Reliability Evaluation of Bogie Assembly Process Based on FMEA-FTA

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Abstract. Assembly is crucial in the manufacturing of complex products, and assembly quality directly affects product quality. In order to verify the assembly reliability of high-speed train bogies, taking the drive device as a research object, the assembly reliability of the drive device was evaluated and the weak links in the assembly process were obtained based on the comprehensive analysis method of FMEA-FTA. And an assembly process visualization system was developed to realize the real-time monitoring of the assembly process and improve the reliability of the assembly process. It has certain reference significance for the reliability evaluation of assembly process of similar complex products.

Keywords. Bogie, drive device, assembly reliability, PFMEA, FTA

1. Introduction
Nowadays, the influence of high-speed trains in the field of public transportation is growing. Bogies, as the core components of high-speed trains, are a key part to ensure the safety, comfort and reliability of trains. Studies show that 60% of the quality problems in trains come from the bogie manufacturing process [1], and bogie assembly is a key link in the manufacturing process, so the reliability of the assembly process of the bogies is particularly important. LA Shah [2] studied the process-oriented risk assessment methods in the manufacturing process, D. Antonelli [3] studied the prediction and prevention of errors in the human-machine collaborative assembly process, and ZHANG [4] studied the modularized fault tree modeling and multi-dimensional mapping of assembly reliability. GAO[5] and HUANG[6] studied the assembly reliability of CNC machine tools. Based on the theoretical research of FMEA and FTA, the comprehensive analysis method of FMEA-FTA is applied to the assembly process of the bogie drive device, and the reliability of the assembly process is analyzed, which has certain reference significance for the study of the assembly reliability of large equipment.

2. PFMEA of drive device
FMEA [7] is a systematic reliability analysis program. It determines the potential failure modes and the causes and effects of each failure mode of components, equipment and software in the design and manufacturing process through systematic analysis, and finds out potential weaknesses and provides suggestions for improvement. FMEA plays an important role in reliability, maintainability, supportability, testability, and safety analysis.

FMEA mainly includes DFMEA and PFMEA. DFMEA analyzes the failures that may occur during the product design stage. PFMEA analyzes potential failures in the manufacturing, assembly or logistics
process. The purpose of PFMEA is to find the weak links of each process step in the production process in the absence of product design defects, and provide measures to improve product quality and reliability.

The PFMEA implementation process can be summarized as the "seven-step method": planning and preparation; structural analysis; functional analysis; failure analysis; risk analysis; optimization; documenting the results.

The risk analysis results are scored with S, O and D. S is the severity, O is the occurrence, and D is the detection. The scores of the three are from 1 to 10. The higher the score, the greater the risk [8].

The PFMEA of the bogie drive device is established based on the above theory, and the results are shown in the table 1.

**Table 1. PFMEA of drive device assembly.**

| Process element | Failure mode | Cause of failure (5M1E) | Effect of failure | S | O | D | A | P |
|-----------------|--------------|-------------------------|------------------|---|---|---|---|---|
| Drive gear assembly | Excessive radial or end face run-out of the coupler | Operation error; measuring instrument failure | Not running smoothly | 4 | 3 | 3 | L |
| | Inflexible bearings | Improper installation | | | | | | |
| | The distance between the end face of the coupling and the flange surface of the gear box is unqualified | Worn positioner; inaccurate measuring tool | Affect subsequent assembly | 4 | 4 | 3 | L |
| | Bearing radial or axial clearance is unqualified | Improper installation; inaccurate measuring tools | Affect work performance | 4 | 4 | 3 | L |
| | The bearing box and the gear box do not fit tightly | Irregular operation | | | | | | |
| | The bearing inner ring and the gear do not abut | Incorrect installation temperature | Affect work performance | 4 | 3 | 3 | L |
| Driven gear assembly | Bearings are not installed properly | Bearings are not pretreated | Unable to cooperate, unstable working performance | 4 | 2 | 3 | L |
| | The seal is installed in the wrong direction | Seal ring is not easy to identify | Drive device leak oil | 6 | 5 | 4 | L |
| | Bearing radial or axial clearance is unqualified | Improper installation; inaccurate measuring tools | Drive device leak oil | 4 | 4 | 3 | L |
| | Gear lateral clearance is unqualified | Incorrect fixture; inaccurate measuring tools | Transmission is not smooth | 4 | 4 | 3 | L |
| Hollow shaft assembly | Rubber joint press fitting error | Operator error; failure of hydraulic press | Affect work performance; scrap parts | 4 | 2 | 3 | L |
| | Incorrect bolt tightening sign | Tightening torque is unqualified | Unable to read information | 2 | 2 | 2 | L |
Wheelset press fitting

- The distance between shaft shoulder and hub’s end face is unqualified: Improper positioning; failure of hydraulic press
- The inside distance of the wheelset is unqualified: Improper positioning; failure of hydraulic press

Axle box assembly

- Dust intrusion: Substandard operating environment
- Labels are missing or defective: Operator negligence

Motor cable assembly

- Wire length is unqualified: Irregular operation; faulty measuring
- Circuit failure: Wire number error

Motor assembly

- The gap between the motor and the gearbox is unqualified: Improper installation; faulty measuring
- Labels are missing or defective: Operator negligence

Drive device oil leakage

- Seal ring installation failed: Rework; reassembly
- Improper bearing installation; thermometer malfunction: Affect work performance and scrap parts

Bearing temperature rise is too high

- Loose bolts; unqualified lubricant: Affect work performance and scrap equipment

Excessive vibration

In the old FMEA standard, the risk priority number (RPN) \( [9-10] \) is the product of S, O and D, ranging from 1 to 1,000. The RPN distribution can provide some information about the rating range, but RPN alone cannot determine whether more measures need to be taken because RPN has equal weight of S, O and D. Therefore, RPN may have the same risk priority number for different combinations of S, O and D, making it impossible for the team to determine how to prioritize. Therefore, an Action Priority (AP) method is proposed. This method also provides all 1000 possible combinations of S, O and D, but the method focuses on the severity first, then the occurrence, and finally the detection. The assessment results of the AP are divided into three levels H, M and L. H indicates that measures need to be taken for improvement, M indicates that measures should be taken for improvement, and L indicates that measures could be taken for improvement.

It can be known from the table that the reliability level of the assembly process of the drive device is relatively high, and the failure mode of oil leakage is the item that takes priority to improve. In order to further determine the basic cause of oil leakage, the fault tree analysis of the drive device oil leakage is performed below.

3. Fault tree analysis

Fault tree analysis is a result-to-cause analysis method. When used, it can find the related causes, conditions, and laws according to the possible accidents or the results of the accidents that have occurred. It can also identify the source of danger that caused the accident. Taking the drive device oil leakage as the top event and listing all the causes that may cause this fault, so as to build a fault tree, as shown in the figure 1. The meaning of each symbol in the figure is listed in the table 2.
Figure 1. Fault tree of drive device oil leakage.

Table 2. The meaning of symbol in fault tree.

| Symbol | Event name                                      |
|--------|------------------------------------------------|
| T      | Drive device oil leakage                       |
| M₁     | Oil leakage at drive gear                      |
| M₂     | Oil leakage at driven gear                     |
| M₃     | Oil leakage at the end cap                     |
| M₄     | Oil leakage at the bearing cap                 |
| M₅     | Oil leakage at the coupler                     |
| M₆     | Driven gear assembly’s seal ring fail          |
| M₇     | End cap’s seal ring fail                       |
| M₈     | Bearing cap’s seal ring fail                   |
| M₉     | Coupler’s seal ring fail                       |
| M₁₀    | Labyrinth seal ring fail                       |
| X₁     | Bearing cap’s bolts are not tightened          |
| X₂     | Bearing cap’s seal ring is not embedded in the groove |
| X₃     | Bearing cap’s seal ring is missing             |
| X₄     | Oil retaining ring installed incorrectly       |
| X₅     | Bearing box’s seal ring is missing             |
| X₆     | Labyrinth cap’s seal ring installed incorrectly|
| X₇     | Centrifugal ring’s seal ring installed incorrectly |
bly process, the detection and occurrence of process failure mode have been greatly optimized. Then provide data support for later time, and highlight key components and error-prone links in the assembly process, the detection and occurrence of process failure mode have been greatly optimized. Then provide data support for later
digital transformation.

Using Boolean algebra to find the minimum cut set. The OR gate of the fault tree corresponds to the logical sum and the AND gate corresponds to the logical product. For the fault tree in the figure above:

\[
Z = M_1 + M_2 + M_3,
\]

\[
= (M_4 + M_5) + (M_6 + X_{11}) + (M_7 + X_{14})
\]

\[
= (M_4 + X_2 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9 + X_{10} + X_{11})
\]

\[
= X_2 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14}
\]

From the above Boolean algebra solution results, we know that there are 11 minimum cut sets for the Drive device oil leakage fault tree, which are \(X_1 \cdot X_2\), \(X_3\), \(X_4 \cdot X_5\), \(X_4 \cdot X_6\), \(X_4 \cdot X_7\), \(X_8\), \(X_9\), \(X_{10}\), \(X_{11}\), \(X_{12} \cdot X_{13}\), \(X_{14}\). There are 6 first-order minimum cut sets and 5 second-order minimum cut sets. The impact importance of the first-order minimum cut set to the top event is greater than the second-order minimum cut set. \(X_4\) appears repeatedly in the second-order minimum cut set. Therefore, \(X_3\), \(X_8\), \(X_9\), \(X_{10}\), \(X_{11}\), \(X_{14}\) are the most important, \(X_4\) are the second most important, and the remaining events are the least important.

4. Optimization measures

According to the above analysis results, during the entire assembly process of the drive device, the assembly quality of the sealing ring directly determines the assembly quality of the drive device. In order to improve the assembly reliability of the drive device, for but not limited to the quality of the seal ring installation, an assembly process visualization system is setting up, as is shown in Figure 2. The system mainly includes 3 functional modules: assembly process simulation module, intelligent tool interaction module, and operation information storage module.

(1) The main function of the assembly process simulation module is replace the physical prototype with virtual prototype, and visually simulate the entire assembly process in a computer virtual environment. During the simulation, the current parts and their key geometric elements are highlighted. Special technical requirements are displayed in the user interface by text, to avoid rework problems such as wrong component installation orientation and so on.

(2) The main purpose of the intelligent tool interaction module is introduce intelligent tool to realize the real-time interaction, which makes the operation more convenient and efficient. Operation information is more visualized such as bolt torque, etc. At the same time, the switching between the upper and the lower processes is also realized by intelligent remote sensing equipment, to avoid the error of part assembly sequence and so on.

(3) The main function of the operation information storage module is to record a series of operation data generated by the worker during the actual assembly process, including working hours and technical parameters. Then output them as separate data file, or transfer them directly to a corporate database, which realized the traceability of information and provided the underlying data support for enterprise digital transformation.

In summary, based on virtual simulation, this system can monitor the user’s operation process in real time, and highlight key components and error-prone links in the assembly process, the detection and occurrence of process failure mode have been greatly optimized. Then provide data support for later
information traceability, thereby improving the reliability of the entire assembly process and even the entire life cycle of the product.

![Figure 2. Assembly process visualization system.](image)

5. Conclusion
This article applies the FMEA-FTA comprehensive analysis method to the assembly reliability evaluation of the bogie drive device, finds out the potential weak links of the equipment in the assembly process, and plans to build an assembly process visualization system to realize the real-time monitoring and improves assembly process reliability. It has certain reference significance for the reliability evaluation of assembly process of similar complex products.

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