Research on Testability Design and Evaluation Method for Ship Electromechanical Equipment

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Abstract. As a relatively large amount of electromechanical equipment was installed in the ship systems, it was difficult to position and eliminate the faults of the M&E equipment if any. Hence, there was a need to improve the fault detection and isolation capabilities of the equipment depending on testability design and to develop the corresponding fault diagnosis system when necessary, thus improving the overall availability of the equipment and ensuring that the ship could successfully complete the missions. In view of the above requirements, this paper, taking the most representative M&E equipment - pump set on the ship as a research object, gave the testability design process of the M&E equipment - pump set for product development, illustrated the equipment testability design methods from 4 aspects (namely determination of equipment testability and fault diagnosis system requirements, testability analysis & design, comprehensive fault diagnosis system design and testability verification process design), specified the testability design & monitoring object selection principles and fault characteristic determination methods, and finally provided the testability design evaluation methods for the M&E equipment for verifying whether the testability requirements were met.

1. Introduction

As typical complex electromechanical (or M&E for short) equipment, a ship features very complex system composition and interface, and the corresponding devices are interrelated. However, the current testability design methods and guiding principles are mostly suitable for electronic equipment. [1] Besides, a mature method system for M&E equipment testability has not been established yet, and the existing design methods are less targeted. This paper, taking the pump set - common M&E equipment on the ship as an example, analysed and studied its testability design process, emphatically elaborated the design principles for three test methods (namely built-in test, external test equipment and manual test of the pump set), and finally gave the equipment testability verification and evaluation methods.[2] Through equipment testability design, the system equipment had the functions of status monitoring, fault detection and fault diagnosis. In this case, not only could the equipment monitor the "health" status, and display and store the corresponding information, but also it could send an alarm and give a prompt when necessary during operation; in addition, the equipment could determine its working state, detect the faults, and judge the fault position if any, thereby improving the maintenance efficiency of the equipment and guaranteeing the overall availability.
2. Analysis on Testability Design Process of M&E Equipment
The testability design focus varied with the objects, categories and levels. The pump set was classified into M&E type and equipment level. Through analysis of its fault mechanism, fault mode and fault characteristics and research on comprehensive fault diagnosis technology, the faults of the pump set were mainly tested from the outside. If the testability requirements and design were taken into consideration in the whole life cycle (including concept design, technology design, construction design and manufacturing) from the beginning of pump set development, the testability design means (such as built-in test (BIT)) could be integrated into the design and manufacturing process of the pump set through the corresponding design analysis, or the development of the pump set and comprehensive fault diagnosis system could be considered in parallel, so as to reach the corresponding testability requirements and ensure its integrity.[3]

2.1. Determination of pump set testability and comprehensive fault diagnosis system requirements
The testability and comprehensive fault diagnosis system requirements mainly included qualitative and quantitative requirements, and were determined according to the operation and maintenance requirements for system equipment and operation support analysis. Multiple test methods such as BIT, automatic test, manual test and comprehensive fault diagnosis system could be comprehensively adopted, thus providing diagnostic test capability according to the requirements for availability and life cycle cost under the constraints of design, fund, use, etc. The requirements mainly included qualitative and quantitative requirements for testability and comprehensive fault diagnosis system.

2.2. Pump set testability analysis and design
It aimed to analyze the function and hardware of the pump set through the corresponding analysis means, determine the monitored objects and monitoring means of the pump set, and improve the fault detection capability through corresponding testability design means. It mainly included the selection of monitored objects of the pump set, fault characteristics of the monitored objects and selection of the monitoring means, and the pump set testing methods included built-in test (BIT), external test equipment (ETE) and manual test.

2.3. Design of comprehensive fault diagnosis system of the pump set
As for M&E equipment like pump set, in consideration of relevant facts (most fault characteristic signals could not be directly measured through equipment BIT; it was difficult for a person to carry out manual test or ETE using a measuring tool; a large number of fault signals were sent from lots of equipment; and the fault mechanism was relatively complex), it was necessary to develop the corresponding comprehensive fault diagnosis system. Through the design of the fault diagnosis system, starting from sensor and modules such as fault acquisition module and data analysis module, the pump set had a better online status monitoring and fault diagnosis capability, and the testing technology and comprehensive diagnosis problems of the pump set were solved. It mainly included comprehensive fault diagnosis system architecture design, system hardware and software design of the pump set, among which the hardware design involved sensor, data acquisition unit and data processor, and one of the keys for software design lied in diagnosis algorithm design.

2.4. Design of pump set testability verification process
During design and development of the pump set, in order to confirm the correctness and effectiveness of the pump set testability analysis & design and the comprehensive fault diagnosis system, identify the design flaws and check whether the developed pump set fully met the testability and comprehensive fault diagnosis system design requirements, the pump set testability must be verified. The verification work mainly included the establishment of general testability verification criteria, specific testability verification criteria, and testability design evaluation.
3. Monitored Object Selection Method

3.1. Identification of functional significant items

For the M&E testability design objects (mainly for the functional significant items (FSI)), there was a need to specify the testability design content such as fault characteristics, characteristic signal and monitoring means. A functional significant item was a product of which the fault met one of the following conditions:

- The fault possibly affected its safe operation
- The fault possibly affected the completion of the missions;
- The fault possibly caused significant economic losses;
- The co-occurrence of a hidden fault of the product and fault of another relevant or standby product possibly caused the above one or more of the above effects;
- The fault possibly led to a dependent fault which had one or more of the above impacts.

Other products were classified into non-functional significant items (NFSIs). The faults of the NFSIs had no significant impact on the security, mission success and economic efficiency of the entire equipment or system, so there was no need to deeply analyse the testability design but a need to carry out some preventive maintenance work through failure mode effects and criticality analysis (FMECA) or reliability centred maintenance analysis (RCMA). Alternatively, maintenance suggestions on preventative maintenance type and interval can also be proposed according to past similar product experience or suggestions of the design unit. [4]

The functional significant items of the pump set were generally selected from the equipment level (from top to bottom), and were broken down into the components, parts, etc., until the product fault at a level was not severe. The determination of the functional significant items (FSIs) was a top-down and rough process. During determination, the product fault consequences were generally determined using the engineering judgment method. The determination steps are as follows:

- Draw a block diagram for the equipment structure from the equipment level to a unit at the lowest level where direct replacement or repair was feasible on the devices, and list the components by levels;
- Determine the functional significant items: determine the products on each level from top to bottom (starting from the equipment level). If a product was a functional significant item, there would be a need to continuously determine whether the products from the next level were a functional significant item. This process was repeated until a non-functional significant item or the unit from the lowest level where direct replacement or repair was feasible on the devices.

4. M&E Equipment Testability Design

4.1. Built-in test design of pump set

The built-in test of the pump set was carried out mainly based on the testability requirements. After FSI and FMEA analysis (specific information is not repeated herein), the components/parts corresponding to the fault mode with high severity and high detection difficulty after the fault occurred mainly included M&E components/parts, such as motor and controller of the pump set.

In order to acquire current signals of the pump set, the current signal acquisition unit shall be designed as the BITE of the pump set during development, and shall be embedded in the motor of the pump set or other devices connected to the circuit. The current BIT shall have real-time display and alarm functions, so that the users can judge the fault in time.

In order to acquire the outlet flow signals of the pump set, the flow signal acquisition unit may be designed as the BITE of the pump set according to the user requirements, and shall be embedded at the outlet of the pump set. The flow BIT shall have real-time display and alarm functions, so that the users can judge the fault in time.

The speed signals were monitored; the speed signal acquisition unit should be designed as the BITE of the pump set. According to the pump set structure and maintainability design, an appropriate position was selected to embed the pump set.
Regarding the acquisition of the vibration signals of the pump set, considering that the vibration signals were unclear, it was required to carry out corresponding complex pre-processing and conversion analysis for the acquired signal and equip with the corresponding acquisition cards and processors with high performance. Therefore, this equipment should not be designed as BIT, but the corresponding sensor would be embedded into the pump set as planned during development, which facilitated signal tapeout. If the sensor was embedded into the pump set, the maintenance support efficiency would be improved depending on maintainability design of the pump set, as well as modular, general and serial design planned during development, maintenance accessibility design and spare parts configuration.

The shaft centerline orbit vibration signals essentially were displacement signals acquired in two directions, and also needed to be converted accordingly like vibration signals, so this equipment should not be designed as BIT.

As for the design of other acquisition signals of the pump set (such as oil contamination and oil temperature), this equipment should also not be designed as BIT.

The fault corresponding to the temperature fault characteristics of the pump set was unobvious, and was greatly interfered by environmental factors, as well as running time and load of the pump set and other working conditions. Generally, as an auxiliary testing means, this equipment should not be designed as BIT from the perspectives of economic efficiency and maintenance support.

4.2. External test design of pump set

The built-in test of the pump set was carried out mainly based on the test requirements. After FSI and FMEA analysis, the components/parts corresponding to the fault mode with low severity, obvious fault characteristics and low detection difficulty mainly included electronic and electrical components/parts.

The signal detection devices (such as current, outlet flow, speed and other signals) designed into BIT mentioned in the previous section and BIT devices could be externally tested by externally connecting a sensor. During external test, there was a need to consider relevant support conditions for operation, such as power supply and sensor wiring.

The vibration signals should be externally tested. The vibration signals were generally acquired and sensed by the corresponding vibration sensor, and the specific model, range accuracy and other parameters needed to be selected according to the size, installation space and other support conditions of the pump set.

The shaft centerline orbit of the pump set should be externally tested. The shaft centerline orbit signals were generally acquired and sensed by the corresponding vibration sensor, and the specific model, range accuracy and other parameters needed to be selected according to the size, installation space and other support conditions of the pump set. Due to large installation space, a traditional eddy current displacement sensor may be selected for the main drainage pumps, bilge pumps and other large-volume pump sets among underwater equipment; a permanent magnet displacement sensor may be selected for the compensating water pump and other small pump sets.

In summary, multiple test interfaces shall be arranged for the external test design of the pump set. According to the pump set testability requirements and FMECA analysis results for testability and fault diagnosis, the monitoring fault characteristics can be reasonably selected for the purpose of monitoring and checking the running conditions of the unit at any time and sending a fault early warning, and the quantity and positions of test interfaces shall meet the function and monitoring requirements. Besides, the external test design of the pump set must adapt to the operation and maintenance support conditions for overall optimization. In comprehensive consideration of support conditions of external support points and active sensors, the pump set was rationally designed.

4.3. Manual test design of pump set

Manual test mainly refers to that the staff regularly or irregularly test the equipment using external test equipment (such as handheld point detector) without affecting its normal operation. Its purposes are to
quickly detect whether the pump set has failed and to judge the current running state of the pump set, as a relatively direct, quick and rough fault detection method. For the pump set, manual test is mainly carried out under the fault mode with obvious fault characteristics, and these fault characteristics are easily obtained without stopping the machine or changing the structure of the existing system equipment.

The current signals of the pump set should not be manually tested. As the corresponding acquisition device must be connected to a circuit loop for acquiring the current signals, it is impossible to manually test the working status of the pump set. Therefore, current can only be detected by BITE or through external test. In addition, current shall be detected in real time, so that the operation and maintenance support personnel can monitor the running conditions of the pump set. Therefore, the current can also only be monitored through BITE or by external test.

Two test methods were available for oil contamination and oil temperature signals of the pump set, one of which was manual test. The steps are as follows: shut down the pump set for overhaul, and extract oil in a corresponding way for analysis. This monitoring method inevitably affected the capabilities of the pump set to execute relevant tasks and complete the corresponding functions, and there were higher requirements for the support capabilities (skill levels of staff and support resources, such as detecting instrument) for the repair level (submariners/grassroots). This method was suitable for small pump set. This pump set should be manually tested according to economic affordability, support and operation requirements. The large pump sets or pump sets that significantly affected the mission success and safety of the entire underwater equipment should be externally tested. The corresponding devices shall be designed to make pump oil flow into the corresponding special detection device for analysis, judge the running state of the pump set and display relevant information without affecting the normal running of the pump set.

The speed signals, vibration signals and temperature signals of the pump set can be monitored by external test or by manual test mainly based on real-time monitoring on the running status of the pump set and other requirements. With continuous upgrading of simple manual testing methods such as hand-held point detector and infrared imaging device, more and more fault signals can be monitored by manual test. Not only were the functions such as local data preprocessing and status detection achieved, but also data acquired and preliminarily analyzed can be uploaded to the equipment status management system/fault diagnosis system such as host computer management system for further analysis. Therefore, during manual test design for the above signals, consideration shall be given to whether the faults should be further diagnosed and the fault diagnosis system should be established, as well as the interface with the diagnostic system and other elements. In addition, there is a need to consider the matching of human resources, security equipment and other support factors.

The shaft centreline orbit signals of the pump set should not be manually tested, because the shaft centerline signals must be acquired when the displacement sensors in multiple directions were close to the main shaft of the pump set under the running status, but most of the main shafts were sealed and packed according to functional performance design. If it was difficult to carry out manual test in real time or at fixed time, the shaft centerline orbit signals cannot be directly obtained during shutdown for overhaul. As described in the previous section, external test should be carried out.

5. M&E Equipment Testability Verification Method

By analysing and evaluating the equipment testability, verify whether the equipment design met the testability design requirements and identify the existing problems, and take improvement measures as soon as possible. [5] This part gave the general testability verification process.

5.1. Testability verification criteria

Verify product testability, firstly establish a common knowledge base for testability design verification criteria, and verify the product testability from different aspects including test requirements, inherent testability and compatibility, built-in test design, circuit and component design, system testability and diagnosis system construction. The testability verification criteria varied with products from different
levels (such as equipment, components and parts) and different types (circuits, mechanical parts and photosensitive devices). The following table is a knowledge base for testability verification criteria, and is only for reference during development of verification criteria. Taking the knowledge base for general testability design verification criteria as a basis, according to the specific characteristics of the pump set, tailoring and refining were special verification criteria for verifying the specific pump set. For example, the mechanical system status monitoring, optoelectronic equipment testability design, sensor testability design verification criteria were not applicable to electronic equipment, while the testability verification criteria relating to digital circuit design, large-scale integrated circuit and RF circuit were not applicable to M&E products. Therefore, in developing the equipment-specific testability verification criteria, the criteria applicable to the equipment must be selected. Some items needed to be revised before operation, and the testability design verification criteria which were not included in the general verification criteria but necessary for the pump set may also be added. Finally, more comprehensive and special testability verification criteria were formed based on the characteristics of the pump set.

5.2 Testability design evaluation

Different testability design requirements of the equipment were different for the realization of the predetermined testability indexes in contribution and importance, so the influence was considered by assigning different weights. According to the relative importance of each testability design requirement for equipment testability, the corresponding weights shall be determined respectively. A high weight was assigned for critical indexes, while a low value was assigned for unimportant indexes. The Evaluation steps are as follows:

Establish an equipment testability design checklist;
Determine the weighted coefficient for each testability criteria;
Determine the scoring methods (100 scores mean all actual testability requirements are implemented, while 0 score means the testability design requirements are not considered.);
Analyse and count the number of design objects for each testability criteria;
Determine the number of design objects for each testability criteria according to design data;
Calculate and determine the score for each testability criteria;
Calculate the total testability design score.

6. Conclusion

This paper established the M&E equipment testability design process from 4 aspects (namely testability and fault diagnosis system requirements, testability analysis and design, comprehensive fault diagnosis system design and testability verification process design), emphatically elaborated the design principles for different test methods such as built-in test, external test and manual test of the pump set according to the design characteristics of the pump set, and finally gave the equipment testability design evaluation methods based on the testability verification criteria, which provided technical supports for the designers in integrating the testability requirements into product design starting from the early equipment development scheme stage, hereby positioning and diagnosing the equipment operation faults, laying a basis for improving the maintenance support efficiency, and finally increasing the readiness ratio of the ship and shortening the maintenance cycle.

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