Reliability Analysis of Certain Rocket Engine Based on Fault Tree

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Abstract. In this paper, a fault tree model of certain rocket engine is established according to its structure and working principle. Through qualitative analysis and quantitative calculation, the factors affecting the reliability of a certain type of rocket engine are obtained, and the corresponding improvement measures are put forward to improve the reliability and safety of a certain type of rocket engine.

1. Introduction
A fault tree is a logical diagram used to mark out the failure of certain components of a product or external events or their combination that will cause a given fault of the product [1, 2]. It is a special inverted tree logic diagram of causal relationship, with events and logic gates are the compositional elements.
Fault Tree Analysis (FTA, for short) takes an undesired product failure event (or catastrophic product hazard) as the top objective for analysis [3]. By using rigorous top-down failure analysis with cause-and-effect logic [4], the necessary and sufficient direct causes of fault events based on deductive reasoning will be hierarchically found out, and all the causes and “cause packs” of the top event will be finally exposed. Calculate the occurrence probability of the top events, and try to reduce the occurrence rate through design improvement and implementation of effective fault detection, maintenance and other measures. Suggestions for product improvement will also be provided, which can be used for fault diagnosis and safety analysis. FTA will be helpful in analyzing the impact of the combined multiple fault factors on the product [5].
A certain type of rocket engine is of high reliability, which determines the life safety of the pilot in emergency ejection [6]. In this paper, FTA is used to analyze the reliability of a certain type of rocket engine, hoping to further confirm its reliability as well as the safety of pilot under emergency.

2. Establish the Fault Tree of A Certain Type of Rocket Engine

2.1. A Certain Type of Rocket Engine Works
When the ejection seat is preparing for ejection [7], the remote ignition system and the process control system will, at the same time, respectively gives an igniting signal to the gas ignition device and
electric ignition device of a certain type of rocket engine. As soon as the black powder is ignited, the high temperature and high pressure gas will ignite the major fuel grain and start the rocket engine, promoting the pilot and the ejection seat rise continuously to the life-saving height.

2.2. FTA Procedure for A Certain Type of Rocket Engine
The FTA program of a certain type of rocket engine is shown in Fig. 1 which mainly includes relevant technical data and information prepared before FTA implementation [8, 9], such as project design report, failure modes and effects analysis (FMEA, for short) report, fault history data, etc; reasonable top events determined according to FMEA analysis results; the establishment of a fault tree and all the causing fault patterns; qualitative analysis through downlink method, up-link method or software instruments, obtaining all the minimum cut sets; the occurrence rate of top event and the importance of basic event according to the occurrence rate of basic event; and the design improvement to weak-links of the product, for improving the reliability of the certain type of rocket engine.

![Fault tree qualitative analysis](image)

Figure 1. FTA procedure for a certain type of rocket engine.

2.3. Construction of A Certain Type of Rocket Engine Fault Tree
According to the FMEA carried out to a certain type of rocket engine, the critical fault modes (1 severe degree of failure mode) that affecting safety and the success of tasks as well as the corresponding outcomes will be found out as top event, namely, the selected top event of a certain type of rocket engine is that the certain type of rocket engine is not able to provide thrust force. A top-down search will be carried out grade by grade according to the selected top event, various basic cause events will be found out and linked by appropriate logical gate symbols [10], so as to complete the establishment of the fault tree of a certain type of rocket engine top event, in which the Isograph was used, seeing Figs. 2 and 3.

3. FTA for A Certain Type of Rocket Engine

3.1. Qualitative Analysis
The task of qualitative analysis is to collect all the minimum cut set of fault tree. Minimum cut set has the minimum number of basic events, which means it will not be a cut set any more if any discard of the basic event happens. Many methods can be adopted to find the solution of the minimum cut set, among which upward method and downward method are most commonly used. However, for complex fault trees, commercial FTA software are often applied. As the fault tree of the certain type of rocket engine was built with Isograph software, this software will be directly used to calculate the minimum cut set of the top event of certain rocket engine (as shown in Table 1).

It can be seen from Table 1 that there are in total 19 top-event minimum cut sets of certain rocket engine, among which 9 are first-order minimum cut sets, 8 belong to second-order, and 2 are third-order.
Figure 2. Fault tree main diagram of a certain type of rocket engine top event.

Figure 3. Fault tree diagram for percussion black powder function loss.
Table 1. The minimum cut set of the top event of a certain type of rocket engine.

| Serial number | Cut set coding | Description of the minimum cut set event | Minimum cut set order |
|---------------|----------------|------------------------------------------|-----------------------|
| 1             | 111            | Attachment bolt fracture                  | 1                     |
| 2             | 112            | Nozzle seat fracture                      | 1                     |
| 3             | 121            | Combustion chamber crack                  | 1                     |
| 4             | 122            | Back file medicine plate fracture         | 1                     |
| 5             | 123            | Screw cap crack                           | 1                     |
| 6             | 124            | Nozzle seat crack                         | 1                     |
| 7             | 125            | Nozzle crack                              | 1                     |
| 8             | 1312           | The black powder damp                     | 1                     |
| 9             | 132            | Main charge damp                          | 1                     |
| 10            | 13111, 131121  | Electric detonator is not working, Shear copper wire is not cut | 2                     |
| 11            | 13111, 131122  | Electric detonator is not working, Firing pin break | 2                     |
| 12            | 13111, 131123  | Electric detonator is not working, Firing pin deformation | 2                     |
| 13            | 13111, 131123  | Electric detonator is not working, Breakage of sealing ring | 2                     |
| 14            | 131112, 131121 | Conversion nozzle break, Shear copper wire is not cut | 2                     |
| 15            | 131112, 131122 | Conversion nozzle break, Firing pin break | 2                     |
| 16            | 131112, 131123 | Conversion nozzle break, Firing pin deformation | 2                     |
| 17            | 131112, 131123 | Conversion nozzle break, Breakage of sealing ring | 2                     |
| 18            | 131111, 1311221, 1311222 | Electric detonator is not working, The primer 1 misfire, The primer 2 misfire | 3                     |
| 19            | 131112, 1311221, 1311222 | Conversion nozzle break, The primer 1 misfire, The primer 2 misfire | 3                     |

Table 2. Failure rate of each bottom event of a certain type of rocket engine fault tree.

| Serial number | Bottom event                              | Failure rate (×10^-6/h) |
|---------------|-------------------------------------------|-------------------------|
| 1             | Attachment bolt fracture                   | 0.5567                  |
| 2             | Nozzle seat fracture                       | 0.1933                  |
| 3             | Combustion chamber crack                   | 0.22                    |
| 4             | Back file medicine plate fracture          | 0.256                   |
| 5             | Screw cap crack                            | 0.1927                  |
| 6             | Nozzle seat crack                          | 0.1288                  |
| 7             | Nozzle crack                               | 0.0484                  |
| 8             | The black powder damp                      | 0.0198                  |
| 9             | Main charge damp                           | 0.0198                  |
| 10            | Electric detonator is not working          | 0.18                    |
| 11            | Conversion nozzle break                    | 0.3744                  |
| 12            | Shear copper wire is not cut               | 0.1027                  |
| 13            | Firing pin break                           | 0.12                    |
| 14            | Firing pin deformation                     | 0.28                    |
| 15            | The primer 1 misfire                       | 0.0097                  |
| 16            | The primer 2 misfire                       | 0.0097                  |
| 17            | Breakage of sealing ring                   | 0.4458                  |
3.2. Quantitative Analysis
Quantitative analysis refers to the calculation of the occurrence probability of the top event of the fault tree based on the occurrence probability of the basic event of the fault tree, as well as the calculation of the importance of the basic event. According to the “Non-electronic Parts Reliability Manual” and the accumulated data in the past engineering experience, the failure rate of each component is obtained. The failure rate of each basic event is also calculated by referring to the frequency ratio of each failure mode in the FMEA, seeing Table 2.

The probability significance of each basic event was calculated by Isograph software (as shown in Table 3).

Input the failure rate of each basic event into the software. The probability of occurrence of certain rocket engine top event is $1.308 \times 10^{-5}$/h.

Table 3. Probability importance of each bottom event of a certain type of rocket engine fault tree.

| Serial number | Bottom event                        | Probability importance |
|---------------|------------------------------------|------------------------|
| 1             | Attachment bolt fracture           | 0.3404                 |
| 2             | Nozzle seat fracture               | 0.1182                 |
| 3             | Combustion chamber crack           | 0.1345                 |
| 4             | Back file medicine plate fracture  | 0.1565                 |
| 5             | Screw cap crack                    | 0.1178                 |
| 6             | Nozzle seat crack                  | 0.07875                |
| 7             | Nozzle crack                       | 0.02959                |
| 8             | The black powder damp              | 0.01211                |
| 9             | Main charge damp                   | 0.01211                |
| 10            | Electric detonator is not working  | $8.351 \times 10^{-7}$ |
| 11            | Conversion nozzle break            | $1.737 \times 10^{-6}$ |
| 12            | Shear copper wire is not cut       | $2.785 \times 10^{-7}$ |
| 13            | Firing pin break                   | $3.254 \times 10^{-7}$ |
| 14            | Firing pin deformation             | $7.593 \times 10^{-7}$ |
| 15            | The primer 1 misfire               | 0                      |
| 16            | The primer 2 misfire               | 0                      |
| 17            | Breakage of sealing ring           | $1.209 \times 10^{-6}$ |

3.3. Results Analysis
According to the calculation of the minimum cut set of certain rocket engine, nine single point failure of the top event of a certain type of rocket engine can be found, which will lead to the occurrence of the top event. Therefore, related design improvement or compensating measures must be carried out to reduce the occurrence rate of the single point failure. For example, use 30CrMnSiA materials to increase the fatigue strength and solve the cracks problem in the combustion chamber, carry out hydraulic pressure strength test, and perform magnetic inspection to the combustion chamber before assembly. The probability importance results of the basic event and the minimum cut set analysis results indicate that the weak link of the certain type of rocket engine is connecting bolt, so special attention should be paid to improve the strength of the connecting bolts. In addition, the rocket engine, as an initiating explosive device with limited service life, must be changed based on its life span (storage period or usage period), and the whole process must be performed strictly in accordance with the maintenance instructions for replacement. In Table 3, the probability significance of the primer 1 misfire and the primer 2 misfire is 0, which means that neither the primer 1 misfire nor primer 2 misfire make any contribution to the occurrence of the top event. It mainly because the top event can only be occurred through two redundancy design with primer 1 misfire and primer 2 misfire, which also proved that the reliability of the product can be improved with the addition of the redundancy design.
4. Conclusions
In this paper, a fault tree model is established for certain rocket engine that cannot provide thrust as a top event, and qualitative and quantitative analysis is carried out to find out the cause of the fault. By taking corresponding measures, the reliability of certain rocket engine is effectively improved. Sexuality provides a theoretical basis for further optimization of certain rocket engine.

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