Study of Fuze Structure and Reliability Design Based on the Direct Search Method

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Abstract. Redundant design is one of the important methods to improve the reliability of the system, but mutual coupling of multiple factors is often involved in the design. In my study, Direct Search Method is introduced into the optimum redundancy configuration for design optimization, in which, the reliability, cost, structural weight and other factors can be taken into account simultaneously, and the redundant allocation and reliability design of aircraft critical system are computed. The results show that this method is convenient and workable, and applicable to the redundancy configurations and optimization of various designs upon appropriate modifications. And this method has a good practical value.

1. Introduction

With the development of aerospace technology, the requirement for the system reliability design is getting higher and higher [1]. The fundamental approach is to produce more reliable components by means of appropriate improvement measures. However, in actual production process, a series of problems are involved in the improvement of component reliability such as: the quality of raw materials, manufacturing process and design standards of components. In case of improving component reliability when it reaches a certain value, the cost will increase incredibly, while the effect of this method on the overall reliability of the system is not obvious in such case.

Redundant design improves the reliability of the system by means of configuration and rational management of multiple resources of the system. However, increasing the redundancy will increase resources, cost or weight, because of the increase the complexity and error rate of the system [2], the reliability is reduced on the contrary. So need to consider the impact of multiple factors to get a more perfect redundancy configuration proposal.

2. Reliability allocation problem models

Generally, the reliability allocation can be divided into two categories, one is constraint condition based on reliability index, with the lower limit value being given, taking cost, structural weight and other factors as objective function. The other one is to calculate the upper limit value by taking cost and structural weight as constraint conditions [3], and the highest reliability of the system as objective function.

Because of the constraint of many factors in aircraft design, the reliability allocation is not only a matter of simple mathematical programming, but to specifically assign the reliability index such as importance level, complexity level, technical level and work environment, into each sub-system, determine the reliability index of each sub-systems, and then assign to the overall unit according to its
mathematical mode [4], and finally, assign to each component based on the functions and the environment of the overall unit and some other factors.

- Assume the total requirements of system reliability is given, and the subsystems relations, system reliability the components, cost, structural weigh and other factors are known, it is required to design (allocate) the quantity of the components of each subsystem to minimize the total cost or structural weight.
- Assume cost, structural weight and other factors as given as constrain condition, and the subsystems relations, system reliability the components, cost, structural weigh and other factors are known, it is required to design (allocate) the reliability of each subsystem to maximize the system reliability (minimize the unreliability).

Several components may be paralleled on the existing series system when making redundant design. In order to build the series parallel system model which takes the minimum cost as the objective function and the reliability index and quality as the constraint conditions, a cost function must be established first. The cost function shows the relationship between reliability and cost, it is an abstract concept, including the sum of all kinds of costs for manpower, material resources and financial resources which are used to improve unit reliability. It is originally named effort function. It is a monotonically increasing function. Because it is difficult to obtain the statistical data between the cost and reliability of each unit, so an empirical formula is generally unable to be established. For the redundant design of a complex system, in order to make it convenient for the study, it can be assumed that the parallel components in subsystems are identical, and the cost of each component is a constant. So for the general series parallel system, it is as shown in Figure 1.

![Figure 1. Reliability block diagram of typical series-parallel system](image)

Reliability of typical series-parallel system

\[ R_i = \prod_{i=1}^{n} (1 - F_i^{x_i}) \]  

(1)

The above problems can be summarized as the following mathematical forms:

\[
\begin{align*}
\min f(x) \\
f(x) &= \sum_{i=1}^{n} w_i x_i \\
R_i &= \prod_{i=1}^{n} (1 - F_i^{x_i}) \geq R^* \\
x_i &\geq 0, i = 1, 2, \cdots, n
\end{align*}
\]  

(2)
Among the formula, \( n \) is the number of sub-systems, \( F_i \) is the unreliability of subsystem components, \( x \) is the number of parallel elements in the subsystem. \( W_i \) is the cost (or structural weight) of the system components, \( f(x) \) is the total cost of the system, \( R_s \) is the system reliability, \( R^* \) is the index required by the system, \( C^* \) is the constraint value of the total cost (structural weight) of the system.

Make following assumptions before making redundancy optimal and allocation:
(1) Each subsystem is independent and not repairable in mission phase.
(2) Each subsystem has two states, namely, the working state and the fault state.
(3) The reliability of each subsystem is a constant.

There are many kinds of reliability allocation method with constraint conditions, such as dynamic programming method, Lagrange multiplier method and integer programming method [5], but in practice, there is a relatively simple engineering algorithm of Direct Search Method.

3. **Algorithm principle of Direct Search Method**

The basic idea of Direct Search Method is to find a link (subsystem) and to parallel a redundant part on the link so as to achieve a maximum system reliability increment compared to unit cost, then checks constraint conditions and continuously search in this way, and constantly increase system reliability, until all constraint conditions are satisfied [6]. The approaches to the above problems of the Direct Search Method are as follows:

- Search a certain level. Parallel a redundant part in this level to maximize the system reliability increment compared to unit cost, and search within constraint conditions. Search constantly and continuously until the constraint conditions are satisfied.
- Each time, parallel a redundant part on the series system with largest unreliability, check constraint conditions, and maximize the system reliability by doing a series of tests.

4. **Numerical example**

Fuze is a key link in the weapon system to realize the effective damage to the target. If its reliability cannot be guaranteed, a military operation will be either hindered due to the failure to complete the scheduled mission because of fuze blind fire, or the outcome of a battle will be even directly affected. Or because of the premature burst or early burst of the fuze, it cannot destroy enemy, but cause casualties and damage equipment of our side.

Generally, mechanical and electrical products work above ground or in indoor environment, environmental force the bear in work process is not large, and failure detection and failure maintenance can be done in work process. Fuze working process is featured by long-term storage, with a storage life of generally 10-20 years, and gradual declining reliability in the long-term storage process, so its function cannot be predicted. IN addition, it is required to pass through launch, flight and missile target intersection and other process, the environmental conditions in working process is very harsh, such as High impact overload and high speed rotation. To ensure the normal operation under high and low temperatures, the components and parts are required to have small size and light weight, good performance, low price, and high reliability and safety. Another feature of the fuze working process is a very short working time, the failure occurred during the course of the work...
cannot be troubleshooted and maintained manually, and it is also hard to take failure detection of fuze in launch process. In such circumstances, it is very important to improve the reliability of the fuze.

The redundancy technology provides an effective way to improve the reliability, safety, reliability and fault tolerance ability of the system. This study is intended to consider the reliability, cost and weight when making design of redundant system of the fuze, study on the optimal allocation of redundancy, so as to effectively improve the reliability of the system.

The key components of fuze are composed of four elements in series, and their respective weight and reliability data are shown in table 1. Because its work reliability directly related to whether the aircraft can successfully complete the task, and its work is not reversible, so its reliability is required to be higher than 0.99.

### Table 1. Unit weight and reliability.

| Unit | Weight (kg) | Reliability |
|------|-------------|-------------|
| 1    | 0.53        | 0.92        |
| 2    | 0.28        | 0.94        |
| 3    | 1.12        | 0.97        |
| 4    | 0.74        | 0.95        |

Its reliability logic block diagram is simplified as Figure 2:

![Figure 2. System reliability logic block diagram.](image)

### 4.1 Computation of initial reliability

In the case of non-redundant design, system reliability is

\[ R_s = \prod_{i=1}^{n} R_i = 0.7879 \]

It can be seen from the computation result that the reliability of the system does not meet the specified requirements, so redundant design must be done to improve the reliability of the system. Applied redundancy technology can effectively improve the reliability of the system composed of components with relatively low reliability, that is, "exchange the high reliability with the cost of unconventional resources". It is an effective means to improve the reliability and safety of the system.

### 4.2 Reliability optimization design

The optimization model of the system obtained from the above problems is as follows: when system reliability is or above design reliability \( R_0 \), compute \( n = \{ n_1, n_2, \ldots n_k \} \), to compute the minimum value of weight of \( \sum_{i=1}^{k} w_i n_i \).

The specific algorithm of Direct Search Method is as follows:

Step one:
(1) Obtain from constraint conditions:

\[ 1 - q_i^* > R_0, i = 1, 2, \ldots, k \quad (q_i = 1 - R_i) \]  (4)

Making \( n_i^* \) as the number of due parallel components at least of the \( i^{th} \) subsystem,
Then get

\[ n_i^* > \ln(1 - R_0) / \ln q_i \]  

(5)

Because the number of components \( n_i^* \) must be a positive integer, so take

\[ n_i^* = \ln(1 - R_0) / \ln q_i + 1 \]  

(6)

So the minimum weight of the system is

\[ W^* = \sum_{i=1}^{k} w_i n_i^* \]  

(7)

(2) If taking the formula now

\[ \prod_{i=1}^{k} (1 - q_i^{n_i^*}) \geq R_0 \]  

(8)

Then we get the optimum answer of \( \{n_1^*, n_2^*, \ldots, n_k^*\} \). Otherwise transfer to Step Two.

Step Two:

(1) Use the answer form \( \{n_1^*, n_2^*, \ldots, n_k^*\} \) to compute \( \Delta Q_i = q_i^{n_i^*} - q_i^{n_i^*+1} \) and \( \Delta Q_i / W_i \)

(2) Given

\[ \Delta Q_{i\alpha} / w_{i\alpha} = \max_{i=1,k} \{ \Delta Q_i / w_i \} \]  

(9)

Add a parallel component on \( i_0 \) part, so as to make the number of parallel components as \( n_{i_0}^* + 1 \).

Then compute

\[ R_r = \left( 1 - q_i^{n_i^*+1} \right) \prod_{i=1}^{k} \left( 1 - q_i^{n_i^*} \right) \]  

(10)

If \( R_r \geq R_0 \), then get the optimum answer of \( \{n_1^*, n_2^*, \ldots, n_{i_0}^*+1, \ldots, n_k^*\} \)

(11)

Otherwise repeat the computation of Step Two until the optimum answer is obtained. The detailed computation process is shown in Table 2 below.

| \( j \) | Items | 1         | 2         | 3         | 4         |
|-------|-------|-----------|-----------|-----------|-----------|
| 0     | \( n_i^0 \)    | 2         | 2         | 2         | 2         |
|       | \( Q_i \)      | 0.0064    | 0.0036    | 0.0009    | 0.0025    |
|       | \( \Delta Q_i \) | 0.005888  | 0.003384  | 0.000873  | 0.002375  |
|       | \( \Delta Q_i / W_i \) | 0.011109  | 0.012086  | 0.000779  | 0.003209  |
|       | \( R_r \)      | 0.9866    |           |           |           |
| 1     | \( n_i^1 \)    | 2         | 3         | 2         | 2         |
|       | \( Q_i \)      | —         | 0.000216  | —         | —         |
|       | \( \Delta Q_i \) | —         | 0.00020   | —         | —         |
|       | \( \Delta Q_i / W_i \) | 0.011109  | 0.000714  | —         | —         |
|       | \( R_r \)      | 0.989984  |           |           |           |
| 2     | \( n_i^2 \)    | 3         | 3         | 2         | 2         |
|       | \( Q_i \)      | —         | 0.000512  | —         | —         |
|       | \( R_r \)      | 0.995872  |           |           |           |
In the Table, \( R_i = \prod_{k} (1 - q_i^k) = \prod_{k} (1 - Q_i) \approx 1 - \sum_{k} Q_i \), the blank square refers to the value without need to recomputed, and the underlined square refers to the number of parallel components of this level + 1.

By computation the optimum answer is obtained \( n = \{ 3, 3, 2, 2 \} \). On the premise of ensuring reliability, \( W^* = \sum_{i=1}^{k} w_i n_i^* = 6.15\text{kg} \).

4. Conclusion
The study only discusses the redundancy of single equipment, and the redundant design of multiple equipments can be done with slight modification. In practical work, the reliability model can also be designed into other forms based on actual needs such as series and parallel models and embedded model, which only require corresponding modification on this basis. And tabulation method is used in the computation process, which is simple and intuitive, easy to calculate the answers, so that the reliability allocation can be quick and accurate. With small amount of calculation, it is convenient for engineering and practical use. In addition, the algorithm can be realized by using VC++6.0 language programming on compute. Direct Search Method is a process of mathematical optimization, and it is applicable to large and complex systems such as airplanes and ships. Satisfactory effect can be achieved by using the method into reliability allocation and design.

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