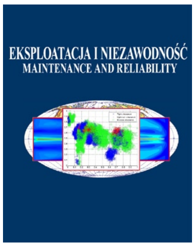

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Research on reliability allocation strategy for gear transmission system of high-speed train

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Highlights

- A reliability allocation model is proposed based on AGREE allocation and cost function.
- The reliability allocation strategy considers variable cost, complexity and constraints.
- The strategy is more suitable for reliability design stage of complex mechanical system.

Abstract

High-speed train industry is in the stage of rapid development, and the reliability allocation strategy is helpful to improve the reliability of the system and reduce the economic cost of components. In this paper, the reliability allocation of gearbox transmission system of high-speed train is studied. Combining AGREE allocation method and reliability allocation method based on cost function, the reliability allocation of high-speed train gear transmission system is carried out. Considering the quantity, importance, cost and complexity of various parts of high-speed train gear transmission system, the feasibility factor of improving reliability based on the cost function allocation method was improved to acquire the improved cost function, and the reliability optimization allocation model based on the improved cost function was established. Compared with AGREE allocation method and the traditional allocation method based on cost function, the improved optimization allocation strategy proposed in this paper is more suitable for high-speed train gear transmission system.

Keywords

reliability allocation strategy, cost function, high-speed train, gear transmission system.

1. Introduction

Due to its large mass, fast speed, more people and long braking distance, high-speed train has been widely used in transportation, and once an accident occurs, the harm, influence, involving a large area [8]. Since the components of the gear transmission system of high-speed train are manufactured according to the design requirements, it is important to optimize the reliability of the components in the reliability design stage for improving the safety of the whole high-speed train in service. At the same time, in the stage of improving the reliability of components, there is a problem of only considering the reliability demand, and ignoring the cost and cost of human and material resources and other constraints. Therefore, it is of great significance to optimize the reliability of each component by applying the improved cost function to reduce unnecessary economic losses and improve the utilization rate of resources. In the past half century, with the development of the world economy and the rapid progress of science and technology, driven by one industrial revolution after another, the world railway passenger transport major mobile equipment high-speed train has developed rapidly [10]. China's high-speed train industry is in a rapid development stage. On the constant exploration and production research, China gradually achieved its high-speed train localization, and preliminary grasp of the world's top design and manufacture key technology of high-speed railway passenger car, has become the world's most complete high-speed rail system technology, the integration ability of the strongest and longest running mileage, highest speed, the largest country in the construction scale [15]. With the rapid development of high-speed train, its potential hidden trouble could not be underestimated.

In the study of train dynamics characteristics, the mass of the transmission system is often equivalent to bogie and wheelset without considering its transmission characteristics. However, with the continuous improvement of train speed, the dynamic characteristics of the vehicle system becomes more complicated and difficult to measure. Higher safety is being proposed for trains to ensure the safety of passengers.

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The transmission system could transfer the traction motor torque through coupling, gear box, axle box and other devices and convert it into wheelset torque to drive the train. The gear transmission system studied in this paper is based on CRH6 intercity train gear transmission system.

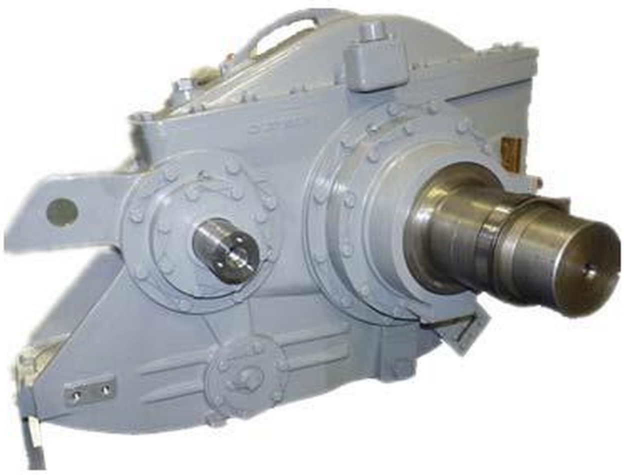

Fig. 1. Gear transmission system of CHR6 intercity train

According to the actual structure of the gearbox system, the multi-level system of the high-speed train was established, and according to its working principle, the reliability model of the three-level system of the high-speed train was established, which were "gear transmission system-gearbox, traction motor-parts", as shown in figure 2.

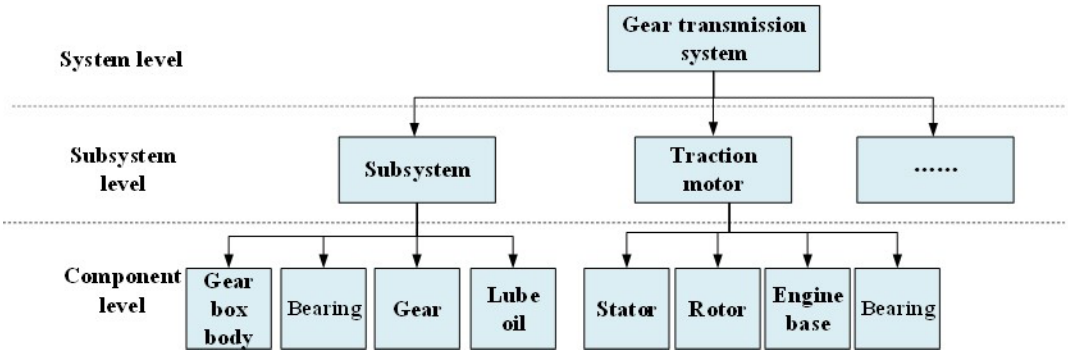

Fig. 2. Reliability block diagram of gear transmission system of high-speed train

The gear transmission system is system level. As the key system of railway locomotive, the gear transmission system plays an important role in the power transmission between traction motor and wheelset in the process of traction or braking, thus producing resistance and resistance to the longitudinal movement of locomotive. At the subsystem level, as an integration of components, it plays a very significant role in the study of the system reliability model. At the subsystem level, it sets the reliability of components and transmits reliability according to the working characteristics of subsystems, so as to form a complete reliability model. As a component with direct failure index in system reliability, its service status is related to subsystem level, system level and vehicle level. Through the establishment of reliability block diagram of high-speed train system level, the modeling foundation is laid for the establishment of reliability model.

The reliability research of high-speed train components has become the focus of people's attention. As an important part of reliability design, reliability allocation is to distribute the reliability of the system quantitatively to each component of the system according to certain criteria, and then distribute the system reliability index to each subsystem or unit for guiding the development of products or subsystems to meet customer needs [6]. Since the components of the gear transmission system of high-speed train are manufactured according to the design requirements, it is important to optimize the reliability of the components in the reliability design stage for improving the safety of the whole high-speed train in service. At present, there is a problem that only considering the reliability requirements, but ignoring the cost and other constraints such as human and material resources in the stage of improving the reliability of components [18].

The purpose of reliability allocation is to distribute the system reliability index to each subsystem or component, so that the related product designers could define the reliability design requirements of each unit. The specific significance has two aspects. One is to provide reliability design indicators for designers of each unit of the system to ensure that the system meets the specified reliability requirements. Second, through the reliability allocation, the product reliability indicators of each subcontracting manufacturer or supplier will be defined, so as to control the implementation and management of product production by the system contractor [21]. System reliability allocation and optimization in the system design stage is a multi-objective optimization problem, whose main idea is to calculate the reliability allocated to each component under the condition of reliability constraints, so as to achieve the purpose of minimizing costs. In the past decades, scholars have proposed many algorithms for reliability allocation [17], such as genetic algorithm [3] and ant colony optimization algorithm [13]. These algorithms mainly improve the results of system reliability allocation, but seldom consider the cost requirements in the actual research and development process.

Reliability allocation [2] is a necessary and cost-effective task in reliability design. Before starting any task, there needs to be a clear goal or target. In the stage of task objective determination, only the reasonable allocation of indicators could avoid the blindness of design. Although reliability allocation is mainly focused on the early analysis and demonstration of the work, for the actual work required manpower and cost is not much, reliability allocation in guiding production largely determines the design of the product. The establishment of a reasonable index allocation scheme is of great significance for the system to achieve the specified reliability target economically and effectively [5].

In the product design stage, in order to improve the feasibility and rationality of reliability index allocation, the principle of reliability allocation should be fully used in the allocation of reliability index. If the allocation result could not guarantee its accuracy, the relative reliability of each component or subsystem should be highlighted so that the designer could work flexibly in the design process.

In the gear transmission system of high-speed train, the allocation principle of reliability [20] is as follows:

(1) Complexity of components or subsystems. For complex parts or subsystems on the allocation of low reliability index, due to the more complex products, the more the unit composed of, in order to achieve high reliability is more difficult and to pay more cost.

(2) The technical maturity of the product. For products that are not technically mature, lower reliability indicators are allocated. For products with immature technology, if higher reliability is proposed, it may prolong the development time and cost, so lower reliability is allocated to them.

(3) Working environment. The service working environment of the product also affects the reliability of the product. For products under harsh working conditions, we allocate low reliability to them because harsh working conditions will increase the failure rate of products.
(4) The importance of parts or subsystems. Importance also refers to functionality, that is, the degree to which a component or subsystem affects the failure of the system. The failure of a product with high importance directly affects personal safety or task completion. Therefore, a high reliability indicator is allocated to a product with high importance.
(5) Working hours. For products that need long-term work, the reliability of the products will gradually decrease with the increase of working hours, so the products that need long-term work will be allocated low reliability.
(6) Products with low maintainability are allocated higher reliability indicators. Ensure that parts or subsystems in the system service life to reach a long period of time.

2. AGREE allocation method

The AGREE allocation method is proposed by American Electronic Equipment Reliability Advisory Group. Because it fully considers the complexity, importance, working time of each unit (parts or subsystems) of the system and the failure relationship between them and each system, it is also called the allocation method based on the complexity and importance of the unit. It is an allocation method to balance the importance and complexity, which is suitable for series systems with exponential distribution of cell life.

The AGREE allocation method [19] requires that the failure rate of each unit is constant during operation, and the system studied is an independent series system [1]. The complexity referred to is the ratio of the number of important parts contained in the first unit to the total number of important parts in the system, expressed by K_i , then:

$$K_i = \frac{n_i}{N} \tag{1}$$

The significance refers to the degree of influence of the ith unit on system reliability when failure occurs, and is represented by W_i , then:

$$W_i = \frac{M}{r_i} \tag{2}$$

where M is the number of system failures caused by the failure of the ith unit; r_i is the number of failures of the ith unit.

If the reliability of the system obeys an exponential distribution, its failure rate allocation formula is:

$$\lambda_i = \frac{n_i \cdot (-\ln R_{obj})}{NW_j t_i} \tag{3}$$

The reliability allocation formula is:

$$R_i = 1 - \frac{1 - R_{obj}{}^{K_i}}{W_j} \tag{4}$$

where λ_i is the failure rate assigned to the ith unit; R_{obj} is the reliability required by the system.

AGREE allocation method embodies two basic principles in the allocation process:

(1) Allocate a lower reliability to a subsystem with high complexity;
(2) For subsystems with high importance, higher reliability is allocated to them. The key to AGREE method is the way in which the importance and complexity of the subsystems are determined.

In the gear transmission system of high-speed train, the key to the reliability allocation of the system using AGREE allocation method is to determine the importance and complexity of the subsystem.

The importance refers to the evaluation of the importance of the components, and the components with high importance are allocated higher reliability indicators. Since the probability of occurrence of events at the bottom of the system's preliminary design stage is unknown, the importance of the components is represented by the structural importance; the complexity refers to the evaluation of the number of components that make up the system and the ease of assembly, the allocation of complex components lower reliability indicators.

In AGREE allocation, the reliability allocation for the reliability of the high-speed train component level was improved, and the reliability was actually reduced after the allocation. The reason for this is that AGREE allocation method could calculate the reliability according to the structural characteristics and failure characteristics of each part of the system. This is an unconstrained reliability allocation method, which is the target reliability of the known system, to redistribute the unit reliability of the subsystem. However, due to the lack of constraints, when allocating, only the top-to-bottom allocation is considered, and whether the allocated reliability has a positive effect on the improvement of the system reliability is not considered. Therefore, this method provides limited guidance for the reliability design stage.

3. Reliability allocation method based on cost function

The cost function constrained optimization method is to establish the nonlinear programming model of the system in combination with the cost function when considering the reliability of each unit in the system in series mode [14]. This method uses the Lagrange multiplier method to calculate its optimal allocation results. The current cost-based allocation methods mainly focused on the optimal planning of allocation, there are two main ways to consider the cost. One is regarding cost as a specific constant which obtained from statistics or assumption. The other one is considering the cost as an increasing function with the reliability of system [7, 9]. Yadav et al. noticed the efforts of reliability improvement and described it as a function which related to failure rate [16]. This paper used the three-parameter cost function to carry out the optimal allocation calculation of reliability under the given reliability design conditions.

Assuming that the high-speed train multi-level system consists of units (referring to subsystems or components), the reliability index of the system is R_{obj} . The reliability structure function of the system is (5):

$$R_{sys} = \prod_{i=1}^{n} R_i, i = 1, 2, \cdots, n \tag{5}$$

where R_{sys} is the probability that the system works normally; R_i is the probability that ith unit will work properly.

Then the nonlinear programming model of the system was established as follows:

$$\begin{cases} \min C = \sum_{i=1}^{n} c_i(R_i) \\ s.t. R_{sys} \geq R_{obj} \\ R_{i,\min} \leq R_i \leq R_{i,\max}, i = 1,2,\cdots,n. \end{cases} \quad (6)$$

where R_i is the optimized reliability level of the *i*th unit; C is the total cost of the system under the action of the reliability level; $c_i(R_i)$ is the required cost of each unit under the action of the reliability level; $R_{i,\min}$ is the current reliability level of the unit; $R_{i,\max}$ is The highest reliability level of the unit.

To solve the above mathematical model, it is of the great necessity to obtain the reliability structure function of the system, that is, the reliability model of the system. This chapter aims at the reliability model of the series system, and establishes the system reliability structure function under the independent assumptions, so as to carry out the primary system reliability index allocation.

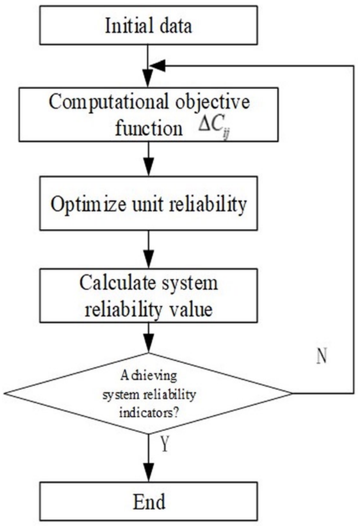

Fig. 3. Optimization algorithm flow chart of independent failure system

The cost function represents the relationship between reliability and cost, including the sum of manpower, financial resources, and material resources to improve the reliability of the unit. It was originally called the effort function, that is, Effort Function.

The properties of the cost function are as follows:

It is difficult to obtain statistical data between the cost and reliability of each unit in the project, so an empirical formula could not be established. To solve this problem, Winterbottom and Dale proposed some properties that the cost function needs to satisfy in 1986:

If $0 \leq R_i^{(1)} \leq R_i^{(2)} \leq 1$, denoted by $c(R_i^{(1)}, R_i^{(2)})$, represents the effort to raise R_i from $R_i^{(1)}$ to $R_i^{(2)}$, then the cost function has the following properties [11]:

(1) $c(R_i^{(1)}, R_i^{(2)}) \geq 0$, $0 \leq R_i^{(1)} \leq R_i^{(2)} \leq 1$;

(2) $c(R_i^{(1)}, R_i^{(3)}) = c(R_i^{(1)}, R_i^{(2)}) + c(R_i^{(2)}, R_i^{(3)}) \geq 0, 0 \leq R_i^{(1)} \leq R_i^{(2)} \leq R_i^{(3)} \leq 1$;

(3) $c(R_i)$ Differentiable;

(4) $c(R_i)$ is a convex function, which is $\frac{\partial^2}{\partial R_i^2} C(R_i) \geq 0, 0 \leq R_i \leq 1$;

(5) For a fixed $R_i^{(1)}, 0 \leq R_i^{(1)} \leq 1$, if $R_i^{(2)} \to 1$, then $c(R_i^{(1)}, R_i^{(2)}) \to \infty$;

(6) $c(R_i)$ is a monotonically increasing function.

In this study, a three-parameter cost function is used, and the formula is:

$$c_i(R_i) = \frac{1}{f_i} \ln \frac{R_{i,\max} - R_{i,\min}}{R_{i,\max} - R_i} \quad (7)$$

In the formula f_i is the feasibility of improving the reliability of the unit, that is, the degree of difficulty (0< f_i <1). If the value of f_i is larger, it indicates that the reliability of the unit is greater. $R_{i,\min}$ is the current reliability of the unit, that is, the initial reliability of the parts, and also the initial iterative value in the process of reliability optimization allocation; $R_{i,\max}$ is the final reliability obtained by the ith unit after reliability allocation, and its value ranges from $R_{i,\min}$ to $R_{i,\max}$; $c(R_i)$ represents the cost of improving the reliability of unit I from $R_{i,\min}$ to $R_{i,\max}$ [12].

4. Reliability allocation method based on improved cost function

Currently, there exists abundant literatures contributing to the reliability allocation domain. As for the allocation techniques, there are two main research directions: weight method and optimization approach [4]. In the reliability optimization allocation algorithm based on the cost function, although the constrained allocation of reliability allocation takes into account the cost of improving the reliability of the system compared with the unconstrained method, the reliability is optimized under the consideration of multiple factors distribute. However, for the high-speed train gear transmission system, the traditional three-parameter cost function could not satisfy the reliability allocation of the gear transmission system studied in this paper because of the individual differences of the components of the train gear transmission system. Therefore, under the traditional reliability optimization allocation method based on cost function, individual differences at the component level are considered, and a more appropriate allocation strategy is proposed for the reliability optimization allocation of high-speed train gear transmission systems.

4.1. Modify the feasibility factor scheme for improving reliability

In the traditional reliability allocation model based on cost function, the three-parameter cost function used is:

$$c_i(R_i) = \frac{1}{f_i} \ln \frac{R_{i,\max} - R_{i,\min}}{R_{i,\max} - R_i} \quad (7)$$

In the traditional algorithm, when allocating reliability to the gear transmission system of high-speed train, the index factors that need to be considered for the feasibility factor of improving unit reliability include: importance, standardization, technology maturity, and maintainability. After establishing the reliability allocation model and carrying out the reliability allocation based on the cost function of the high-speed train gear transmission system, the final reliability allocation results for the gear box, bearings, gears and lubricating oil are basically at the same level.

However, for the gear transmission system of high-speed trains, different components have individual differences and differences in quantity, and such allocation is obviously not very reasonable. The gear case is a non-repairable component in the gear transmission system and has a service life of up to 20 years at the design stage. In the reliability design stage of the system, it is difficult to improve the reliability of the existing reliability level. Bearings and gears are repairable parts. In the design stage, due to their good maintainability, in terms of service life, the service life of bearings is 4 million km per vehicle, and the service life of gears is 9 million km per vehicle, and it is much shorter compared with the gearbox body. Lubricating oil is

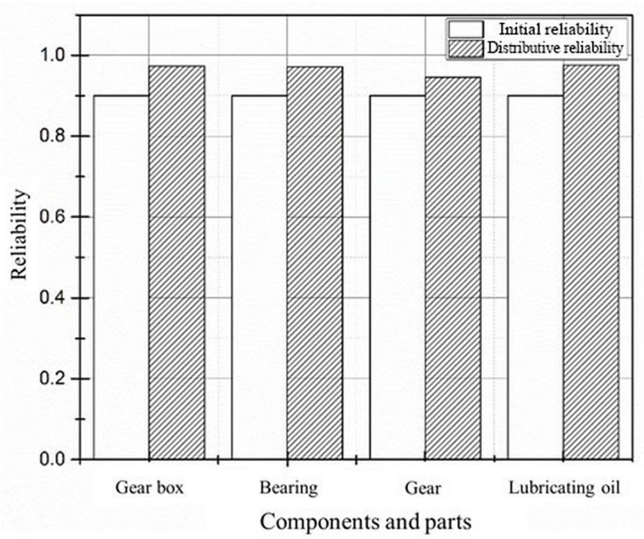

Fig. 4. Reliability allocation results based on cost function

the easiest component to maintain. The adjustment range of reliability is in a large space. How to determine its reliability, in terms of system cost, could be flexibly controlled to meet the actual supply of human and material resources.

In AGREE allocation method, although the allocation process is an unconstrained allocation process, in the process of considering the influence of reliability allocation, the main factors considered are the importance and complexity of components in the system. In the gear transmission system of high-speed train, the complexity has a very important influence on the reliability allocation of the system due to the difference in the design life of the components and the number of component levels.

Therefore, based on the above considerations, the traditional three-parameter cost function f_i is improved. The indicators considered in the feasibility factor of improving unit reliability are due to importance, technology maturity, standardization, and maintainability. Combined with the AGERR allocation method the complexity factors that affect the system reliability allocation, the feasibility factor f_i was improved, and a new feasibility factor $f_{i,new}$ was obtained:

$$f_{i,new}=\mathrm{K}_i \cdot f_i \tag{8}$$

where K_i is the complexity of the ith unit.

After the improved feasibility factor was obtained, it was substituted into the three-parameter cost function to obtain a new improved cost function:

$$c_i(R_i)=\frac{1}{f_{i,new}}\ln\frac{R_{i,\max}-R_{i,\min}}{R_{i,\max}-R_i} \tag{9}$$

For the improved cost function, curve fitting is performed on its function, and the fitting curve graph is shown in figure 5.

From this figure, it could be seen that the improved cost function has the following characteristics:

(1) The cost is the nonlinear growth of the reliability of parts and components;
(2) As shown in the figure, when the highest reliability is infinite, the cost to be paid is infinite.
(3) When the required reliability is higher, the required cost increases faster.

The above characteristics show that the improved cost function conforms to the nature of the cost function proposed by Winterbottom and Dale.

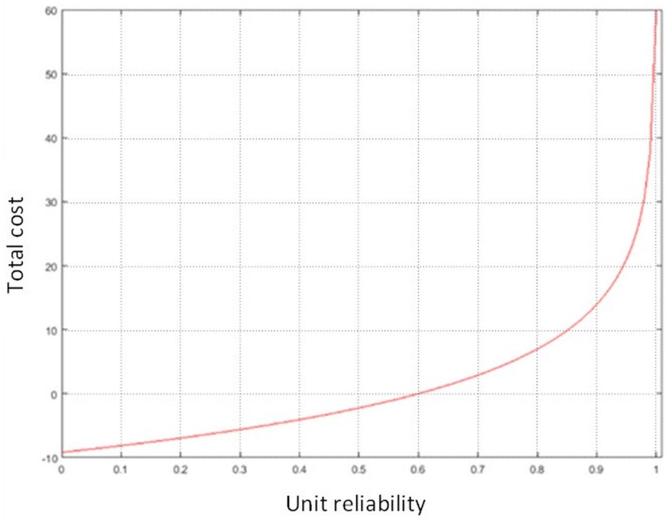

Fig. 5. Improved cost function curve variation diagram

In the following reliability allocation model, the improved cost function is used as the objective function to establish the model, which provides a better solution strategy for the reliability optimization allocation method.

4.2. Improved cost function reliability optimization allocation algorithm

For the high-speed train gear transmission system, in order to better compare the improved reliability allocation results with the traditional reliability optimization allocation model based on cost function, to observe the allocation effect of the improved algorithm. In the improved algorithm, the original hypothesis is kept unchanged, that is, the components in the gear transmission system of the high-speed train are all connected in series, and the reliability index of the system is R_0 =0.9. It is assumed that the component levels of the system are independent failure correlations. The reliability structure function of the system is:

$$R_{sys}=R_1\times R_2\times R_3\times R_4 \tag{10}$$

The first step is to determine the complexity of each component in the gear transmission system based on the index factors (importance, technology maturity, standardization, and maintainability) in the traditional cost function. Since the AGREE algorithm is an unconstrained allocation method that only considers the importance and complexity, it takes into account the individual differences of components in the allocation process. In this algorithm, the complexity evaluation method in the AGREE algorithm is adopted, that is, the subsystem complexity K_i is defined as the ratio of the number of components included in the subsystem to the total number of system components:

$$K_i=\frac{n_i}{\sum_{i=1}^{m} n_i} \tag{11}$$

where n_i is the number of parts included in the ith subsystem; m is the number of subsystems in the system.

The second step is to establish the traditional nonlinear programming model based on the cost function according to the fourth chapter. Based on the traditional nonlinear programming model of the cost function, the prototype of the nonlinear programming model of the improved cost function is established. The model basis is established for the improvement of the three-parameter cost function in the next step:

$$\begin{cases} \min C = \sum_{i=1}^{4} c_i(R_i) = \sum_{i=1}^{4} \frac{1}{f_i} \ln \frac{R_{i,\max} - R_{i,\min}}{R_{i,\max} - R_i} \\ s.t. R_{sys} = R_1 \times R_2 \times R_3 \times R_4 \geq R_0 \\ R_{i,\min} \leq R_i \leq R_{i,\max}, i = 1,2,3,4. \end{cases} \quad (12)$$

The third step is to improve and optimize the feasibility factor of the traditional three-parameter cost function. In order to comprehensively consider the complexity of the component level in the reliability allocation model, the feasibility factor is modified by factor, and the complexity is weighted to obtain the modified feasibility factor. The improved formula is formula (8):

$$f_{i,new} = K_i \cdot f_i, i = 1,2,3,4 \quad (8)$$

The fourth step, the improved three-parameter cost function is returned to the nonlinear programming model in the second step to obtain an improved reliability optimal allocation model. The improved reliability optimization allocation model is:

$$\begin{cases} \min C = \sum_{i=1}^{4} c_i(R_i) = \sum_{i=1}^{4} \frac{1}{f_{i.new}} \ln \frac{R_{i,\max} - R_{i,\min}}{R_{i,\max} - R_i} \\ s.t. R_{sys} = R_1 \times R_2 \times R_3 \times R_4 \geq R_0 \\ R_{i,\min} \leq R_i \leq R_{i,\max}, i = 1,2,3,4. \end{cases} \quad (13)$$

Through K-T conditions, the improved model could be transformed into:

$$\begin{cases} \min C = \sum_{i=1}^{4} c_i(R_i) = \sum_{i=1}^{4} \frac{1}{f_{i.new}} \ln \frac{R_{i,\max} - R_{i,\min}}{R_{i,\max} - R_i} \\ s.t. R_{sys} = R_1 \times R_2 \times R_3 \times R_4 = R_0 \\ R_{i,\min} \leq R_i \leq R_{i,\max}, i = 1,2,3,4. \end{cases} \quad (14)$$

The fifth step is to solve the reliability allocation model based on the improved cost function iteratively, and finally obtain the global optimal solution of the model, which is the reliability optimization allocation strategy after the improved algorithm.

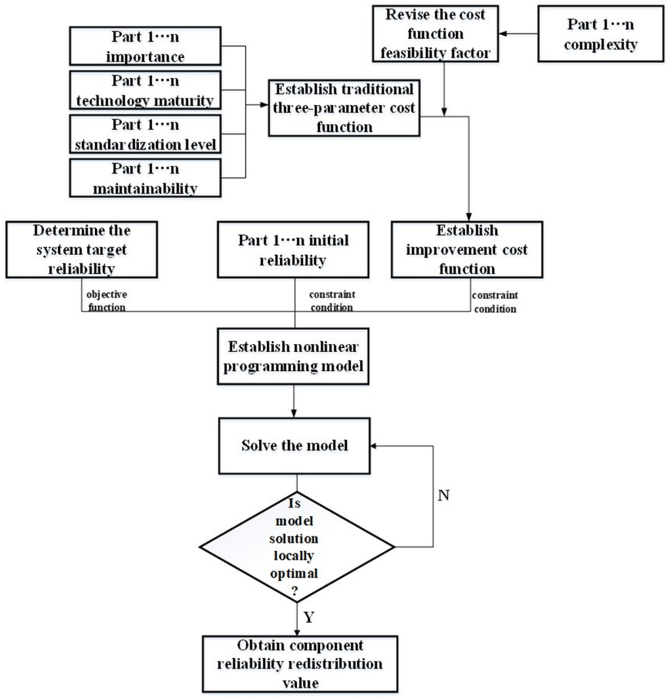

Fig. 6. Algorithm flow chart of reliability optimization allocation method based on improved cost function

The following figure is the algorithm flow chart of reliability optimization allocation method based on improved cost function.

4.3. Improved nonlinear programming model solution

In the gear transmission system of high-speed train, the reliability optimization allocation method based on improved cost function is applied. According to the operation instruction of the gear transmission system of CRH6 high-speed train set, the index factors in the cost function are determined in table 1:

The above rating scale is substituted into the reliability allocation model built by the improved cost function, using the augmented Lagrange multiplier algorithm to solve, after many iterations, when the system achieves the global optimal solutions, which reached the minimum total cost, reliability allocation value at this time is for us to get the high-speed train gear transmission system reliability allocation policy. Table 2 shows the reliability allocation process obtained by Lagrange multiplier algorithm.

Table. 1. CRH6 high speed train gear transmission system expert rating distribution table

Components and parts	Important degree	Complex rate	Technology maturity	Standardization level
Gear box body	10.000	0.105	9.000	9.000
Bearing	10.000	0.421	9.000	6.000
Gear	10.000	0.211	10.000	10.000
Lube oil	10.000	0.263	9.000	10.000

Table. 1. CRH6 high speed train gear transmission system expert rating distribution table (Continued)

Components and parts	Maintainability	Current reliability	Maximum reliability
Gear box body	7.000	0.900	0.999
Bearing	8.000	0.900	0.999
Gear	8.000	0.900	0.999
Lube oil	10.000	0.800	0.999

Table 2. Reliability distribution process table based on improved cost function

Iterations	Gear box body	Bearing	Gear	Lube oil	Total cost
0	0.90000	0.90000	0.90000	0.90000	89.10351
1	0.99900	0.99900	0.99900	0.90489	48.83351
2	0.94950	0.99900	0.99900	0.94863	36.25966
3	0.95562	0.99900	0.97958	0.96122	31.18541
4	0.96105	0.98702	0.98110	0.96595	31.46476
5	0.93706	0.98690	0.98949	0.98247	38.57092
6	0.95047	0.98718	0.95946	0.99900	33.61079
7	0.96260	0.98771	0.95215	0.99350	31.88384
Iterations	Gear box body	Bearing	Gear	Lube oil	Total cost
8	0.95144	0.98764	0.96386	0.99303	30.85172
9	0.94294	0.98820	0.97519	0.99030	30.54130
10	0.94360	0.98868	0.97622	0.98819	30.22352
11	0.94738	0.98921	0.97518	0.98477	30.14179
12	0.94869	0.98911	0.97591	0.98277	30.10544
13	0.94979	0.98869	0.97646	0.98150	30.08462
14	0.95060	0.98807	0.97680	0.98095	30.06794
15	0.95115	0.98727	0.97700	0.98097	30.06013
16	0.95124	0.98667	0.97700	0.98148	30.05912
17	0.95112	0.98652	0.97693	0.98181	30.05910
18	0.95107	0.98654	0.97691	0.98186	30.05910

In the process of solving the model, the global optimal solution is obtained in the 18th iteration. Therefore, the 18th iteration is regarded as the final value of the reliability allocation, which is the reliability allocation strategy of all parts of the gear transmission system of high-speed train. The reliability of gearbox was increased from 0.90000 to 0.95107, with an increase of 5.107%. The gear reliability increased from 0.90000 to 0.98654, with an increase of 8.65%. Bearing reliability increased from 0.90000 to 0.97691, with an increase of 7.96%. The reliability of lubricating oil was improved from 0.8000 to 0.9819, with an increase of 8.19%. The overall reliability is 0.9000 from the original 0.5832, while the cost is controlled at 30.06.

4.4. Analysis of model solution results

Based on the improved cost function, it could be seen that the reliability allocation of the gearbox has been greatly weakened. The main reason for its weakening is that the gear box is designed to serve for a long time and it is an unrepairable part. Because the domestic production of gear box is still in the immature stage, so the use of imported gear box, its own comprehensive maintenance is low, but the degree of standardization is high, the technology is more mature. In its initial reliability design stage, it has high reliability requirements. Based on the principle of reliability allocation, not on the allocation of products and the low value of reliability allocation, once on the high reliability allocation values, you need to pay fees, costs on the economic front, but for now have the technology is also a huge challenge, therefore, in this chapter, the reliability of the proposed optimization allocation strategy. It weakens the reliability allocation value of non-maintainable and less structural parts such as gearbox.

Bearing, gear and lubricating oil are maintainable parts with short design life, so the d allocation effect obtained in the improved reliability allocation model is not much different from that of the traditional reliability allocation algorithm.

4.5. Analysis of results of three models

In this study, reliability allocation strategies for high-speed train gear transmission system are carried out under three methods, namely, AGREE allocation method (hereinafter referred to as method 1), reliability allocation method based on cost function (hereinafter referred to as method 2) and improved cost function allocation method (hereinafter referred to as method 3). The reliability allocation strategies obtained by the three methods are different. The following table compares the reliability allocation results of the three methods under the same initial system reliability conditions.

In the reliability allocation using these three algorithms, the calculation results are substituted into the three-parameter cost function, and the cost of using method 1 is 9.852, using method 2 is 6.340, using method 3 is 30.059. As the gearbox is an unmaintainable part in the service of high-speed train, it has little space for improvement and is difficult in the reliability design stage of the gearbox. Therefore, the reliability of the gearbox itself is set low in the example, which leads to the high cost in the calculation example after adding complexity.

As could be seen from table 3, method 1 has a certain optimization effect on the reliability redistribution of the system. However, in terms of reliability improvement, it has a poor effect on both reliability improvement and cost reduction due to the few factors it considers. In the method 2, on the premise of fully considering the total cost of the system and the four factors affecting system reliability improvement, the reliability of each unit of the system is greatly improved through the traditional

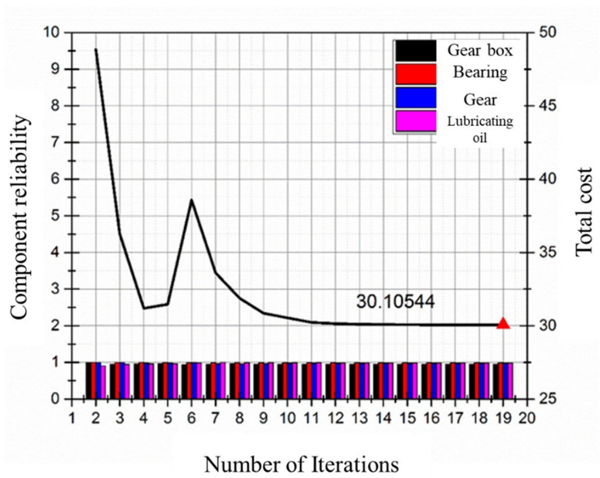

Fig. 7. Reliability distribution result graph based on improved cost function

Table 3. Three methods are used to compare the allocation results of system reliability

Components and parts	Original reliability of parts	method 1	method 2	method 3
Gear box body	0.90000	0.95599	0.97321	0.95107
Bearing	0.90000	0.82645	0.97164	0.98654
Gear	0.90000	0.91206	0.97528	0.97691
Lube oil	0.80000	0.89068	0.97589	0.98186

cost function constraint, which also meets the actual production demand and greatly reduces the cost. Method 3 combines AGREE method and the cost function constraint optimization method, and adds the complexity factor in AGREE algorithm on the premise of considering the importance, technology maturity, standardization degree and maintainability, then carries out reliability optimization allocation by improving the feasibility of subsystem reliability. Compared with the previous two methods, the final reliability optimization allocation results are significantly improved. Although there is an obvious increase in cost, the algorithm is carried out under the constraint condition of the minimum cost target. Therefore, compared with the extent of reliability improvement, the cost of upgrading key service components in high-speed trains is still within a reasonable range. Thus, fluctuations in the cost remain acceptable.

On the basis of the above, method 2and method 3 are further analyzed. The allocation strategy of method 2 and method 3 are obviously better than the allocation strategy of method 1. In the comparison of method 2 and method 3, for the convenience of comparison, the improvement degree of the reliability allocation strategy obtained by each method is calculated.

Table 4. Comparison of reliability improvement degree between two non-linear programming methods

Components and parts	Method 2: Improve the degree	Method 2: Improve the degree
Gear box body	8.140%	5.107%
Bearing	7.960%	8.650%
Gear	8.360%	7.960%
Lube oil	8.420%	8.190%

According to the analysis of the improved nonlinear programming model, it could be seen that it is very difficult to improve the reliability of the gear box. Therefore, method 3 is closer to the actual state of the gear transmission system of high-speed train at the cost of slightly abandoning some other reliability, and has a more scientific planning for the reliability allocation of the system.

In the stage of reliability design, limited to the design of components and other feasible costs, the allocation of reliability of mechanical system does not reach the optimal condition under existing conditions. The following conclusions are based on the condition that each component is unrelated and could not fail in the system:

1) Optimization is carried out through the AGREE algorithm. Based on the simplicity of the AGREE algorithm, the reliability of parts with low complexity will be improved more. The lifting effect of the other three components (bearing, gear and lubricating oil) is not good.
2) Based on the reliability optimization method of cost function, a reliability allocation scheme is obtained in which all four components are promoted to the same level. But the complexity of the actual parts is not taken into account.
3) When there is little difference in other conditions of components and the maintainability varies greatly on the premise of fully considering the complexity of components, the improved cost function reliability optimization allocation method could effectively improve the reliability of components in the reliability design stage and provide security guarantee for subsequent production and service. This method could be used effectively under reasonable technical conditions and cost conditions, and it has important guiding significance to improve the reliability of mechanical system components with high service importance and high replacement cost during service.

5. Conclusion

In this paper, the reliability optimization allocation algorithm based on the traditional cost function is improved, and a new index factor is added to the feasibility factor of improving the reliability of components in the cost function. By considering the individual differences among components, the objective function -- three-parameter cost function in the nonlinear programming model is redefined. In the AGREE allocation method, the allocation process is a top-down unconstrained allocation process, which is a method with poor system reliability constraints. In the traditional cost function, considering the optimization of the feasibility factor of its three-parameter cost function, in the actual allocation process, by considering the individual differences and quantity differences between components, the improved algorithm proposed in this paper is effective in the allocation results: the gear box is increased by 5.107%; the bearing is increased by 8.650%; the gear is increased by 7.960%; and the lubricating oil is increased by 8.190%. Compared with the AGREE algorithm, the improved algorithm applies the nonlinear programming method, which plays a good role in maintaining the system reliability in the process of reliability allocation. Compared with the traditional reliability allocation method based on the cost function, adding after reducing the complexity and fully considering the characteristics of the components, the increase in the reliability of the gear box has been reduced by 3%, and the reliability of bearings, gears and lubricants oil has been improved by about 1%. Component-level reliability allocation proposes a more scientific allocation method. It is of great guiding significance to the assignment work in the reliability design stage of high-speed train gear transmission system.

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