Reliability analysis of self-developed mechanical Meta action test-bed based on FTA

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Abstract. In view of the complex mechanical product assembly failure frequency and difficult to control the problem. In this paper, based on the independent research and development of the reliability test-bed of the mechanical Meta action unit, the reliability of the worm rotation Meta action test-bed is analyzed by the method of fault tree analysis (FTA). Firstly, the structure model of the action assembly unit of worm rotating Meta is established. By analyzing the assembly condition of the action unit and using the principle and steps of fault tree, the assembly fault tree model of the test-bed of worm action unit is established, and the minimum cut set is obtained. On the basis of the minimum cut set, the importance of each assembly behavior is determined by quantitative analysis. The basic events are sorted according to the importance degree; each basic event is determined as the reliability control point, and the reliability control measures of the assembly process of the meta action unit are formulated by analyzing the fault source of the reliability control point. Through quantitative analysis, the probability of the top event is 0.163, and the reliability of the experimental device system is 82.7%. The results show that FTA is simple, easy to understand, universal and reasonable in conclusion to analyze the reliability of the self-developed action unit test-bed. The modeling idea, calculation process and analysis method formed provide a reference for the reliability analysis of the self-developed action unit test-bed.

1. Introduction
Reliability is an important index to determine whether the product function can be realized normally. Assembly is the process of assembling various parts into a whole with certain function. Reliability is mainly reflected in the economy and service life of products. The quality control of assembly is also an important part to ensure product quality. Therefore, it is very important to improve the reliability of products and ensure the quality control of products in the assembly process. In view of the reliability analysis of the self-developed mechanical Meta action assembly unit test-bed studied in this paper, the results of modeling analysis using FTA are clear, scientific and reasonable.

In the aspect of reliability research of mechanical products, many scholars at home and abroad have carried out in-depth discussions on the reliability of mechanical products from different perspectives. Wang Juan [1] in the face of complex fault tree, through MATLAB programming simulation, carries out qualitative and quantitative analysis and calculation quickly, so as to find the weak point of transformer. Zhou Wei [2] et al. put forward the "system reliability cost function" model to solve the
problem of "related cost problem of improving reliability". In order to solve the system reliability optimization problem, a system reliability optimization model is proposed, which is a hybrid algorithm model combining GA (traditional optimization algorithm) and PSO (particle swarm optimization algorithm). Chen Ren long [3] systematically expounds the calculation method of fault tree analysis, and uses the fault tree analysis to analyse the failure reason of cab unable to activate. Jaise [4] In the process of building power system fault tree, established the minimum cut set by using Boolean equation method. Mihail Florin [5] determined the possibility of failure recurrence through fault tree analysis, and modified the preventive maintenance plan and verification of facilities and other similar devices, as well as internal standardization of preventive procedures. Gabriel [6] established a fault tree of web server, and made qualitative analysis and quantitative analysis.

In this paper, when we study the reliability of the mechanical Meta action unit test-bed, we adopt the logic thinking from the whole to the part. First, the FTA is proposed to be used to establish the fault tree model of the whole test-bed, after qualitative analysis, the main fault part of the test-bed is found to be worm rotation meta action unit, and then the worm rotation meta action unit is taken as the research object to build the fault tree model of the main fault part, on this basis, further quantitative analysis is carried out to obtain the reliability analysis results. And according to the reliability analysis as a result, the measures to increase the reliability of the test-bed are put forward.

2. Fault tree analysis

FTA is a graphic deduction, reliability, safety analysis and prediction of complex environment fault analysis method [7]. It analyzes the various causes of the failure (hardware, software, environment, human factors, etc.). obtains the system logic diagram (fault tree), and then analyzes the causes of the system failure. Through the FTA results, we can find out the weak links, key parts, measures to be taken and the requirements of reliability test. FTA can also find out the internal relations of the system by analyzing the potential faults of the system, which has a guiding significance for the formulation of maintenance plan and maintenance strategy, and plays a greater role in system support and management maintenance. In this paper, the failure of the self-developed mechanical Meta action unit is taken as an example to establish the corresponding fault tree model and its mathematical description and quantitative analysis.

The mathematical description of fault tree mainly uses structure function, which is a Boolean function to represent the system state, and its independent variable is the state of the system components. In addition, the structure function is the structure function of the system fault, the occurrence of the event corresponds to the fault state, and the non-occurrence of the event corresponds to the normal state.

Structure function for or gate:

$$\Phi(x) = 1 - \prod_{i=1}^{n}(1 - x_i)$$  \hspace{1cm} (1)

Where $x_i$ represents the state variable of the bottom event, with a value of 0 or 1; when $x_i = 0$, it means that the bottom event I does not occur. When $x_i = 1$, it means that the bottom event $i$ occurs. According to the Boolean algorithm, as long as there is one $x_i = 1$, then $\Phi(x) = 1$, that is, as long as one component fails, the system will fail.

In fault tree analysis, Boolean variables are used to represent the state of the bottom event, and $x_i(t) = 1$ is used to represent the failure of the ith component at time t. then the probability of occurrence of event $i$ is the expected value of random variable $x_i(t)$:

$$E[x_i(t)] = P[x_i(t) = 1] = F_i(t)$$  \hspace{1cm} (2)

The physical meaning of $F_i(t)$ is the probability of occurrence of event $i$ in $[0, t]$. At the same time, the probability of top event of or gate structure fault tree is calculated as follows:

$$F_S(t) = \prod_{i=1}^{n}[1 - F_i(t)]$$  \hspace{1cm} (3)
Then the reliability function of the system is:

\[ R_s(t) = 1 - F_s(t) = 1 - \prod_{i=1}^{n} [1 - F_i(t)] \]  

(4)

Where \( F_i(t) \) the cumulative fault function of the ith component is, \( F_s(t) \) is the cumulative fault function of the system, and \( R_s(t) \) is the reliability function of the system.

For the self-developed mechanical Meta action unit researched in this paper, the fault tree model is composed of 6 logic or gates, 1 top event, 5 intermediate events and 12 bottom events. The symbols corresponding to the logic gates and events are shown in the table below:

**Table 1. List of fault tree terms and symbols**

| Event          | Event symbols |
|----------------|---------------|
| Bottom event   | Elementary event |
| Result event   | Top event     |
|                | Intermediate event |
| Logic Gates    | Logic gate symbol |
| OR gate        |               |

In the fault tree, the basic events in the bottom event do not need to find out the cause in the specific FTA; the result event can be divided into the top event and the intermediate event. The top event is the result event concerned in FTA, which is located at the top of the fault tree, while the intermediate event is located in the middle of the bottom event and the top event. It is not only the output event of one logic gate, but also the output event of another logic gate Enter the event.

3. **Reliability analysis of self-developed mechanical meta action test-bed**

3.1. **Analysis of self-developed mechanical Meta action test-bed**

Reliability test is a means to investigate, analyze and evaluate reliability. Its function is to evaluate the reliability of products, find out the weak links of reliability and recommend improvement suggestions through the statistical analysis and failure analysis of experimental results, so as to improve the reliability of products. In this paper, the self-developed worm rotating Meta action unit is taken as the research object, and an independent test-bed is built. Through many experiments and experimental data analysis, the reliability of the self-developed worm rotating Meta action unit is studied [8-12]. The schematic diagram of the experimental device is as follows:
The working principle of the experimental device is as follows:

The regulated power supply provides 10V voltage for the normal use of the speed control knob; the speed control knob controls the speed of the servo motor through adjustment; the transformer provides 5V voltage for the normal operation of the opt coupler module; the sensor tests the worm speed and transmits the collected speed data to the upper computer for analysis.

3.2. Fault tree modelling of self-developed mechanical Meta action unit test-bed

According to the above theory, determine the top event, intermediate event and bottom event in turn, build the fault tree step by step according to the functional process and the nature of each logic gate, and research the fault tree diagram of the mechanical Meta action unit test bench, as shown in the following figure:
T: Failure of experimental equipment  
E₁: Voltage regulator power failure  
E₂: Servo drive failure  
E₃: Worm rotation behavior is abnormal  
A₁: Unstable rotation  
A₂: Inflexible rotation  
X₁: Poor contact of output cord  
X₂: Input power cord slack  
X₃: The speed knob is out of order  
X₄: Drive switch failure  
X₅: Insufficient expansion force of sleeve ring  
X₆: The coupling between the motor and the worm is slack  
X₇: Motor rotor and worm rotation is not coaxial  
X₈: There is assembly error between worm support and bearing  
X₉: The bottom end of the worm base is not on the same level  
X₁₀: Transformer damaged  
X₁₁: Damage to optocoupler module  
X₁₂: Multi-function data acquisition card damaged

Fig. 2. Fault tree of experimental device

According to the calculation method of the minimum cut set of fault tree [13-14], the minimum cut set of fault tree shown in Figure 2 is: \{X₁\}, \{X₂\}, \{X₃\}, \{X₄\}, \{X₅\}, \{X₆\}, \{X₇\}, \{X₈\}, \{X₉\}, \{X₁₀\}, \{X₁₁\}, \{X₁₂\}. There is only or gate relationship in the fault tree, any bottom event in the fault tree can cause the top event to fail. At the same time, under the condition of ensuring the connection of the whole experimental circuit in good condition, there is no failure in any form in the components such as stabilized voltage power supply, servo driver, transformer, optocoupler module, multi-function data acquisition card, etc., that is to say, the reliability of the components is 1. Therefore, the main part of the failure of the experimental device is the worm rotation Meta action unit, so the worm rotation Meta action unit is analysed and studied independently.

3.3. Experimental analysis of Meta action unit of worm rotation
In the process of analyzing the key failure factors of the experimental device, this paper uses the self-developed worm rotation Meta action unit experimental device to carry out experiments. For the detection of a single form of failure, the number of repeated experiments is set to 1000, and the experimental process is shown in the figure below:
In order to ensure the validity of the experimental data and the scientificity and rationality of the experimental process, during the experimental process, the voltage is controlled to be 10V, the speed of the motor is controlled to be 450R / min by the speed regulating motor, and the experimental period is 4min; among them, the time to assemble the meta action unit is 2min, the time to dismantle the meta action unit is 1min, and the time to record the experimental data is 1min; When the worm rotation meta action unit operates stably, the measured speed data is shown in the figure below [15-16]:

![Experiment flow chart](image)
It can be seen from the above figure that when the worm rotation Meta action unit operates stably, the speed of worm always fluctuates up and down, but the speed always fluctuates up and down at 450R/min, and it is in a stable state.

Repeat the above experiment, control the voltage to constant voltage 10V, control the motor speed to 450R/min constant through the speed regulating motor, and the experiment period is 4min. When the worm rotating Meta action unit fails, the measured speed data is as follows:

Figure 4. Speed waveform in normal operation

Figure 5. Speed waveform in case of failure
It can be seen from the above figure that when the worm rotation meta action unit breaks down, the rotation is not flexible and unstable due to the different rotation shafts of the motor rotor and worm, the assembly clearance between the support and worm, the different shafts of the shaft worm and the sleeve worm, etc., resulting in the asynchronous rotation speed of the worm and the electric machine, and the motor speed has multiple average values, and with the progress of time, the speed of the fluctuation is large.

3.4. Reliability analysis of Meta action unit of worm rotation
The Meta action unit of worm rotation is the key link that leads to the failure of the whole machine of the test-bed. Because the reliability of other experimental devices of the test-bed is 1, when the Meta action unit of worm rotation fails, the whole machine of the test-bed will fail. Therefore, by improving the reliability of the Meta action unit of the worm rotation, the reliability of the whole test-bed can be further improved. In the independent analysis and Research on the Meta action unit of worm rotation, firstly, the Meta action unit model of worm rotation is established, secondly, the fault tree diagram of the Meta action unit of worm is drawn according to figure 2; its assembly diagram is shown in the figure below:

![Figure 6. Worm rotation Meta action unit model](image)

The operation principle of worm rotation Meta action unit is as follows:
The coupling connects the worm and the motor, and the motor drives the worm to rotate coaxially; the surface of the worm is attached with a reflective strip, and the photoelectric sensor collects the speed information of the worm by receiving the signal released by the reflective strip.

The fault tree diagram of worm rotation Meta action unit is as follows:
Through the above (2.3) experiments and the statistical experimental data, the probability of each bottom event is obtained as follows:

| Events | Probability of occurrence |
|--------|---------------------------|
| $X_5$  | 0.0275                    |
| $X_6$  | 0.0315                    |
| $X_7$  | 0.026                     |
| $X_8$  | 0.049                     |
| $X_9$  | 0.041                     |

Then the probability of the top event is:

$$F_s(t) = 1 - (1 - 0.0275)(1 - 0.0315)(1 - 0.026)(1 - 0.049)(1 - 0.041) = 0.163$$

The system reliability of the self-developed mechanical meta action test-bed is as follows: $R_s(t) = 82.7\%$

4. **Measures to increase assembly reliability of self-developed mechanical meta action test-bed**

According to various failure behaviors, analyze the causes of failure, find out the corresponding reliability control points, and finally develop the control measures of assembly reliability [17-18], and the table of the measures for assembly reliability growth is as follows:
Table 3. Table of assembly reliability control measures

| Fault form          | Influence reason                          | Reliability control point                      | Assembly reliability control measures                                      |
|---------------------|-------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------------|
| Unstable rotation   | Insufficient expansion force of sleeve ring | Ring deformation control, prevent ring expansion force is too small | Control ring torque to ensure that the relative position of base and bearing does not change |
|                     | The coupling between the motor and the worm is slack | Connection control between motor and worm | Replace the new connection key to increase the expansion force in the middle of the coupling |
| Rotational inflexibility | Motor rotor and worm rotation is not coaxial | Motor rotor and worm rotation control | The motor rotor and worm are tested by rotating coaxial detection |
|                     | There is assembly error between worm support and bearing | Assembly process control of base and bearing | Grease the outer surface of the bearing and the inner surface of the base |
|                     | The bottom end of the worm base is not on the same level | Horizontal height control for two bases | Replace the two bases and adjust the horizontal height of the two bases to ensure that the sizes of the bases are the same and the worm is in a horizontal position |

5. Conclusion

(1) By establishing the fault tree model of the self-developed mechanical meta action test-bed, the minimum cut sets of the fault tree are determined as: \{X_5\}, \{X_6\}, \{X_7\}, \{X_8\}, \{x_9\}, and the minimum set of basic events of the test-bed fault events are determined.

(2) According to the minimum cut set, the reliability control points of the self-developed mechanical meta action test-bed are determined. The reliability control points are: coupling, expansion sleeve, bearing and worm support. It provides a basis for improving the reliability of the self-developed mechanical element action test-bed.

(3) Through quantitative analysis of the main failure parts of the self-developed mechanical Meta action test-bed, through probability calculation, the failure probability of the test-bed is 0.163, and the system reliability of the self-developed mechanical Meta action unit test-bed is 82.7%.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (No.51705417, 51805428), and the Shanxi Provincial Natural Science Fund (No.2019JQ-086), and the National Key Research and Development Program of China (2018YFB1703402).

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