The Fault Criticality Analysis of Missiles Based on Multi-level Fuzzy Comprehensive Evaluation Theory

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Abstract. To solve the problem that the FMECA of missiles is difficult to be quantified and the indicators are diverse, a method to describe the fault criticality of missiles based on multi-level fuzzy comprehensive evaluation theory is proposed. In this paper, a television guidance missile is taken as an example, factor sets, evaluation sets, weight sets, comprehensive evaluation based on multi-level fuzzy theory of missile is established. A comprehensive evaluation indicator $C_i$ is proposed to quantitatively describe the fault criticality of missiles. This method is exact and effective to solve the problem of indicator diversity, and can provide basis for reliability research of missiles.

1. Introduction
With the rapid development of complexed weapon equipment, the cost of logistical support and the probability of fault becomes higher and higher [1]. The reliability of these complexed weapon equipment has been placed high value on. At present, the FMECA method and the artificial judgement method are mixed for our reliability analysis of complexed weapon equipment. Nevertheless, the mixed method has the problem that the FMECA of complexed weapon equipment is difficult to be quantified and the indicators are diverse, which results in the inaccuracy of reliability analysis. So how to use a kind of new method to get rid of the fuzziness and quantify the fault criticality of complexed weapon equipment has aroused popular attention [2-5].

In recent years, a kind of reliability analysis of complexed weapon equipment based on multi-level fuzzy comprehensive evaluation method is very hot. The multi-level fuzzy comprehensive evaluation method, based on subjection degree theory in fuzzy math, is applied to give comprehensive evaluation for complexed research objects which are restricted by various factors [6]. This method has many advantages such as easy to know, strong systematicness and multi-level analysis, which can solve the problem of FMECA quantitation difficulty of complexed weapon equipment properly.

Aiming at the problems that the FMECA of complexed weapon equipment is difficult to be quantified and the indicators are diverse, in this paper, a method to describe the fault criticality of missiles based on multi-level fuzzy comprehensive evaluation theory is proposed. We take a kind of complexed weapon equipment, a television guidance missile, as an example to establish factor sets, evaluation sets, weight sets, comprehensive evaluation based on multi-level fuzzy theory. Furthermore, a comprehensive evaluation indicator is proposed to quantitatively describe the fault criticality of missiles, which can provide basis for reliability research of the missile.
2. Steps of multi-level fuzzy comprehensive evaluation

According to different research objects, the level of fuzzy comprehensive evaluation we need is also different. In general, before the comprehensive evaluation is received, there are several steps need to finish. Firstly, the fuzzy evaluation of single factors and first-level fuzzy evaluation for low-level factors of system are essential. Secondly, according to the evaluation requirements, considering whether can we regard the first evaluation results as the factor in the second-level fuzzy evaluation. And the rest can be done in the same manner. The specific steps can be described as:

1. Establish factor sets of the evaluation object

Factor sets are the assemble of all factors which influence the evaluation object. We used \( U \) to represent it generally

\[
U = \{u_1, u_2, \ldots, u_i, \ldots, u_n\}
\]  

(1)

\( u_i (i = 1, 2, \ldots, n) \) represents the \( i_{th} \) factor element.

2. Establish weight sets of the influence factors

We define \( A = \{a_{ij}\}_{i \times n} \) as the judgement matrix. To set more scientific weight sets, ratio scale method [7] is introduced to construct the judgement matrix

\[
A = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}
\]  

(2)

\( a_{ij} (i, j = 1, 2, \ldots, n) \) is the importance degree for \( u_i \) to \( u_j \). In the ratio scale method, Nine-scale quantitation Standard is usually used to judge the relative importance degree, which is shown in Table 1. The conclusion is obvious that \( a_{ij} = 1/a_{ji} (i, j = 1, 2, \ldots, n) \), \( a_{ii} = 1(i = 1, 2, \ldots, n) \).

Table 1. Nine-scale quantitation Standard

| \( a_{ij} \) | Evaluation standard |
|-----------|---------------------|
| 1         | \( u_i \) and \( u_j \) are the same important |
| 3         | \( u_i \) is a little more important than \( u_j \) |
| 5         | \( u_i \) is obviously more important than \( u_j \) |
| 7         | \( u_i \) is much more important than \( u_j \) |
| 9         | \( u_i \) is extremely more important than \( u_j \) |
| 2 or 4 or 6 or 8 | the importance of \( u_i \) comparing with \( u_j \) between the above two scales |

3. Establish evaluation sets

Evaluation sets are the assemble of all evaluation results for different research objects. We used \( V \) to represent it generally

\[
V = \{v_1, v_2, \ldots, v_j, \ldots, v_m\}
\]  

(3)

\( v_j (j = 1, 2, \ldots, m) \) represents the \( j_{th} \) evaluation result.
(4) Fuzzy evaluation for single factors
Fuzzy evaluation for single factors is used for factor sets to evaluate the subject degree to evaluation sets. The common method is to set up an expert panel with $f$ people, every expert gives an evaluation level $v_j$ to influence factor in the failure mode $k$. If $f_j$ people evaluate $u_i^k$ belongs to $v_j$, then the evaluation set $u_i^k$ can be described as

$$R^k = \left[ \frac{f_{11}^k}{f}, \frac{f_{12}^k}{f}, \ldots, \frac{f_{1m}^k}{f} \right] \quad f_j^k (j = 1, 2, \ldots, m) \geq 0$$

(4)

To describe the fuzzy relationship between $U$ and $V$, the fuzzy evaluation for single factors matrix is introduced and can be defined as

$$R^k = \begin{bmatrix}
\frac{f_{11}^k}{f} & \frac{f_{12}^k}{f} & \cdots & \frac{f_{1m}^k}{f} \\
\frac{f_{21}^k}{f} & \frac{f_{22}^k}{f} & \cdots & \frac{f_{2m}^k}{f} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{f_{n1}^k}{f} & \frac{f_{n2}^k}{f} & \cdots & \frac{f_{nm}^k}{f}
\end{bmatrix}$$

(5)

(5) first-level fuzzy evaluation
Fuzzy evaluation for single factors only reflect the influence of the different independent factors to research object. To improve the scientificity and rationality of evaluation results, every factor influence should be taken into consideration. The fuzziness transform is needed for $R^k$ and weight sets which have been normalized. The first-level fuzzy evaluation matrix can be described as

$$B^k = w^k \cdot R^k = (\frac{w_1^k}{f}, \frac{w_2^k}{f}, \ldots, \frac{w_n^k}{f}) \cdot \begin{bmatrix}
\frac{f_{11}^k}{f} & \frac{f_{12}^k}{f} & \cdots & \frac{f_{1m}^k}{f} \\
\frac{f_{21}^k}{f} & \frac{f_{22}^k}{f} & \cdots & \frac{f_{2m}^k}{f} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{f_{n1}^k}{f} & \frac{f_{n2}^k}{f} & \cdots & \frac{f_{nm}^k}{f}
\end{bmatrix} = (b_1, b_2, \ldots, b_n)$$

(6)

(6) The indicator for fuzzy comprehensive evaluation
For more visualized evaluation results, weighting $B^k$ is needed after we receive it. To improve the influence of maximum subject degree, $b_j^k$ is taken as the weight, a weighted average of $v_j$ is undertaken. Then the indicator $C^k$ for fuzzy comprehensive evaluation is received, the criticality increases with the rise of $C^k$ value. $C^k$ can be calculated by $B^k$ and $V$, the value is

$$C^k = \frac{\sum_{j=1}^{n} (b_j^k \cdot v_j)}{\sum_{j=1}^{n} b_j^k}$$

(7)
(7) The multi-level fuzzy comprehensive evaluation
For complexed weapon equipment, the whole equipment is composed of many multi-level subsystems. During the multi-level fuzzy comprehensive evaluation, the first-level fuzzy evaluation for failure modes in the low-level is needed first, and then the first-level fuzzy comprehensive evaluation matrices $B^1, B^2, \cdots, B^k$ and the fuzzy comprehensive evaluation indicators $C^1, C^2, \cdots, C^n$ are received. Secondly, the low-level failure modes are taken as the new factor set of the second-level fuzzy comprehensive evaluation, $V$ is the same. The new influence factor weight set can be solved by AHP method, and the second-level fuzzy comprehensive evaluation can be undertaken by fuzzy comprehensive evaluation method. And the rest can be done in the same manner. Finally, the multi-level fuzzy comprehensive evaluation of whole equipment can be received.

3. The fault criticality analysis of a television guidance missile
We take the failure mode “no image putout” of a television guidance as an example to verify the multi-level fuzzy comprehensive evaluation method. The FMEA analysis results is shown in Table 2.

| No. | Component          | Failure mode                                                                 | Test method                                      | Maintenance strategy     | Severity |
|-----|--------------------|------------------------------------------------------------------------------|--------------------------------------------------|--------------------------|----------|
| 1   | image transmitter  | Image transmitter has no image output.                                       | Break the plug and test the output signal of image transmitter | replace Control cabinet  | II       |
| 2   | image amplifier    | The output of the image amplifier is abnormal                                | Test the image amplifier output signal           | replace image amplifier  | III      |
| 3   | test cables        | Low reliability of cables connection                                         | break the plug and check the image output signal | check the plug or replace test cables             | IV       |
| 4   | image transmitting antenna | The faults of the transmitting antenna                                      | Recheck image signal after replace antenna      | replace image transmitting antenna               | III      |

Based on FMECA, the specific steps of fuzzy comprehensive evaluation are
(1) Establish factor sets of the evaluation object
The factor set adopted by fault criticality evaluation of television guidance can be represented as $U = \{\text{fault probability } u_1, \text{severity } u_2, \text{test difficulty } u_3, \text{maintainability } u_4\}$
(2) Establish weight sets of the influence factors
We define the “Image transmitter has no image output”, “The output of the image amplifier is abnormal”, “Low reliability of cables connection”, “The faults of the transmitting antenna” as failure mode 1, failure mode 2, failure mode 3 and failure mode 4. The relative importance degree distribution of different influence factors in failure 1 is shown in Table 3.
Table 3. The relative importance degree distribution of different influence factors in failure 1

| factor | $u_1$ | $u_2$ | $u_3$ | $u_4$ |
|--------|-------|-------|-------|-------|
| $u_1$  | 1     | 2     | 7     | 5     |
| $u_2$  | 1/2   | 1     | 6     | 4     |
| $u_3$  | 1/7   | 1/6   | 1     | 1/2   |
| $u_4$  | 1/5   | 1/4   | 2     | 1     |

The judgement matrix of failure mode 1 is

$$A_1 = \begin{bmatrix} 1 & 2 & 7 & 5 \\ 1/2 & 1 & 6 & 4 \\ 1/7 & 1/6 & 1 & 1/2 \\ 1/5 & 1/4 & 2 & 1 \end{bmatrix}$$

The eigenvalue of $A_1$, $\lambda_{max} = 4.0453$, and the relative weight of different factors in the failure mode 1 is calculated. And the other three failure modes can be done in the same manner. After the normalization of the four failure modes, the eigenvalue weight is received

$$W^1 = (0.5124, 0.3298, 0.0586, 0.0992)$$
$$W^2 = (0.5542, 0.2912, 0.0974, 0.0572)$$
$$W^3 = (0.5780, 0.2611, 0.0627, 0.0982)$$
$$W^4 = (0.5531, 0.2685, 0.1201, 0.0583)$$

(3) Establish evaluation sets

The evaluation result is divided into four class $V = \{1, 2, 3, 4\}$, the evaluation class classification of different factors is shown in the Table 4.

Table 4. The evaluation class division of different factors

| factor          | class classification       |
|-----------------|---------------------------|
|                 | 1     | 2     | 3     | 4     |
| $u_1$ hardly happened | Sometimes happen | usually happen | frequent happen |
| $u_2$ hardly influence   | Little danger   | medium danger  | deadly danger  |
| $u_3$ accurate test     | trouble to test  | hard to test   | fail to test   |
| $u_4$ simple adjustment | reassembled   | replace element | replace system |

(4) Fuzzy evaluation for single factors

By the comprehensive evaluation of experts, for failure mode 1, the fuzzy evaluation set of fault probability $R^1_1 = [0.2, 0.6, 0.2, 0.0]$, the fuzzy evaluation set of severity $R^1_2 = [0.0, 0.1, 0.7, 0.2]$, the fuzzy evaluation set of test difficulty $R^1_3 = [0.6, 0.3, 0.1, 0.0]$, the fuzzy evaluation set of maintenance
4. Conclusion

Aiming at the problems that the FMECA of complexed weapon equipment is difficult to be quantified and the indicators are diverse, in this paper, a method to describe the fault criticality of missiles based on multi-level fuzzy comprehensive evaluation theory is proposed. We take a kind of complexed weapon equipment, a television guidance missile, as an example to establish factor sets, evaluation sets, weight sets, comprehensive evaluation based on multi-level fuzzy theory. Furthermore, a comprehensive evaluation indicator is proposed to quantitatively describe the fault criticality of missiles, which can provide basis for reliability research of the missile.

5. References

[1] PENG Y, LIU D T. Data-driven prognostics and health management: A review of recent advances [J]. Chinese Journal of Scientific Instrument, 2014, 35 (3): 481-495.

[2] SUN W C, LI W H, LI W F. Avionic Fault Diagnosis Based on Rough Set and D-S Theory [J]. Journal of Beijing University of Aeronautics and Astronautics, 2015, 41 (10): 1902-1909.
[3] ZHENG N, ZGANG L, TANG Y, et al. Research on Fault Diagnosis of Complex Equipment Based on Wavelet Transformation and Support Vector Machine [J]. Fire Control and Command Control, 2016, 41 (6): 104-107.

[4] ZHANG Z, YUAN Y H, JIAN D D. Research on Application of Mechanical and Electrical Equipment Fault Diagnosis Signal of the Self-Healing System [J]. Computer Simulation, 2015, 32 (4): 450-454.

[5] GUO T, YU H T, XIAO L, et al. Application of Probabilistic Neural Network in Fault Diagnosis of Weapon Equipment [J]. Ordnance Industry Automation, 2015, 34 (6): 10-13.

[6] ZHOU A M. Research on the Management and Application of Multi-Source Heterogeneous Knowledge for Wind Turbines Based on Ontology [D]. HUNAN: HUNAN University, 2014.

[7] GAO M, WANG J Z, LIN Y, et al. Reliability Analysis of Guided Ammunition Based on Fuzzy FMECA [J]. Equipment Environment Engineering, 2013, 10 (6): 127-130.