Reliability analysis of the optimized carrying door frame based on six-sigma

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Abstract. The door frame is a key component of the track door system. This paper uses the Six-sigma Analysis module in the finite element software ANSYS Workbench to analyze the reliability of the door frame, and regards its geometric dimensions and materials as random variables. Test design, Latin hypercube sampling, and Monte Carlo simulation calculations respectively obtained the reliability values of static strength and static stiffness of the door frame. The reliability values were analyzed to verify the rationality of the design.

1. Introduction
Six-sigma as a product quality standard, its meaning is that when the structure-related parameters obey a normal distribution and are all related to product quality and performance, there is a probability of product failure per 10,000 products. In the process of reliability analysis, you can analyze which random variables have a greater impact on structural stress or deformation, and describe them through statistical distribution functions, so that product designers can consider these uncertain parameters for product reliability in the design stage. It is effectively controlled to improve the reliability of the product structure.

In traditional structural design, deterministic analysis is generally used, that is, the deterministic value of each design variable (size, material property) of the structure is defined, and various analyses are performed on the basis of specified parameter values. However, in the actual production process, there are various uncertain factors in the change of design parameters, which lead to the uncertainty of the relevant parameters of the same batch of materials and parts, which makes the design parameters to some extent uncertain and dispersive. Therefore, the traditional structural design has certain defects. The use of reliability analysis can take into account the influence of these uncertainties on structural performance. Determined the impact of the uncertainty or dispersion of an input variable on the dispersion of output parameters (stress, deformation, frequency, etc. in finite element analysis). Determined the degree of influence of each random variable on the dispersion of output results and the probability of failure. Determined how sensitive the input parameters are to the output parameters. If the output parameters are indeed affected by the dispersion of the input variables, which leads to the dispersion of the analysis results, then the probability of meeting the design criteria is a quantitative description of the reliability.
2. Parameter setting
The structure of the carrying door frame: The carrying door frame is composed of a connecting plate, a square tube arm, a buffer head and a roller, which is shown in the Figure 1.

![Figure 1. The structure of the carrying door frame.](image)

Determination of analysis goals: For mechanical structural parts, component fracture is one of the most serious structural failures, which can lead to serious consequences. Therefore, it is necessary to first consider the reliability of the mechanical structure's strength and rigidity.

2.1. Selection and statistical treatment of random variables:
(1) Geometric size
Due to many uncertain factors in the manufacturing process, the size of each part will be different in mass production. Therefore, the size must be treated as a random variable. After practical inspection, it is found that the size can generally be considered to obey a normal distribution.

In this design, the tolerance level requirement of the door frame is GB/T1804-m, and the variation range of the selected random variable can be checked according to the standard tolerance table. When performing structural reliability analysis, usually the dimensional deviation of mechanical structural components conforms to the normal distribution [1]. The actual size value is used as the mean value of the main input parameter, and the tolerance is its standard deviation.

(2) Material characteristics
The material selected for the door frame in this design is Q235A, and the elastic modulus of the material has an important influence on the maximum stress and maximum deformation of the door frame structure. In this reliability analysis, the elastic modulus is taken as a random variable. The modulus of elasticity is generally considered to obey a lognormal distribution. The average value of the modulus of elasticity is 2E11pa, and its coefficient of variation is 0.03.

In summary, the random variables selected in this chapter and their distribution laws and values are shown in the table 1:

| Random Variables                  | Distribution type     | Mean   | Standard deviation |
|-----------------------------------|-----------------------|--------|--------------------|
| Length of connecting plate        | Normal distribution   | 288    | 0.5                |
| Width of connecting plate         | Normal distribution   | 95     | 0.3                |
| Connection board thickness       | Normal distribution   | 6      | 0.1                |
| Square tube arm width             | Normal distribution   | 65     | 0.3                |
| Square tube arm height            | Normal distribution   | 65     | 0.3                |
| Square tube arm thickness         | Normal distribution   | 6      | 0.1                |
| Bolt hole spacing of connecting plate | Normal distribution | 45     | 0.3                |
| Young's modulus                   | Lognormal distribution| 2E11   | 6E9                |
2.2. Parametric experiment design

Carry out the reliability analysis of the door-carrying frame. After the random variables are determined, the random variables shall be tested and designed. In this chapter, the Latin hypercube sampling design is selected. It can avoid the phenomenon that the calculation is invalid due to repeated sampling points during direct sampling. A total of 81 random sample points are generated, and a random combination diagram of design variables can be obtained as shown in the figure 2:

![Random Combination Chart of Design Variables](image_url)

Figure 2. Random Combination Chart of Design Variables.

Through the random combination diagram, you can see the random combination relationship between the design point and the parameter variable. The data of the variable has good dispersion and representativeness.

2.3. Parametric response surface analysis

(1) The influence of input parameters on output parameters.

After the experimental design, the influence of each parameter on the variable can be analyzed by establishing a parameter response surface model. The influence of some parameters on the maximum stress and deformation of the door frame is shown in the figure 3:
Figure 3. The influence of some parameters on the maximum stress and deformation of the door frame.

(2) Random parameter sensitivity and correlation coefficient analysis

After running Six Sigma analysis and calculation, the random parameter sensitivity histogram can be obtained in the response surface module. In the sensitivity histogram, you can intuitively see the influence of each design random variable on the reliability of different output results. The higher the column height of the variable, the greater the influence of this variable on the output variable, and the coefficient is negative. Negative correlation, a positive coefficient indicates a positive correlation, which is shown in the figure 4.

Figure 4. Parameter sensitivity graph.

3. Reliability analysis based on Six-sigma

When using Ansys Workbench for reliability analysis, Latin hypercube sampling is selected to extract random variables, and Monte Carlo method is used for simulation. According to Bernoulli’s law of large numbers, it can be known that as the number of simulations increases, the closer to the real one is Probability value, but the increase in the amount of data will lead to an increase in the number of
cycles and an increase in the amount of calculation, so the number of cycles is initially set to 10,000 here. When carrying out the static strength reliability analysis of the door frame, it is considered that its allowable stress is 80Mpa, and when the static stiffness reliability analysis of the door frame is carried out, it is considered that its allowable deformation value is 0.5mm.

(1) Histogram of random variable sample distribution
When using ANSYS Workbench for reliability analysis, you can intuitively observe the dispersion of random variables through the histogram of random variable sample distribution [2], and the histogram of random variable sample distribution can describe the distribution of random variables. The histogram of the random variable distribution after 10,000 simulations of the 7 random variables with geometric dimensions and elastic modulus selected through the sensitivity analysis is shown in the figure 5:

![Figure 5. Random variable histogram.](image)

(2) Reliability analysis results
The sample distribution curve shown in the figure is smooth and without gaps, indicating that the number of simulations meets the requirements.

Carry out the reliability analysis of the static strength of the door frame, that is, calculate the probability that the maximum stress of the door frame is less than the allowable stress of the door frame. Through 10,000 times of Monte Carlo simulation, the stress distribution histogram and cumulative distribution function of the door frame structure are extracted. The cumulative distribution function curve of the maximum stress of the door frame is shown in the figure:6:
Figure 6. Stress histogram.

Figure 7. Deformed histogram.

The sampling sample histogram is very close to the distribution curve, indicating that the number of simulations is appropriate, and the cumulative distribution function graph reflects the probability values corresponding to all samples. It can be seen from the figure that the maximum stress of the door frame is concentrated between 71~73Mpa, which is in this interval[3]. The probability accounts for more than 90%. Figure 8 is the probability list of the maximum stress of the door frame. The probability value of the parameter can be described more accurately through the table. From the table,
the probability that the maximum stress of the door frame does not exceed 80Mpa is 99%. It has high strength and reliability.

![Figure 8. Stress parameter probability list.](image1)

![Figure 9. Probability list of deformation parameters.](image2)

The histogram and cumulative distribution function of the maximum deformation distribution of the door frame are shown in the figure 8. In order to analyze the reliability of the maximum deformation of the door frame more quantitatively, the parameter probability list can be obtained as shown in the figure 9.

As shown in Figures 7 and 9, the probability that the maximum deformation value of the door frame is less than 0.14664mm is close to 1, indicating that the maximum deformation of the door frame is far less than the engineering allowable deformation of 0.5mm under the influence of random variables, and there is still a lot of Large safety margin[4].

This paper uses the Six-sigma reliability analysis module in ANSYS Workbench to perform a reliability analysis on the strength and stiffness of the gantry after optimization. Taking the geometric dimensions and material properties of the door frame structure as random variables, the reliability values of the static strength and static stiffness of the door frame are obtained through experimental design of random variables, Latin hypercube sampling and Monte Carlo simulation calculation. The reliability value is analyzed to verify the rationality of the design.

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