A_{\mathrm{III}}^{M_i} x_{\mathrm{III}}^{M_i} + B_{\mathrm{III}}^{M_i} u_{\mathrm{III}}^{M_i} \\ y_{\mathrm{III}}^{M_i} = C_{\mathrm{III}}^{M_i} x_{\mathrm{III}}^{M_i} + D_{\mathrm{III}}^{M_i} u_{\mathrm{III}}^{M_i} \end{cases},$$

$$M_{\mathrm{III}}^{M_j} : \begin{cases} \dot{x}_{\mathrm{III}}^{M_j} = A_{\mathrm{III}}^{M_j} x_{\mathrm{III}}^{M_j} + B_{\mathrm{III}}^{M_j} u_{\mathrm{III}}^{M_j} \\ y_{\mathrm{III}}^{M_j} = C_{\mathrm{III}}^{M_j} x_{\mathrm{III}}^{M_j} + D_{\mathrm{III}}^{M_j} u_{\mathrm{III}}^{M_j} \end{cases} M_{\mathrm{IV}}^{A_i} : \begin{cases} \dot{x}_{\mathrm{IV}}^{A_i} = A_{\mathrm{IV}}^{A_i} x_{\mathrm{IV}}^{A_i} + B_{\mathrm{IV}}^{A_i} u_{\mathrm{IV}}^{A_i} \\ y_{\mathrm{IV}}^{A_i} = C_{\mathrm{IV}}^{A_i} x_{\mathrm{IV}}^{A_i} + D_{\mathrm{IV}}^{A_i} u_{\mathrm{IV}}^{A_i} \end{cases}$$

$$M_{\mathrm{IV}}^{A_j} : \begin{cases} \dot{x}_{\mathrm{IV}}^{A_j} = A_{\mathrm{IV}}^{A_j} x_{\mathrm{IV}}^{A_j} + B_{\mathrm{IV}}^{A_j} u_{\mathrm{IV}}^{A_j} \\ y_{\mathrm{IV}}^{A_j} = C_{\mathrm{IV}}^{A_j} x_{\mathrm{IV}}^{A_j} + D_{\mathrm{IV}}^{A_j} u_{\mathrm{IV}}^{A_j} \end{cases}$$

where $y(t)$ is the output variable, $y = (y_1, y_2, \cdots, y_m)^T$; $x(t)$ is the state variable, $x = (x_1, x_2, \cdots, x_n)^T$; and $u(t)$ is the input variable, $u = (u_1, u_2, \cdots, u_r)^T$. A is the object (system) matrix describing the characteristics of the controlled object:

$$A = [a_{ij}]_{n\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{31}$$

B is the control matrix describing the characteristics of the control mechanism:

$$B = \left[b_{ij}\right]_{n\times r} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1r} \\ b_{21} & b_{22} & \cdots & b_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nr} \end{bmatrix} \tag{32}$$

C is the observing matrix describing the characteristics of the observing device:

$$C = \left[c_{ij}\right]_{m\times n} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} \tag{33}$$

D is the observing matrix describing the characteristics of the observing device:

$$D = \left[d_{ij}\right]_{m\times r} = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1r} \\ d_{21} & d_{22} & \cdots & d_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mr} \end{bmatrix} \tag{34}$$

5.2.2 Synthesis

Because the complete electromechanical products are composed of a series of units, according to the research on coupling and decoupling technology based on MUs, the spatial state variables of the complete product can be expressed as the weighted sum of that of some function units. Furthermore, the spatial state variables of function units can be expressed as the weighted sum of that of some motion units. Finally, the spatial state variables of motion units can be expressed as the weighted sum of that of some MUs. The specific model can be expressed as

$$\begin{cases} x_I^W = w_i x_{\mathrm{II}}^{F_i} + w_j x_{\mathrm{II}}^{F_j} \\ x_{\mathrm{II}}^{F_i} = w_i x_{\mathrm{III}}^{M_i} + w_j x_{\mathrm{III}}^{M_j} \\ x_{\mathrm{III}}^{M_i} = w_i x_{\mathrm{IV}}^{A_i} + w_j x_{\mathrm{IV}}^{A_j} \end{cases} \tag{35}$$

6. Discussion

With the increase of structure complexity of electromechanical products, the quality control of electromechanical products by parts is too complicated, and its quality control becomes significantly difficult. The control method based on MUs provides a good idea properly analyzing the formation mechanism of the key quality characteristics (precision, precision life, performance stability, and reliability) of electromechanical products is studied based on MUs. On the one hand, due to the appropriate granularity, it is more convenient for quality control; on the other hand, because the meta-action decomposition method is a dynamic decomposition process of electromechanical products, the quality characteristics of electromechanical products can be controlled by the four key quality characteristics (the precision, the precision life, the stability, the reliability) of the quality of the control MUs. It makes up for the deficiency of traditional control methods.

7. Conclusions and prospects

The research shows that it is adaptive and feasible to study the formation mechanism of key quality characteristics and quality control through the proposed analysis method based on the meta-action theory. MU has specific functions and can independently complete the specified motion or operation, which is more suitable for quality and reliability analysis. In this paper, the forming mechanism of MU's four key quality characteristics (the accuracy, the precision life, the performance stability, the reliability) is deeply studied, and its parameter expression model is obtained. The model of quality characteristic state space of unit is established; based on that, the basic principle of predictive control and the forming mechanism of the quality characteristics of MUs are analyzed and clarified. Starting from the quality control of MUs, the quality control of the whole machine is accomplished through the quality control of the unit level. This control mode is more simple, effective, and conducive to the accomplishment of refined quality control.

Due to a variety of electromechanical products, different functions and their implementation processes are complex. On the one hand, the data acquisition of MU quality index is very difficult. On the other hand, the factors influencing the quality uncertainty are various. Moreover, the meta-action theory also has certain limitations up to now, and some deficiencies exist here. Thus, we plan to further improve the following research work in the future:

1. In the follow-up study, the quality characteristic database of meta-action units should be continuously increased through various channels such as collecting process data or conducting meta-action unit tests so as to better verify the theoretical methods.

2. This paper only studies the four key quality characteristics (the reliability, the precision, the precision life, the performance stability). In order to make the later quality prediction and control more accurate, it can be considered to increase the research of quality characteristics such as usability.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (No. 51705048; 51835001) and the National Major Scientific and Technological Special Project for "High-grade CNC and Basic Manufacturing Equipment" of China (2018ZX04032-001; 2016ZX04004-005).

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