Fault diagnosis study of complex mechanism based on FMA function decomposition model
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Abstract
In the study of Reliability Technology, failures reflect in the inability to perform of basic parts. In order to seek the fundamental causes, FMA (function-motion-action) function decomposition model was utilized. By the decomposition stepwise, all basic actions formed the complex mechanism functions were found out, which were called Action. The failure model of action units was built by the fuzzy control theory. The key actions were worked out and the improved design measures were put forward, which proves the method valid.

Keywords: fault diagnosis, FMA, function decomposition, Fuzzy Control Theory

1. Introduction
In recent years, machinery fault diagnosis technology is developing rapidly, research tools and methods with each passing day, and its application has been around in various industrial fields. Since the 1980s, with the signal processing technology, control theory, reliability theory, neural networks and other related scientific developing, fault diagnosis technology has also entered the stage of knowledge-based intelligent[1]; Achmad Widodo, He Luo, Yao Xinhua and Xu Yuetong etc, established on-line fault diagnosis by single sensor or multi-sensor acquiring signal [4-6], which failure modes and failure causes will be detected, but there is no effect on failure mechanism; Zhou Zheng, Luo Tianhong presented a new fault diagnosis expert system based on FTA, however FTA is used to static system diagnostics products do not represent the mechanical working condition; Peishu Qu applied the neural network to fault diagnosis, established simulation testing expert diagnostic system based on BP neural network[2]; Zhang Xiaoyu, Liu Hua improved diagnosis expert system property greatly by combining the fuzzy theory and neural network[3].

Due to the complexity of the mechanism structure, characteristics and causes of failure perform fuzziness and complexity. The use of diagnostic signals is way to diagnose the fault characteristics and failure modes, but the primary cause of the failure can not be determined. It is too difficult to conduct the fault directly and dynamically. In this paper, FMA(Function-Motion-Action) function decomposition was introduced, a method of decomposing complex systems into basic action unit, which layer we called “Action”. In order to identify the primary causes of failure, fuzzy control theory was applied to the layer of “Action” for fault diagnosis, which can improve the design and guide maintenance.

2. FMA Function Decomposition
2.1. Complex mechanical mechanism
In the field of the reliability study, the event or state that the product can not complete the predetermined function was called fault. Failure is essentially constituted by stress, failure mechanism and failure mode. The system under the effect of failure stress, failure represented a phenomenon that the machine lost the system function. In order to meet user needs and design, the functional design of a product estimated the function of input parameters, output property and actuator, also is a gradual mapping process of “user domain →functional domain →physical domain→ process domain”. Therefore, for the system fault diagnosis, analysis of the function property and structure is to identify the cause of failure from the source, and effective control will be reduced malfunction as much as possible.

From the perspective of movement, machine is achieving
the function of a motor, pump and other power input into the pre-movement in some way system, that is the input parameters is converted into the required properties through the power actuator movement or motion, such as rack and pinion is to achieve "rotary - movement" (or vice versa) conversion, Figure 1 is Components of the mechanical mechanism.

1) Input parameter: Actuator as part of the movement chain, must have the power input to make it work, the input parameters in general is velocity or force (torque), which are not only the most basic but also the best descriptive characteristics.

2) Actuator: After transmitting and converting of input parameters by actuator, end-effectors complete the predetermined motion, the actuator also known as transmission mechanism, it can change the way, direction and velocity of motion mainly by assembling and moving parts to achieve.

3) Output property: output property also was called quality characteristics, like reliability, accuracy and accuracy preservation, it is refer to not only the ability of completing the predetermined function but also the indicators of measuring functional design, such as reliable, flexibility, smooth rotation and accuracy. Different mechanical actuators have different properties, the more critical functions, the higher property requirements.

2.2. FMA functional decomposition model

According to the components mechanical motion, excepting input parameters and output property, actuators were fundamental components for achieving functional motion. On the basis of ensuring the reliability of the designing and processing, complex machinery was assembled by mechanism which having a motor function and the support components, and inputted parameters (such as servo motors) to complete the pre-designed function. Failure of complex machinery is mainly caused by the basic action which can not working. Structural decomposition is needed to identify functional element—Action, and figure 2 introduced the FMA function decomposition. At last, according to the outliers, control measures should be taken to improve the functional property.

**Function:** the function is generally based on user requirements to design mechanism which can complete the function. Usually a function is the combination of one or more pre-movement mechanism to achieve desired motion. For example, the jaw crusher crushed by rubbing, squeezing the stones.

**Movement:** Movement was consisted of the various drive train mechanism, including power, actuators, end-effectors and frame, such as the active jaw moving up and down.

**Action:** Space motion of component have both rotary and motion which have strong coupling relationship. According to the design principle of non-coupled, active component only design one motion, moving or rotating, and distortion, like jaw moving, pulley rotating, stretching or compressing of spring, which called “action”.

![Fig. 1 Components of the mechanical mechanism](image)

![Fig. 2 FMA function decomposition model](image)

Assume \( A = \psi(U) \) and existing H-sets mapping:

\[ A \rightarrow H(\lambda) \]

For \( \lambda \in [0,1] \), \( A_\lambda = H(\lambda) \), then:

\[ A = \bigcup \lambda \in [0,1] A_\lambda \]

According to the results of FMA functional decomposition, \( H(\lambda) \) stands for "Action"; \( \lambda \) presents probability of failure does not occur. According to the function mapping, like \( F = F(X) = H(B) \), established the function decomposition of the model.

\[ F = \bigcup \text{\lambda} A_\lambda + \bigcup \text{\lambda} B_\lambda \]

Where \( A \) represents actuator movement; \( B \) represents component action, and \( A \) meets B with \( A \cup B = X \). \( A \cap B = \phi \).

3. Fault diagnosis model based on actions

**3.1. Fault diagnosis model**

For complex machinery, faults are mainly caused by basic parts which cannot work, such as the movement is not in place, movement disorders, parts damaged. Aiming at analysis of actions of FMA function decomposition, which failure model will be occurred when they failed, and control measure should be taken to improve the system reliability.

Failure Sets: \( X = x_1, x_2, \ldots \)

Failure model sets: \( Y = y_1, y_2, \ldots \)

\( K \): \( n \rightarrow \emptyset \), indicates the degree of impact on the failure mode, that means the possibility of failure, the bigger \( K \) was, the greater the effect was.
If failure model $Y_j$ is occurred, there is at least one fault causes $X_i$ appeared. The relationship of $X_i$, $Y_j$ can impress as the equation:

$$Y_j = e_1 X_1 + e_2 X_2 + ... + e_n X_n$$

According to the result of FMA, complex machinery will be failed when the “Action” can not work properly. The relative importance of action is evaluated by Expert Evaluation System, and the faulty weight coefficient was determined with the leveraging of triangular fuzzy number defuzzification.

### 3.2. The faulty weight coefficient

Assume triangular fuzzy number $M(l, m, u)$, it’s membership function is defined as follow:

$$\mu_X(x) = \begin{cases} 1, & x < l \\ \frac{x - l}{m - l}, & l \leq x \leq m \\ \frac{u - x}{u - m}, & m \leq x \leq u \\ 0, & x > u \end{cases}$$

And $1 \leq m \leq u$, $l$ and $u$ are supported by upper and lower bounds of $M$, and $m$ is the median.

The expert judgment of the relative importance is ambiguous, and it is necessary to comprehensive expert advice through the triangle fuzzy number, in order to establish a more objective fuzzy judgment matrix based on the subjective opinion of the decision makers. Judgment matrix for comparison between every two action are represented by using Analytical Hierarchy Process (AHP).

Defuzzification was adopted firstly for the faulty weight coefficient. And $\alpha \in [0, 1]$ was Threshold parameters, and about $w = (w', w^0, w^1)$:

$$w'(\alpha) = w^0 - \alpha w^1$$

$$w'(\alpha) = w^1 - (1 - \alpha) w^0$$

$$w'(\alpha) = \alpha w^0 + (1 - \alpha) w^1$$

The result will be achieved by calculating:

$$w'(\alpha) = \frac{\sum_{\alpha \in [0, 1]} w'(\alpha)}{\sum_{\alpha \in [0, 1]} w'(\alpha)}$$

And $\alpha$ reflected the expert judgment opinions: if $\alpha = 0$, $w(\alpha)$ was integration of changes in the maximum range of each expert decisions; and $\alpha = 1$ reflected the minimum message of expert decisions, that is no defuzzification for synthesis approach of experts. $\chi$ represented the integration of optimistic weights: if $\chi = 0$, the experts have taken optimistic opinions, $w(\alpha)_{\chi}$ should be taken the upper limit; and if $\chi = 1$, the experts have taken a conservative approach, lower limit will be taken.

### 4. Case Study

Machining Center, as a typical complex mechanical systems, has the main function, including automatic tool changer, the spindle system, transmission system, APC carrier, indexing of NC rotary table and so on. In this paper, NC rotary table fault diagnosis model is established by FMA function decomposition, Figure 3 is the NC rotary table structure diagram.

The NC rotary table holds an important position in the processing, such as worktable clamping, exchanging, indexing, to adjust the position of the semi-parts. Therefore, according to the main movement of NC rotary table, the table rotation, clamping and releasing motion and braking movement were designed, and FMA function decomposition was developed, fig 4 is FMA decomposition tree of the NC rotary table.

For the FMA function decomposition model, however, the decomposition of the NC rotary table have no specific action, the function mapping model can simplify to:

$$F = \bigoplus_{j=1}^{n} \prod_{i=1}^{m} B_i$$

For the decomposition of the complex machinery, moving, rotating and flexible deformation of the component was the basic movement, also called “action”. And if those “actions” worked abnormally, the system will be failed. Permanent fault of NC rotary table which were gotten from fault records were shown in Table 1.

| $Y_1$ | Liquid, gas, oil leak |
According to FMA function decomposition, the cause set $X$ was established: $X = X_1, X_2, \ldots, X_{15}$, it means “actions” were taken as outlier for fault diagnosis. "Fault–Cause" set was determined by analyzing the functional structure to judge the relationship by the experts, as shown in Table 2.

### Table 2. "Fault–Cause" set of NC rotary table

<table>
<thead>
<tr>
<th>Fault model</th>
<th>Fault cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>y1</td>
<td>X10, X12, X14</td>
</tr>
<tr>
<td>y2</td>
<td>X2, X3, X4, X5, X6</td>
</tr>
<tr>
<td>y3</td>
<td>X7, X14, X15, X1 X1</td>
</tr>
</tbody>
</table>

$X_2$ Geometric accuracy exceeding $Y_3$ noise

According to the results of "Fault–Cause" equation, the greater weight coefficient of the influence on the failure is, the more crucial action is. Piston moving, Worm rotating, Turbine rotating, Rotary body rotating and Pull claw moving were the key action of NC rotary table by analyzing weight matrix $R$.

For the outliers which affected the system function were identified specific to reliability analysis of the key action, and design improvements were proposed to improve system reliability, as shown in Table 3.

### 5. Conclusion

1) From the perspective of functional mechanism, this paper utilized FMA function decomposition model to break the traditional static decomposition, such as "machine - Components - Parts" and "machine - functional modules - function unit ". And all basic actions formed the NC rotary table were found out, which laid the foundation of the dynamic analysis of complex mechanism.

2) Fault diagnosis of complex mechanism studies on actuated outliers which affecting failure modes. The primary causes of failure are found out by FMA function decomposition, and design measures are proposed to improve the system reliability.

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Table 3 The outliers of the key action and design improvements

<table>
<thead>
<tr>
<th>Fault model</th>
<th>The key action</th>
<th>outlier</th>
<th>Improvement measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid, gas, oil leak</td>
<td>Piston moving</td>
<td>seal ring damage scratch aging</td>
<td>1) High reliability seal 2) Component tolerances criterion, assembly quality control 3) Improve the assembly process, strengthen the assembly quality inspection</td>
</tr>
<tr>
<td>Geometric accuracy exceeding</td>
<td>Worm rotating</td>
<td>worm-and-gear Deformation of which caused by give off heat</td>
<td>1) Optimize the structure and assembly process 2) Strengthen the assembly quality inspection</td>
</tr>
<tr>
<td></td>
<td>Turbine rotating</td>
<td>Large transmission clearance</td>
<td>Component tolerances criterion, assembly quality control</td>
</tr>
<tr>
<td>Pull claw moving</td>
<td>Erroneous position accuracy</td>
<td>Control machining and assembly quality of components</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>Worm rotating</td>
<td>Damaged transmission parts</td>
<td>✗ High reliability to prevent leaks from rusted transmission parts</td>
</tr>
<tr>
<td></td>
<td>Turbine rotating</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotary body rotating</td>
<td>Stack Transmission</td>
<td>1) Improve the assembly process, strengthen the assembly quality inspection 2) Component tolerances criterion, assembly quality control</td>
</tr>
<tr>
<td>Pull claw moving</td>
<td>Damaged Pull claw</td>
<td>1) Increase the fatigue strength 2) Improve the control measure of the clamping action</td>
<td></td>
</tr>
</tbody>
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References