Optimization design of hoisting column for multi-casting system of solid rocket motor based on response surface method

Fulong Jiang¹⁺, Zhaoxia Cui¹, Yang Tao¹, Le Zhou²

¹Inner Mongolia University of Technology, Mechanical Engineering, Inner Mongolia, Huhehot, 010000, China
²Aerospace Sixth Institute, Inner Mongolia, Huhehot, 010000, China

*Corresponding author e-mail: 2803541366@qq.com

Abstract. The erection of the solid rocket motor multi-casting system is optimized. The three-dimensional parametric model of the column is established, and the static analysis is carried out to determine the total deformation and the equivalent stress distribution of the hoisting column. Take the important dimensions such as shaft diameter and length of column as design variables, mass, equivalent stress and maximum deformation as target variables. The multi-objective genetic algorithm based on response surface is used to optimize the size of the hoisting column. The results show that after optimization, the overall quality of the column is 28.931kg, which is reduced by 6.16kg, which is 17.7% lower than the original plan.

1. Introduction

The production process of solid rocket motor includes steps such as preheating, pouring, vulcanization and other steps. Pouring is an important part in the manufacturing process of the solid rocket motor. Due to the long casting process cycle, single shot casting has low productivity, it can't meet the needs of actual production. Therefore, the multiple pouring system is used to improve the pouring efficiency [1-2]. Its structure is shown in Fig. 1. The hoisting of the column components plays an important role in the entire system. After the pouring engine is filled with the medicine, the whole structure needs to be lifted from the vacuum casting cylinder through the lifting system. At this time, the overall structure weight of the hoisting parts reaches the maximum, and all the weight is borne by three hoisting columns in the hoisting process. At present, the design of hoisting column in China is traditional experience design. Excessive quality of the column will not only increase the manufacturing cost, but also increase the weight of the entire gating system and affect the work efficiency. Therefore, lightweight and good performance are the goals of the hoisting column design. At present, the design of mechanical structures has begun to change from traditional experience design to modern design. Many domestic scholars began to use modern design methods to optimize the design of mechanical structures. Response surface analysis is widely used in the optimization design of mechanical structures [3]. For example, Chongyang Huang [4] et al. Structural optimization design of bulk carrier based on response surface method, Hanqi Yang [5] et al. Optimization Design of Segmental Structure of Steel Box Bridge Based on Response Surface Model, Peng Wu [6] et al. Optimization design of pipe racking column based on ANSYS and response surface method, the
weight of the optimized scheme is reduced by 3.2%, and the maximum total deformation is reduced by 14.1%, therefore, it is feasible to lighten the column based on the response surface method. However, there is little research on the lightweight design of the hoisting column of the solid rocket motor multi-casting system.

In this paper, the multi-objective variable parameterized model is established for the hoisting column of the multi-engine gating system of solid rocket motor and the static analysis is performed by ANSYS Workbench software. Under the premise of ensuring the strength and deformation of the column, the response surface multi-objective genetic algorithm is used to determine the importance of the design variables through sensitivity, and the design variables are optimized to determine the appropriate lifting column size.

2. Finite element analysis of hoisting columns

2.1. The establishment of model

According to figure 1, the size of the hoisting column model is determined according to the solid rocket motor multiple casting system. As shown in Figure 2, the length of the column is 1367 mm, the diameter is 57 mm, and the thickness of the reinforcing plate is 8 mm. The material of the hoisting column is structural steel, the modulus of elasticity is 2.0×10^5 MPa, the Poisson's ratio is 0.3, and the density is 7890 kg/m^3.

Figure 1. Multiple casting system

1. Hoist ring 2. Hoist ring connection 3. Distribution plate 4. Hoisting column 5. Protective flange 6. Guide part 7. Strap ring 8. Hoisting platform

Figure 2. Lifting column model
2.2. **Meshing**
The upper end of the hoisting column is connected to the sling ring by a threaded connection, due to the small size of the thread structure, it's even much smaller than the cell size, it will affect the calculation process. So before the meshing, the column was unthreaded [7-8]. The quality of the grid determines the pros and cons of the analysis results, the finite element analysis adopts automatic mesh generation, element size is 3mm, generating 1434749 elements and 2006496 element nodes in total.

2.3. **Loads and constraints**
The lifting column and column connecting flange are connected by welding, and the rib plate is welded to enhance the bearing capacity. The flange surface at the lower end of the lifting column is connected with the lifting platform by high-strength bolts. After each pouring container is filled with slurry, the weight is about 800kg, after the weight of the third engine vessel plus the dead weight of the tooling, the overall hoisting weight is about 3t. Therefore, the maximum weight of each hoisting column allocated by the total weight is about 1t. Figure 3 shows the load and constraint conditions of the hoisting column.

![Figure 3. Loads and constraints](image)

2.4. **Analysis of calculation results**
After calculation, as shown in Figure 4, the maximum deformation of hoisting column is 0.025351mm. In the actual working condition, the precision of the pouring system is required to be 0.05mm, which can meet the maximum precision requirement of the hoisting column. The yield strength of the column is 235 MPa. Considering the manufacturing accuracy of column and other uncertain factors, the safety factor is 1.8. Therefore, the maximum allowable stress of the hoisting column is 235 / 1.8 = 130.5Mpa. As shown in Figure 5, the maximum equivalent stress of the column is 11.102 MPa, which meets its own strength requirement, so the size and quality of the hoisting column can be optimized.

![Figure 4. Deformation cloud diagram of the lifting column](image)  ![Figure 5. Equivalent stress cloud diagram of the lifting column](image)
2.5. The establishment of a parametric model

In this optimization, the column length \( H \), column diameter \( D \) and stiffener plate thickness \( L \) are selected as design variables, as shown in Table 1. According to the working conditions and installation coordination, the variable size ranges are established. The mass \( M \), the maximum deformation amount \( Q \) and the equivalent stress \( F \) of the column are taken as target variables. Among them, the weight of the column \( M \) is the most important target variable, and the weight of the column can reduce the quality of the whole system, shorten the process time, and reduce the waste of resources. However, it is required that the maximum deformation \( Q \) shall not exceed 0.05mm and the equivalent stress \( F \) shall not be greater than the allowable stress 130.5Mpa.

Table 1. Variation range of design variables

| Parameter   | Initial value(mm) | Lower limit (mm) | Upper limit (mm) |
|-------------|--------------------|------------------|------------------|
| \( H(\text{length}) \) | 57                 | 50               | 65               |
| \( D(\text{diameter}) \) | 1367               | 1355             | 1375             |
| \( L(\text{thickness}) \) | 8                  | 5                | 10               |

The established mathematical model of optimal design is shown in formula (1) (2) (3):

Optimization target:

\[
\begin{align*}
\text{Min } Z(x) &= \min(M) \\
\text{Min } Z(x) &= \min(Q) \\
\text{Min } Z(x) &= \min(F)
\end{align*}
\]

(1)

Constraint function:

\[
\begin{align*}
M &\leq 40\text{kg} \\
Q &\leq 0.05\text{mm} \\
F &\leq 130.5\text{MPa}
\end{align*}
\]

(2)

The range of values of the optimization variables:

\[
\begin{align*}
50\text{mm} &\leq D \leq 65\text{mm} \\
1355\text{mm} &\leq H \leq 1375\text{mm} \\
5\text{mm} &\leq L \leq 10\text{mm}
\end{align*}
\]

2.6. The multi-objective genetic algorithm

The lightweight model of hoisting column is a multi-objective optimization problem, its solution is more complex, but compared with the original genetic algorithm, its convergence speed is faster and the calculation result is more accurate. The multi-objective genetic algorithm based on response surface avoids the tedious process of repeated modeling calculation and effectively improves the optimization rate [9]. The calculation process is shown in Fig. 6.
2.7. The calculation of the design points Parameter sensitivity and response surface analysis

The generation of design points is the key to multi-objective optimization design. Fifteen design points are randomly generated by Design of Experiments. The three groups of variables are randomly assigned and combined together, and then the calculation results of fifteen sets of target variables are obtained through analysis and calculation. The fifteen groups of data are shown in Table 2, where H (mm) is the length of the column, D (mm) is the diameter of the column, L (mm) is the thickness of the reinforcing rib, M (kg) is the column mass, Q (mm) is the maximum deformation of the column, and F(Mpa) is the equivalent stress.

| Serial number | Column length(mm) | Column diameter(mm) | Stiffener thickness(mm) | Mass (kg) | Maximum deformation(mm) | Equivalent stress(MPa) |
|---------------|------------------|---------------------|-------------------------|-----------|-------------------------|-----------------------|
| 1             | 1365             | 57.5                | 7.5                     | 35.293    | 0.024949                | 11.218                |
| 2             | 1365             | 50                  | 7.5                     | 28.774    | 0.035536                | 14.786                |
| 3             | 1365             | 65                  | 7.5                     | 42.623    | 0.018173                | 7.8521                |
| 4             | 1355             | 57.5                | 7.5                     | 35.089    | 0.024761                | 10.813                |
| 5             | 1375             | 57.5                | 7.5                     | 35.497    | 0.025138                | 10.872                |
| 6             | 1365             | 57.5                | 5                      | 34.253    | 0.024707                | 10.742                |
| 7             | 1365             | 57.5                | 10                     | 36.357    | 0.024707                | 11.049                |
| 8             | 1356.9           | 51.402              | 5.4674                  | 28.931    | 0.033464                | 24.316                |
| 9             | 1356.9           | 63.598              | 5.4674                  | 40.22     | 0.020682                | 7.9955                |
| 10            | 1373.1           | 51.402              | 5.4674                  | 29.196    | 0.033848                | 26.122                |
| 11            | 1373.1           | 63.598              | 5.4674                  | 40.625    | 0.020933                | 8.0465                |
| 12            | 1356.9           | 51.402              | 9.5326                  | 30.744    | 0.033434                | 19.308                |
| 13            | 1356.9           | 63.598              | 9.5326                  | 41.75     | 0.020305                | 8.0621                |
| 14            | 1373.1           | 51.402              | 9.5326                  | 31.009    | 0.033819                | 19.079                |
| 15            | 13373.1          | 63.598              | 9.5326                  | 42.156    | 0.020556                | 7.9239                |

2.8. Parameter sensitivity and response surface analysis

Through the sensitivity analysis, we can get the degree of influence of the independent variable parameters on the target output, and then optimize the optimization of some independent variables.
based on this [8]. Fig. 7 shows the results of the global sensitivity analysis, it can be seen from Figure 7: the influence of the three independent variables on the output variables is different. The influence of the independent variables on the quality is positive correlation. D is the most sensitive to the quality, followed by L and H. D and l have the highest sensitivity to the maximum total deformation. The negative sensitivity coefficient indicates that the maximum total deformation will decrease with the increase of independent variable. D is a negative correlation with the maximum equivalent stress, and L and H are positively correlated.

![Figure 7. The global sensitivity analysis](image)

Through the results of the local sensitivity analysis shown in Fig. 8, the sensitive trend of the respective variable parameters to the maximum mass can be quickly viewed. Each sensitivity curve intersects the response point at which the sensitivity of the respective variables to the maximum mass is consistent.

![Figure 8. The local sensitivity analysis](image)

The Design Explorer module uses a full second-order polynomial to fit the response surface function. Fig. 9 shows the fit degree distribution map.
Combined with the sensitivity analysis results, the focus is on the corresponding surface of the column diameter $D$ and the thickness of the stiffener rib $L$ for the maximum mass, maximum deformation and maximum equivalent stress. Fig. 10 shows the maximum mass response surface. It can be seen from Figure 10 that the effect of $D$ and $L$ on the maximum mass is a linear positive correlation, and increasing $D$ and $L$ will increase the maximum mass. Fig. 11 shows the maximum deformation response surface. It can be seen from Fig. 11 that the influence of $D$ and $L$ on the maximum total deformation is a linear negative correlation, and increasing the values of $D$ and $L$ can effectively reduce the maximum total deformation. The corresponding surface results shown in Fig. 12 show that the influence of $D$ and $L$ on the maximum equivalent stress is nonlinear. As $D$ increases, the maximum equivalent stress first increases and then decreases, and the maximum equivalent stress increases as $L$ increases.

![Figure 9. The distribution of fit conformity](image1)

![Figure 10. Maximum mass response surface](image2)

![Figure 11. Maximum total deformation response surface](image3)
2.9. Optimization design point

Based on the weight reduction, through the analysis and comparison of fifteen sets of test design points, four design points are selected as alternatives. Preferred design points are shown in Table 3.

Table 3. Preferred design points

| Serial number | Column length (mm) | Column diameter (mm) | Stiffener thickness (mm) | Mass (kg) | Maximum deformation (mm) | Equivalent stress (MPa) |
|---------------|-------------------|----------------------|-------------------------|-----------|--------------------------|------------------------|
| 1             | 1365              | 50                   | 7.5                     | 28.774    | 0.035536                 | 14.786                 |
| 2             | 1356.9            | 51.402               | 5.4674                  | 28.931    | 0.033464                 | 24.316                 |
| 3             | 1373.1            | 51.402               | 5.4674                  | 29.196    | 0.033848                 | 26.122                 |
| 4             | 1356.9            | 51.402               | 9.5326                  | 30.744    | 0.033434                 | 19.308                 |

Considering the maximum mass and maximum deformation of the hoisting column, the second group of optimization schemes is selected. After rounding, H=1357mm, D=51mm, L=5.5mm. At this time, the overall quality of the column was 28.931 kg, which was reduced by 6.16 kg, which was 17.7% lower than the original plan.

3. Conclusion

(1) Through parameter sensitivity analysis and response surface analysis, it is found that the diameter D of the hoisting column and the thickness H of the rib are more sensitive to the maximum total deformation. Increasing the values of D and L can effectively reduce the maximum total deformation. The influence of D and L on the maximum equivalent stress is nonlinear. As D increases, the maximum equivalent stress first increases and then decreases. When L increases, the maximum equivalent stress increases.

(2) The response surface method is used to get the optimization scheme, which reduces the mass by 17.7% compared with the original scheme. Under the premise of satisfying the rigidity and strength of the column, the purpose of reducing the quality of the column is achieved, and the rapid optimization design of the column size is realized, which provides a certain reference value for the actual production and application.
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