Reliability Distribution of a Ship Steering Control System Based on Scoring Method

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Abstract. In order to improve the reliability of the ship's steering control system, the structure and function of a new ship steering control system are taken as objects, the basic reliability model of the system is established, the working characteristics of the system are analyzed and the scoring distribution method for the ship's steering control system is proposed, and the reliability index of the unit in the system is distributed. The reliability index of each unit is obtained, which provides the reliability basis for further optimizing the design of the steering control system.

Keywords: steering, reliability, scoring distribution.

1. Introduction
Ship steering control system is extremely important in the process of ship navigation system, it can control the direction of the ship sailing process, ensure the accuracy of the course in the process of sailing, and collect the navigation data in time. The highly reliable ship steering control system can control the ship's continuous and effective navigation and ensure the safety and economy of navigation [1-3]. At present, most scholars' research on control system is mainly focused on control algorithm [4-6], but there are few studies on its reliability. With the development of automatic rudder system towards modularization, automation, information and intelligence, it is not only required to have better robustness and comprehensive functions, but also required to have higher reliability. Therefore, it is of great significance to study the reliability of ship steering control system.

In the process of designing the structure and reliability redundancy of the steering control system, reliability is a very important performance index. Reliability distribution can provide the reliability index of the system design, expose the weak links and key parts in the system design, and provide the basis for the index monitoring and improvement measures. The scoring assignment method is also called "objective feasibility method" or "comprehensive factor method". By scoring several factors that affect product reliability, and making a comprehensive analysis of the score value, the reliability relative ratio (distribution coefficient) among products of each unit was obtained. Then the reliability index of products of each unit is assigned according to the distribution coefficient [7].

2. Basic structure and functions of ship steering control system
Fig.1 shows the structure and connection diagram of a new type of ship steering control system, which is composed of the bridge control console, rudder engine room control console, power supply system,
command control box, servo control box, hydraulic mechanism and rudder Angle feedback mechanism. The system has three main steering modes: simple (emergency) steering, follow-up steering, automatic steering. Steering mode is mainly determined by sea conditions, navigation tasks and navigation environment. The new steering control system is modularized, mainly embodied in the control platform, which is mainly composed of the follow-up hand wheel module, the integrated control module, the rudder Angle and course repeater module, the alarm module, the display control module and feedback module. The display control module is a man-machine interaction module completing the automatic mode which includes the course automatic, track automatic and track automatic control modes. In the system, the bridge control console and the rudder engine-room control console are hardware similar redundancy structures to each other, that is, the structure is completely consistent, and they are used as standby. At the module level, the system has a four-redundancy structure, which allows the system to work normally in the event of a single signal, a two-channel signal, or even a three-channel signal failure. This structural design improves the reliability of the system, but there are some problems in the rationality of the reliability design. Excessive redundancy design for highly reliable units will burden the system, reduce the basic reliability of the system, and increase the cost of equipment maintenance [8].

Figure 1. Structure and connection diagram of a new steering control system.
3. Establish the basic reliability diagram of the system

Reliability is divided into basic reliability and mission reliability. Establishing the basic reliability block diagram is to keep all system modules as series structure \[^9\]. For the new steering control system, the analysis of the main object is needed to complete the control signal module, therefore when modeling system reliability does not consider hydraulic and servo mechanism so that the system is mainly composed of follow-up hand wheel module, integrated control module, display and control module, command sending and receiving module and feedback module. Follow-up hand wheel module includes the steering wheel and shaft angle acquisition device, four redundancy design focused on a board. Integrated control module includes the power drive board, integrated control board and the information interface board, and each circuit board has four identical boards. Display control module includes the MCU board of the display control unit, the button board and the 7-inch screen display drive board, and the module is a double redundant backup. Feedback module is a shaft angle acquisition device, and the four redundancy designs are concentrated on the same board.

The new steering control system is a distributed control structure, and the components of the control system are mostly electronic components. Its failure distribution conforms to the bathtub curve as shown in figure 2, that is, it can be calculated with exponential distribution.

\[
\lambda(t) = \begin{cases} 
\lambda(t) & \text{Early Failure Period} \\
0 & \text{Random Failure Period} \\
\lambda(t) & \text{Loss Failure Period} 
\end{cases}
\]

\[
0 \leq t \leq \text{Working Life}
\]

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{bathtub_curve.png}
\caption{Bathtub curve.}
\end{figure}

Let the reliability functions of the five modules be \( R_1(t) \), \( R_2(t) \), \( R_3(t) \), \( R_4(t) \), \( R_5(t) \). According to the reliability model of the series system, the reliability of the system can be expressed as:

\[
R_s(t) = R_1(t)R_2(t)R_3(t)R_4(t)R_5(t) = \prod_{i=1}^{5} e^{-\frac{t}{\lambda_i}}
\]  

(1)

According to the composition of the system and the interrelationship between modules, the system reliability block diagram of the system is established, as shown in figure 3.
4. Application and results of scoring assignment method

4.1. Scoring factors

The scoring distribution method mainly considers the following factors: complexity, technical maturity, working hours and environmental factors. As the steering control system is repairable equipment, the factors of maintenance accessibility and hazard degree should be considered. The following are the scoring criteria for each element. The higher the score, the less reliable it is.

1) Complexity. The more basic components of the steering control system, the higher the complexity score. The most complex score is 10 points, then the command sending and receiving module scores 10 points. By comparing the circuit schematic diagram of each module of the system with the real object and calculating, the complexity score table of each module of the system can be obtained, as shown in table 1.

| Submodule | Follow-up Hand Wheel Module | Display Control Module | Integrated Control Module | Command Sending and Receiving Module | Feedback Module |
|-----------|-----------------------------|------------------------|---------------------------|--------------------------------------|-----------------|
| Number of Components | 515 | 279*2 | 310*4 | 311*4 | 471 |
| Score | 4.2 | 4.6 | 10 | 10 | 3.8 |

2) Technical Maturity. Technology maturity is divided into design technology maturity, material technology maturity and process maturity. And each maturity level is divided into mature technology, improved technology and new technology. This system can be applied in actual ships, indicating that its materials and process are mature processes, but from the technical perspective, the follow-up handwheel module, feedback module and command sending and receiving module are mature technologies, which have been applied in the initial automatic steering system. With the continuous upgrading of control methods, the comprehensive control module is the improved technology, and the display control module is the latest technology applied, with a high technology maturity score. References [10] refer to the technology maturity score table, and weighted and averaged the three technology maturity scores to obtain the comprehensive score. The maturity score table is shown in table 2.
Table 2. Submodule technology maturity score table.

| Submodule                          | Follow-up Hand Wheel Module | Display Control Module | Integrated Control Module | Command Sending and Receiving module | Feedback Module |
|------------------------------------|----------------------------|------------------------|---------------------------|--------------------------------------|-----------------|
| Design technology maturity         | 3                          | 7                      | 5                         | 3                                    | 3               |
| Material technology maturity       | 1                          | 1                      | 1                         | 1                                    | 1               |
| Technical maturity                 | 1                          | 1                      | 1                         | 1                                    | 1               |
| Comprehensive score                | 1.3                        | 3                      | 2.3                       | 1.7                                  | 1.7             |

(3) Working Hours. The follow-up hand wheel module is only applied in the follow-up mode, while the display control module is applied in the course automatic, track automatic and track automatic steering mode, while the other three modules are always applied in the ship's navigation. It is suggested that the working time of the manual wheel module is 1 unit, and the working time rating criteria in reference [7] are used to score the working time according to the proportion of the longest working time of the sub-module at the same level. The working time score table is shown in table 3.

Table 3. Submodule working time score table

| Submodule                                         | Follow-up Hand Wheel Module | Display Control Module | Integrated Control Module | Command Sending and Receiving module | Feedback Module |
|---------------------------------------------------|-----------------------------|------------------------|---------------------------|--------------------------------------|-----------------|
| Unit Working Hours                                | 1                           | 2                      | 3                         | 3                                    | 3               |
| Score                                             | 4                           | 7                      | 9                         | 9                                    | 9               |

(4) Environmental Factors. Referring to the GJB299C-2006 Electronic Equipment Reliability Estimation Manual [10], the ship environment is divided into $N_{s1}$ in good ship cabin, $N_{s2}$ in normal ship cabin, and $N_{u}$ outside the ship cabin. The follow-up hand wheel module, display control module and integrated control module in the control console of the cab are $N_{s1}$ environment, while the command sending and receiving module and feedback module in the steering gear cabin are $N_{s2}$ environment.

(5) Risk Priority Number (RPN). RPN=$ESR*OPR$, referring to the Effect Severity Rating (ESR) and Occurrence Probability Rating (OPR) scoring criteria of GJB _Z1391 -- 2006 [11], the scores of different modules of the system can be obtained.

4.2. Scoring allocation method and scoring factor calculation
The basic model of scoring distribution is shown in formula (2):

$$\lambda_i = C_i \lambda_i$$ (failure rates assigned to each module) \hspace{1cm} (2)

$$C_i = \frac{W_i}{W}$$ (the normalized factor of subsystem $i$) \hspace{1cm} (3)

$$W_i = \prod_{j=1}^{m} \gamma_{ij}$$ (product of factors of subsystem $i$) \hspace{1cm} (4)

$$W = \sum_{i=1}^{n} W_i$$ (total score) \hspace{1cm} (5)
The steering control system requires high reliability. Generally, a minor repair shall be carried out once every three years, and the sailing time shall be 1/3 of the whole year. If the daily working time is set as 12h, the minimum mean time between failures required by the steering control system shall be 365*12=4380h. Due to the required system failure rate $\lambda_s = 228.3 \times 10^{-6} \cdot h^{-1}$. According to the above allocation model and the selection of scoring factors in 4.1, the overall score allocation results are shown in table 4.

Table 4. A new steering control system scoring factor distribution results table.

| Scoring Factor          | Follow-up Hand Wheel Module | Display Control Module | Integrated Control Module | Command Sending and Receiving module | Feedback Module |
|-------------------------|----------------------------|------------------------|---------------------------|-------------------------------------|-----------------|
| Complexity              | 4.2                        | 4.6                    | 10                        | 10                                  | 3.8             |
| Technical Maturity      | 1.3                        | 3                      | 2.3                       | 1.7                                 | 1.7             |
| Working Time            | 4                          | 7                      | 9                         | 9                                   | 9               |
| Environmental Factor    | 5                          | 5                      | 4                         | 7                                   | 8               |
| Risk Priority Number    | 3                          | 5                      | 8                         | 8                                   | 8               |
| $W_i = \prod_{j=1}^{5} Y_{ij}$ | 327.6                     | 2415                   | 6624                      | 8568                                | 3721            |
| $\sum_{i=1}^{5} \prod_{j=1}^{5} W_i$ | 21655.6                   |                        |                           |                                     |                 |

4.3. Basic reliability distribution results for each submodule

According to the mathematical model of score distribution and table 4, the basic reliability distribution results of sub-modules of the new steering control system can be calculated as follows:

Follow-up Hand Wheel Module, $\lambda_i = \lambda_s \times \frac{W_i}{W} = 3.454 \times 10^{-6} \cdot h^{-1}$

Display Control Module, $\lambda_2 = \lambda_s \times \frac{W_2}{W} = 25.460 \times 10^{-6} \cdot h^{-1}$

Integrated Control Module, $\lambda_3 = \lambda_s \times \frac{W_3}{W} = 69.832 \times 10^{-6} \cdot h^{-1}$

Instruction Sending and Receiving module, $\lambda_4 = \lambda_s \times \frac{W_4}{W} = 90.326 \times 10^{-6} \cdot h^{-1}$

Feedback Module, $\lambda_5 = \lambda_s \times \frac{W_5}{W} = 39.228 \times 10^{-6} \cdot h^{-1}$

5. Summary

According to the new ship steering control system, the basic reliability distribution of the steering control system is carried out by using the scoring distribution method according to the environment, working time, technology maturity and other factors of the sub-modules of the system, and the reliability index is quantified and distributed to each sub-module. It provides the basis for the design and reliability optimization of the future steering control system, and can improve and optimize the vulnerable spot with high failure rate, that is, the command sending and receiving module. Finally, the work of this paper lays the foundation for the subsequent reliability testing and evaluation.
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