Failure criticality evaluation of ship propeller shaft system based on Fuzzy FMECA method

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Abstract: The propeller shaft system is the key system for power transmission on board. The components of the system are complex, the working environment is bad, the failure modes are numerous, and the failure consequences are serious. FMECA (Failure Modes, Effects and Criticality Analysis) is difficult to accurately and quantitatively carry out criticality assessment. Therefore, in view of the complex navigation environment, the fuzzy FMECA method is used to evaluate the failure mode criticality of propeller shaft system. On the basis of FMECA, the factor set with maintainability and testability is established, and the factor level set, fuzzy evaluation matrix and factor weight set are determined, and the consistency judgment is made. Finally, the fuzzy comprehensive evaluation is carried out to obtain the accurate and quantifiable failure mode criticality ranking. Compared with the traditional FMECA method, fuzzy FMECA can consider the limited maintenance conditions and test conditions on board, accurately quantify the criticality degree, and take into account more expert opinions, so as to improve the authenticity, accuracy and repeatability of criticality assessment. Therefore, the fuzzy FMECA method can better evaluate the criticality degree of propeller shaft system, and the results can effectively guide the improvement of propeller shaft design and maintenance work.

1. INTRODUCTION
The propeller shaft system is a necessary device to ensure the power output of the marine engine, and also transfers the thrust generated by the propeller to the hull[1-2]. Therefore, the propeller shaft system is one of the most important devices in the ship propulsion system. The reduction of the reliability of the propeller shaft system will greatly restrict the service life of the ship and increase the maintenance cost of the ship. As for large ships, there are more tunnel shaft bearings, larger torque, higher alignment difficulty and more failure modes. Moreover, the number of spare parts during navigation is limited and the maintenance conditions are poor. Once the fault occurs, it is likely to directly affect the propulsion capacity of the ship, resulting in catastrophic accidents [3-4].

The reliability design and analysis of ship propeller shaft system is an essential link in ship design. The failure mode of propeller shaft system is obtained by analyzing the reliability relationship between various parts. The failure modes obtained from the analysis can be used to guide the design process and maintenance process[5-6]. However, the fault of propeller shaft system is complex and fuzzy, so it is difficult to judge the criticalities of various failure modes. Therefore, it is necessary to find an effective method for failure mode criticality assessment of the propeller shaft system.

Failure mode, effect and Criticality Analysis (FMECA) is a systematic reliability analysis program. FMECA is a step-by-step analysis of the possible failure modes of each component, the impact of each failure mode on the system and the risk level of failure consequences according to a certain format. Li
et al\[7\] analyzed the failure mode and criticality of spacecraft using FMECA method, calculating the criticality of each failure mode by using failure rate, failure mode frequency ratio, failure impact probability and working time, and guided the improvement. The results show that the reliability analysis by using FMECA method can prolong the service life of equipment and greatly improve operational availability. Wang et al\[8\] introduced FMECA method into the field of missile system design and maintenance, and evaluated the S-severity, O-occurrence and D-detection degree of failure mode by using the common risk coefficient method. Finally, the RPN value was obtained to guide the compilation of reliability centered maintenance analysis (RCMA) and maintenance program. Bennouk et al\[9\] thought that RPN value is difficult to truly reflect the criticality degree of failure mode. After considering the influence of environment, state and safety conditions on equipment, the CPN value was designed and used to evaluate the fault criticality of fans. The results show that FMECA considering CPN value can more accurately reflect the criticality degree between different failure modes of fans. After analyzing FMECA standards of different industries, Kim et al\[10\] extended the FMECA method. FMECA method can be well applied to rail transit braking system through adding MA method.

Traditional FMECA can be divided into qualitative analysis and quantitative analysis\[11-12\]. The qualitative analysis method evaluates the Failure Criticality level according to the occurrence probability of failure mode. This evaluation method often has no product technical data and failure rate data, and is more dependent on subjective judgment, so it is difficult to quantify the criticality level of different failure modes. The quantitative analysis method generally adopts criticality evaluation index method or RPN risk coefficient method to quantify the criticality degree of failure mode. However, both the criticality evaluation index method and the risk coefficient method are subjective and arbitrary, and they do not add weight to different influencing factors, so it is difficult to truly reflect the criticality of failure mode, and the evaluation results cannot be reproduced.

From the above analysis, it can be seen that there are many factors affecting the fault criticality of propeller shaft system, and there are fuzzy characteristics. The traditional FMECA method is difficult to accurately evaluate the criticality of each failure mode and its correlation. Therefore, this paper introduces a number of evaluation factors, sets weights for different influencing factors, and applies fuzzy mathematics evaluation and FMECA method to the criticality evaluation of propeller shaft system. Quantitative criticality assessment is carried out for each failure mode to provides theoretical reference for the design and maintenance of propeller shaft system.

2. Failure criticality evaluation of propeller shaft system based on traditional FMECA

The first step of FMECA is the system definition, which includes defining the analysis scope, determining the task function and establishing the block diagram (function block diagram or reliability block diagram). The second step is failure mode, effect and Criticality Analysis (FMEA), including the determination of product or function symbol, failure mode analysis, failure cause analysis, failure impact analysis, determination of severity level, etc. The third step is criticality analysis (CA). The risk coefficient method is used to analyze the criticality degree of each failure mode. According to the analysis results, the criticality degree of different failure modes is evaluated and ranked.

2.1. System definition

The propeller shaft system is generally composed of a series of complex parts such as propeller shaft, propulsion shaft section, thrust bearing and tunnel shaft bearing. In addition, the reliability block diagram of each part of the propeller shaft system is established, and the reliability relationship between the components is used to study the reliability of the propeller shaft system, so as to determine the influence of the component failure on the propeller shaft system.

2.2. FMECA of propeller shaft system

FMEA and CA are combined to carry out FMECA for propeller shaft system, and the information of each product or function mark, failure mode, cause failure, fault effect, severity and probability level of
occurrence are clarified. 8 components and 13 failure modes of propeller shaft system are analyzed. The results are shown in Table 1.

Table 1 FMECA of propeller shaft system

| Number | Product or function mark | Function | Failure mode | Cause of failure | Task stage and working mode | Fault effect | Severity | Probablility |
|--------|--------------------------|----------|--------------|------------------|-----------------------------|--------------|----------|-------------|
| F1     | Propulsion shaft section (intermediate shaft, propeller shaft) | Transfer torque and thrust | Plastic deformation | The material of shaft section does not meet the requirements | Continuous work | Incapacity to work | Propeller shaft system failure | The power system cannot complete the propulsion task | II | D |
| F2     | Fracture of shaft segment | Fracture | The material of shaft section does not meet the requirements | Continuous work | Partial loss of capacity | Propeller shaft system failure | The power system cannot complete the propulsion task | I | D |
| F3     | Main thrust bearing | Transfer torque and thrust | Excessiv e vibration | The temperature and pressure of lubricating oil are too high | Continuous work | Damage to equipment | Affect the performance of propeller shaft system | Impact on overall performance | III | C |
| F4     | | | Oil | Excessiv e vibration | Continuous work | Damage to equipment | Affect the performance of propeller shaft system | Impact on overall performance | III | D |
| F5     | Oil leakage | Poor sealing | Continuous work | Affect the normal operation of equipment | Affect the performance of propeller shaft system | Impact on overall performance | III | C |
| F6     | Oil temperature too high | | Continuous work | Damage to equipment | Increase shaft vibration | Impact on overall performance | III | C |
| F7     | Intermediate bearing Support shaft segment | Increased vibration abrasion of journal | Continuous work | Damage to equipment | Increase shaft vibration | Impact on overall performance | III | C |
| F8     | Oil leakage | Poor sealing | Continuous work | Affect the normal operation of equipment | Affect the performance of propeller shaft system | - | III | C |
### 2.3. Criticality assessment

The risk coefficient method is used in the criticality evaluation. The matrix of risk coefficient is shown in Table 2. In the matrix of risk coefficient, the severity categories I, II, III, IV and failure probability A, B, C, D and E are combined and expressed by 1-20. The smaller the number in the matrix of risk coefficient, the higher the criticality level. For the type I failure mode which will cause casualties or unit damage, if the probability level is A, then the risk coefficient is defined as 1; for the class IV failure mode which only leads to unplanned maintenance or repair, if the occurrence probability is level E, the risk coefficient is defined as 20, and other conditions are between 1 and 20.

**Table 2 Matrix of risk coefficient**

| Probability level | Severity |
|-------------------|----------|
|                   | I    | II   | III  | IV   |
| A                 | 1    | 3    | 7    | 13   |
| B                 | 2    | 5    | 9    | 16   |
| C                 | 4    | 6    | 11   | 18   |
| D                 | 8    | 10   | 14   | 19   |
| E                 | 12   | 15   | 17   | 20   |
In the criticality evaluation, each failure mode is evaluated according to the defined level, and the risk coefficient of each failure mode is obtained. The criticality evaluation result is shown in Table 3. And the rank of criticality of failure mode of propeller shaft system from high to low is \( F_2 > F_1 > F_3 = F_5 = F_6 = F_7 = F_8 = F_9 = F_{12} = F_{13} > F_4 > F_{10} > F_{11} \). From the above results, it can be seen that there are many failure modes with the same risk coefficient, and the traditional FMECA is difficult to distinguish the criticality level.

| Failure mode number | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 | F11 | F12 | F13 |
|---------------------|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|
| criticality level   | 10 | 8  | 11 | 14 | 11 | 11 | 11 | 11 | 11 | 19  | 19  | 11  | 11  |

3. Failure criticality evaluation of propeller shaft system based on Fuzzy FMECA

In order to distinguish the criticality level, the fuzzy mathematics comprehensive evaluation method combined with FMECA (fuzzy FMECA) was used to evaluate the failure mode criticality. The fuzzy FMECA method can quantify the fuzzy evaluation, and consider the weight of different factor sets to comprehensively evaluate the criticality of different failure modes, which has high discrimination and can truly reflect the criticality degree. The basic steps are shown in Figure 1. Firstly, FMECA is carried out. Secondly the factor set composed of different influencing factors of failure mode is established. Thirdly, the level set of factors is built to divide the criticality level. Fourthly, the fuzzy evaluation matrix is determined to ensure the fuzzy mapping relationship between the factor set and the factor level set. Fifthly, the weight set of each factor is determined to represent weight of different factors on fault criticality; finally, fuzzy comprehensive evaluation is carried out to rank the criticality degree of different failure modes.

Figure 1 basic steps of fuzzy FMECA

3.1. Establish factor set

The traditional FMECA method considers that the influence factors of failure mode criticality are severity and failure probability. For ship propeller shaft system, the main factors also include maintainability and testability. Therefore, the four influencing factors are \( u_1 \) severity, \( u_2 \) failure probability, \( u_3 \) maintainability and \( u_4 \) testability. The factor set is represented as follows:

\[
U_i = \{ u_1, u_2, u_3, u_4 \}
\]

3.2. Establish factor level set

The influencing factors are divided into four levels, namely \( v_1 \) very low, \( v_2 \) low, \( v_3 \) medium, \( v_4 \) high and \( v_5 \) very high. The factor levels in factor set are determined as shown in Table 4. The factor level set is expressed as follows:

\[
V_j = \{ v_1, v_2, v_3, v_4, v_5 \}
\]
### Table 4 factor level

| Factor set        | Factor level grade |
|-------------------|--------------------|
|                   | Very low | low | medium | high | Very high |
| Severity          | slight    | light | secondary | deadly | disaster |
| Failure probability | Difficult to happen | Hard to happen | secondary | Easy to happen | Very easy to happen |
| Maintainability   | Easy to maintain | Repairable | Difficult to maintain | Replacement of accessories | Unable to repair |
| Testability       | Predictable | Diagnosable | Can be monitored | Spot check | Difficult to test |

#### 3.3. Determine the fuzzy evaluation matrix

The membership degree of factor set to factor level set is determined by expert evaluation method, and fuzzy evaluation matrix $R$ is determined according to the evaluation results of 10 experts using factor level set $V$ to factor set $U$. Among the 10 experts, the frequency of $V_j$ in the evaluation of $U_i$ is $N_{ij}$, $N_{ij}/10$ is $R_{ij}$. Taking F1 failure mode as an example, 7 of 10 experts considered the severity level as deadly, 1 as disaster and 2 as secondary. Therefore, the fuzzy evaluation vector of severity is

$$R_1 = [0.0, 0.2, 0.7, 0.1]$$  \hspace{1cm} (3)

According to the evaluation, the evaluation vector of failure probability, testability and maintainability are respectively

$$R_2 = [0.3, 0.6, 0.1, 0.0]$$ \hspace{1cm} (4)

$$R_3 = [0.0, 0.2, 0.0, 0.8]$$ \hspace{1cm} (5)

$$R_4 = [0.4, 0.5, 0.1, 0.0]$$ \hspace{1cm} (6)

The fuzzy evaluation matrix of F1 can be obtained by summarizing the above evaluation vectors

$$R^1 = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.2 & 0.7 \\ 0.3 & 0.1 & 0 \\ 0 & 0.2 & 0.8 \\ 0.4 & 0.5 & 0 & 0 \end{bmatrix}$$  \hspace{1cm} (7)

#### 3.4. Establish factor weight set

The factor weight set is established by AHP (Analytic hierarchy process). The factor weight set represents the importance of different elements in each factor set, and the sum of factor weight sets is 1. The factor weight set is expressed as follows:

$$A = [a_1, a_2, a_3, a_4], \sum_{i=1}^{4} a_i = 1, \ 0 \leq a_i \leq 1$$  \hspace{1cm} (8)

First, the important relationship between different elements in the factor set is determined. When $u_i$ is slightly important, generally important and extremely important compared with $u_j$, its scale values are 3, 5, and 7, respectively. The scale values of different elements are defined as shown in Table 5.

### Table 5 scale value matrix

|       | U1 | U2 | U3 | U4 |
|-------|----|----|----|----|
| U1    | 1  | 3  | 5  | 7  |
| U2    | 1/3| 1  | 3  | 5  |
| U3    | 1/5| 1/3| 1  | 3  |
| U4    | 1/7| 1/5| 1/3| 1  |

Therefore, the judgment matrix is
Then the maximum eigenvalue $\lambda_{\text{max}}$ of the judgment matrix is 4.117. The corresponding eigenvector is $x = [0.888, 0.4121, 0.1847, 0.0869]$. The final factor weight set is obtained by normalizing the eigenvector.

$$A = [0.5650, 0.2622, 0.1175, 0.0530]$$

Finally, consistency judgment is made. When the judgment results meet the requirements of consistency, it can be used as an effective evaluation, otherwise the judgment matrix needs to be reconstructed. CI is the general consistency index, RI is the random consistency index, taking 0.9. CR is the test coefficient.

$$CI = \frac{\lambda_{\text{max}} - n}{n-1}$$

$$CR = \frac{CI}{RI}$$

According to the calculation, $CR = 0.043 < 0.1$, Therefore, the judgment matrix meets the requirements of consistency.

### 3.5. Fuzzy comprehensive evaluation

The fuzzy comprehensive evaluation of the criticality of the failure mode of the propeller shaft system is carried out in this section. Firstly, fuzzy evaluation matrix and factor weight set are used to calculate fuzzy comprehensive evaluation vector.

$$B^1 = A \cdot R^1 = [0.1008, 0.1805, 0.1683, 0.3955, 0.1505]$$

The weighted values of the criticality of the five factor level sets are defined as 1, 2, 3, 4, 5, respectively. Then weighted matrix is $H = [1, 2, 3, 4, 5]^T$. Then the final fuzzy comprehensive evaluation value is $U^1 = B^1 \cdot H = 3.3100$. Using the same method, the fuzzy evaluation matrix under other failure modes is calculated as follows.
The fuzzy comprehensive evaluation vectors $B^2 \sim B^{13}$ of each failure mode are calculated by keeping the factor weight set $A$ unchanged. Finally, the fuzzy comprehensive evaluation values were $3.6805, 2.6304, 2.6180, 2.7196, 2.5739, 2.6085, 2.6631, 2.7974, 2.1877, 2.0863, 2.9663$ and $2.9886$, respectively. Therefore, the rank of the criticality of failure mode from high to low is $F_2 > F_1 > F_{13} > F_{12} > F_9 > F_5 > F_8 > F_3 > F_4 > F_7 > F_6 > F_{10} > F_{11}$.

It can be seen that the fuzzy FMECA method can be used to quantify the criticality of the propeller shaft system failure mode, so as to avoid the situation that the evaluation results of multiple failure modes are the same using the traditional method; in addition, the fuzzy FMECA method can consider multiple influencing factors, such as maintainability, testability, etc., to form the factor set, and can add weight to each factor so that criticality of failure mode can be considered comprehensively. And, the opinions of several experts can be integrated to make the final criticality assessment results accurate, reliable and repeatable.

4. Conclusion
Propeller shaft system is an important device of ship power output, which plays an important role in ship navigation. However, the components of propeller shaft system are complex, there are many failure modes and there are fuzzy characteristics. In this paper, fuzzy FMECA method is used to put forward four evaluation indexes: severity, probability, testability and maintainability. The weight value of each influencing factor is determined based on AHP, and the fuzzy comprehensive evaluation is carried out to realize the criticality ranking of 13 failure modes. Compared with the traditional FMECA method, the fuzzy FMECA method can expand the influencing factors and add weight set to evaluate the criticality of failure modes comprehensively. In addition, the fuzzy FMECA method can make the criticality assessment more accurate, and solve the problem that many failure modes have the same criticality degree in traditional methods. In addition, the opinions of many experts are integrated in the evaluation process, which reduces the subjectivity and limitations in the evaluation process, and makes the evaluation results more universal and repeatable. In conclusion, the fuzzy FMECA method can effectively evaluate the criticality degree of the propeller shaft system failure mode, and the evaluation results can be used as an important reference in the ship design and repair, to guide the improvement of the propeller shaft system reliability weak link, and to ensure the safe navigation of the ship.

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References

[1] Qi, L.B., Song, Q.M., Xiao, Z.S., Yue, L. (2019) Use of impedance mismatch in the control of coupled acoustic radiation of the submarine induced by propeller-shaft system. Marine Structures, 65:249-258.

[2] Li, C.Y., Liu, N.N., Su, J.P., Hua, H.X. (2019) Vibro-acoustic responses of a coupled propeller-shaft-hull system due to propeller forces. Ocean Engineering, 173:460-468.

[3] He, J.Y., Li, Y., Cao, J., Li, Y.M., Jiang, Y.Q., An, L. (2020) An improved particle filter propeller fault prediction method based on grey prediction for underwater vehicles. Transactions of the Institute of Measurement and Control, 42(11):1946-1959.

[4] Zhang, S., Fan, L.T., Gao, J.W., Pu, J.X., Xu, K.Q. (2018) Fault Diagnosis of Underwater Vehicle and Design of Intelligent Self-rescue System. Journal of Coastal Research, 42(11):1946-1959.

[5] Zheng, H.C., Xiao, F.S., Yuan, L.H. (2017) A Brief Discussion about Nickel Aluminum Bronze Propeller Failure Modes and its Repair Methods. Key Engineering Materials, 4332:125-129.

[6] Benjamin, P., Murat, Y.N., Gebraeel, K.P. (2020) Severity-based diagnosis for vehicular electric systems with multiple, interacting failure modes. Reliability Engineering and System Safety, 195.

[7] Li, J., Xu, H.B. (2012) Reliability Analysis of Aircraft Equipment Based on FMECA Method. Physics Procedia, 25:1816-1822.

[8] Wang, K. (2018) Research on Application of FMECA in Missile Equipment Maintenance Decision. In: IOP Conference Series: Materials Science and Engineering. Shanghai. pp. 15-17.

[9] Bennouk, A., Nejmi, A. (2018) Wind turbine failures analysis based on performances study and FMECA. In: 4th International Conference on Optimization and Applications. Mohammedia. pp. 1-6.

[10] Kim, J.H., Jeong, H.Y., Park, J.S. (2009) Development of the FMECA process and analysis methodology for railroad systems. International Journal of Automotive Technology, 10(6):753-759.

[11] Siswantoro, N., Priyanta, N., Zaman, D., Semin, M.B. (2020) Failure Mode and Effect Criticality Analysis (FMECA) Fuzzy to Evaluate Critical Level on Main Engine Supporting System. In: IOP Conference Series: Earth and Environmental Science. Surabaya. pp. 012-016.

[12] Ilyas, M., Silvia, C., A, Certa., Zoubir E.F., Joaquín, I. (2020) Assessing Supply Chain Risks in the Automotive Industry through a Modified MCDM-Based FMECA. Processes, 8(5):579.