Research on Lightweight Design of Automobile Collision Safety Structure Based on Multiple Materials

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Abstract. With the increase in car ownership and the increasing pressure of energy conservation and emission reduction, the lightweighting of cars has become an important development direction for traditional cars to reduce emissions and increase the endurance of electric vehicles. Aiming at the lightweight design of automobile crash safety structure, this paper proposes a variable section and multiple materials vehicle lightweight design framework based on collision safety. Taking a certain type of racing car frame as the research object, the lightweight design is carried out, and the optimal design scheme of racing car frame with good collision safety performance is obtained. Taking the lightest frame mass as the design goal, the optimal latin square design and response surface model are used to optimize the thickness of each pipe frame, and the lightweight frame optimization scheme based on the improvement of collision safety performance is obtained. Finally, under the premise that the peak acceleration of the cockpit is reduced by 20.02% and the amount of intrusion at the brake pedal is reduced by 25.31%, weight reduction of 14.38% is achieved. Based on the actual engineering situation, this paper constructs a lightweight design framework for automobiles based on collision safety, and provides an efficient optimization process for lightweight design of automobiles.

1. Introduction

In recent years, with the rapid development of the world's automobile industry, the car ownership has increased dramatically. Energy saving, environmental protection and traffic safety have become the primary focus of automobile research. As an important way to achieve the development goals of energy saving and new energy vehicles, lightweight technology has been listed as one of the core technologies in the energy saving and new energy vehicle technology roadmap[1~3]. There are two kinds of lightweight design methods: one is to use lighter materials; the other is to use optimization theory to optimize the structure design[4~6]. Jambor A. and Carle D. et al. [7,8] proposed a multi-material matching strategy that comprehensively considers the cost and weight reduction effect of the body material mainly with steel materials and supplemented with lightweight materials. The timber plan of the structure provides a reference; Liu Kaiyong of Hunan University [9] used Optimal Latin Hypercube Design to collect sample data such as body-in-white stiffness and modalities, and established a response surface model to lightweight design the body-in-white thickness and main cross-sectional shape. In the actual design and manufacturing, the lightweight and crash safety performance optimization of the vehicle are two design requirements that must be considered at the same time. At present, it is the mainstream method of vehicle optimization design to establish the mathematical model of lightweight by using approximate model and get the lightweight design scheme of crash safety structure by using appropriate optimization algorithm. Andersson J. and Redhe M[10] takes the cockpit intrusion and collision acceleration as the optimization objectives. After the experimental
design, an approximate response surface model is constructed, and the car is optimized based on frontal collision simulation; Zhang Junyuan of Jilin University\cite{11} according to the crash safety performance of the front anti-collision beam assembly in a vehicle collision, the anti-collision beam assembly was evaluated, and the lightweight design was completed by changing the structure and material of the front anti-collision beam assembly. Therefore, it is necessary to combine material replacement with structural optimization to propose a systematic design process. In this paper, the Formula Student Electric China (FSEC) racing frame is taken as the research object. Firstly, the finite element model will be established and statics analysis and collision simulation analysis will be carried out. Then, according to the calculation results, the section shape of the bar with larger deformation will be changed, the material of the bar with smaller deformation will be replaced, the safety performance of the initial design frame of the racing car will be preliminarily improved, and the frame mass will be reduced; Finally, through the optimization framework proposed in this paper, the thickness of each specification of pipe fittings in the preliminary improvement design of the frame is designed based on the lightweight design of collision safety, and finally the frame lightweight design scheme with good collision safety performance is obtained, which also verifies the effectiveness of the optimization design framework studied in this paper.

2. Finite Element Model of FSEC Car Frame

The FSEC is a formula car designing and manufacturing competition for colleges and universities. It is sponsored by China Automotive Engineering Society and faces international universities. It has been successfully held for six times. The competition is of great significance in improving and testing the comprehensive quality of students in automobile industry colleges and universities, accumulating talents for the rapid and sustainable development of the automobile industry, and promoting the exchange and cooperation among the industry-university-research. In this paper, a certain type of car frame is taken as the research object to complete the whole design process of car frame lightweight design. According to the material properties of 4130 steel, the specific parameters are set to give the corresponding material properties. Each part of the load is applied to the corresponding mounting point of the frame in the form of concentrated mass, and the gravitational acceleration is set for the whole vehicle to simulate the effect of gravity.

In this paper, the frame is restrained by the suspension joint, and the movement of the front suspension Y and the rotation along the X axis are restrained during the collision process. Then six degrees of freedom of the rigid wall are constrained. FSEC dynamic events include straight-line acceleration, 8-word surround race, high-speed barrier and endurance test. Among them, high-speed barrier test is the most prone to collision accidents, so the average speed of high-speed barrier test is taken as the initial speed of collision simulation. According to the average speed of race track in the competition, the initial speed of collision simulation is set as 40 km/h, that is 11.1 m/s.

This article uses the average speed in the high-speed barrier test that is the most prone to collision accidents in the FSEC competition as the initial speed of the crash simulation. The final finite element model of car frame frontal impact is shown in Figure 1, including 153545 elements, 151927 nodes, 1365 welding points and the mass of the frame is 45.4kg. After the modeling and parameter setting of the model, K file is generated and submitted to LS-DYNA solver for calculation\cite{12}.

3. Analysis of Collision Simulation Results of Frame

After completing the collision simulation calculation, the energy change curve obtained is shown in Figure 2. It can be seen from Figure 2 that the hourglass energy only accounts for 2.1% of the total energy. In the whole collision process, the energy is transformed from kinetic energy to internal energy and changes with time. After the collision, there is a certain rebound, but the total energy is basically unchanged, which conforms to the basic dynamics theory. The curves are smooth transition, without large hourglass energy and mass change, and the simulation results are reliable.
3.1 Deformation Analysis of Frame

On the premise of confirming the reliability of the calculation results, the deformation process of the front collision of the car frame is analyzed by viewing the model animation through the hyperview. The total calculation time of the simulation calculation is set to 0.05 s.

![Figure 1. Finite element model of front impact of racing frame](image1)

![Figure 2. Global energy change curve in vehicle crash](image2)

After calculation, it can be found that the main deformation of the frame in front collision occurs in the fore-cabin. As shown in Figure 3. At the same time, the front bulkhead and the lower support of the front bulkhead are obviously deformed, absorbing a part of the kinetic energy. Motor installation crossbar, differential installation crossbar and transmission device installation crossbar are deformed greatly, and some adjustments need to be made. The cockpit is less deformed, which can ensure that the driver has enough escape space after a collision. The overall deformation of the frame meets the initial design requirements, but the deformation absorption of the front cabin is insufficient, resulting in unreasonable deformation of the frame and there is room for improvement.

![Figure 3. Deformation diagram of racing car frame at maximum deformation moment](image3)

3.2 Analysis of Brake Pedal Deformation

For racing cars, the deformation at the brake pedal will directly cause the driver's leg injury and even affect the driver's escape safety. Therefore, the deformation analysis at the brake pedal is an important evaluation index for frontal impact. The deformation at the intersection of the left and right front bulkhead supports parallel to the position of the brake pedal can represent the deformation at the brake pedal. This paper selects these two points and outputs the amount of deformation for analysis. As can be seen from Figure 4, the amount of deformation on the left and right sides is slightly different, and the average value is taken as the amount of deformation at the brake pedal. The maximum deformation of the brake pedal in the initial design of the frame during a collision is 89.5mm.
3.3 Acceleration Analysis

Differentiate the speed curve to get the corresponding acceleration curve, and filter out the interference data by SAE60 filtering operation to get a more accurate acceleration curve. The processed acceleration curve is shown in Figure 5. At 0.013s, a peak acceleration of 58.297g appears. This value is close to the chest injury evaluation index $a \leq 60g$ in the frontal impact regulations. When a collision occurs, the driver is extremely vulnerable to the impact of the collision. This also shows that the front of the frame did not absorb the collision energy well during the collision. Therefore, the frame needs to be further adjusted to reduce the impact acceleration.

4. Multi-material Lightweight Design of FSEC Racing Frame Based on Collision Safety

From the results of the crash simulation analysis above, it can be seen that the initial design of the racing frame has some shortcomings in terms of crashworthiness, insufficient deformation and energy absorption in the front cabin, resulting in unreasonable deformation of the frame, excessive impact acceleration, and threatening the life of the crew. Therefore, some rods need to improve the cushioning effect of deformation energy absorption to reduce the impact acceleration.

4.1 Sectional Structure of The Frame Energy-absorbing Rod

The moment of inertia of a section is a geometric parameter that measures the bending capacity of the section. According to the competition rules, the frame can be used in the design of round tubes and square tubes.

According to the steel pipe specifications commonly used in racing frames, two pipe fittings with similar cross-sectional areas are compared. As can be seen from the Table 1, the cross section area of the square tube has a larger moment of inertia when the cross section area is similar, and it has a better resistance to bending deformation.

| Fitting size/mm×mm | Moment of inertia of pipe section/mm$^4$ | sectional area/mm$^2$ |
|--------------------|---------------------------------|---------------------|
| Round Pipe 25.0×1.5 | 7676                           | 110.7               |
| Round Pipe 25.4×1.6 | 8509                           | 119.6               |
| Square Pipe 25.0×25.0×1.2 | 10812                   | 114.2               |
| Square Pipe 25.4×25.4×1.2 | 11366                   | 116.2               |

According to the crash simulation deformation diagram of the initial design frame, we can see that the crossbars in which the motors, differentials, and transmissions are installed in the motor transmission cabin have a large bending deformation. They will be replaced by square pipes of similar cross-sectional area; The overall deformation of the front cabin is large, and the deformation of the support under the front bulkhead is particularly obvious. However, considering the difficulty of connecting the pipes with different cross-sectional shapes, and considering the square pipe is easy to install other
components, only the two pipes in the middle of the lower support of the front bulkhead and the cross bars of the upper support are replaced with square pipes of similar cross-sectional area. The frame structure of mixing round tube and square tube is used to optimize the cross-section shape and parameters of the frame steel pipe, increase its ability to resist bending deformation, and improve the utilization rate of steel pipe materials to achieve the purpose of frame lightweight.

4.2 Multi Material Structure of Frame

The density of aluminum alloy material is about 2700 kg/m³, which is only one third of steel, and has the characteristics of good process performance, easy forming, weldability, and good energy absorption effect. It is the first choice for lightweight vehicles. We can see from the crash simulation deformation diagram of the initial design frame that the side fittings of the motor drive cabin have less deformation during the collision, and they are replaced by aluminum alloy pipe fittings. According to the initial designed crash acceleration curve, it can be seen that the acceleration during the collision is high, which indicates that the front cabin of the frame does not absorb energy effectively. Therefore, the aluminum alloy with better energy absorption effect is used to replace the raw materials, in order to reduce the impact acceleration of the frame and achieve lightweight at the same time.

According to the rules of the competition, the minimum wall thickness of the aluminum pipe must not be less than 3.0 mm. The 25.0mm × 1.5mm pipe fittings in the frame are replaced with aluminum alloy pipe fittings with a thickness of 3.5 mm. The optimized geometric parameters of the frame pipe fittings are shown in Table 2.

| Parts or Uses                                      | outer diameter × wall thickness | material |
|---------------------------------------------------|--------------------------------|----------|
| Main rings, front rings, shoulder strap mounting bar | Round Pipe 25.4mm × 2.4mm      | 4130     |
| Side anti-collision structure, front partition, anti-roll frame diagonal support, power battery protection structure | Round Pipe 25.4mm × 1.60mm     | 4130     |
| Motor installation crossbar, differential installation crossbar, transmission device installation crossbar, two pipe fittings in the middle under the front partition, cross bars on the upper support | Square Pipe 25.0mm × 25.0mm × 1.20mm | 4130     |
| Front bulkhead support, main ring diagonal support | Round Pipe 25.0mm × 3.5mm      | 6061     |

4.3 Multi Material Structure of Frame

(1) Deformation analysis of the frame

View the model animation through HyperView to analyze the deformation of the front collision of the racing frame after lightweight design. It can be found that after the lightweight design, the deformation of the motor installation crossbar, differential installation crossbar and transmission device installation crossbar are greatly reduced, and the maximum deformation of the frame is concentrated at the front of the front compartment. The overall deformation has been improved compared to the initial frame design.

(2) Analysis of the amount of deformation at the brake pedal

After the lightweight design, the deformation curve at the brake pedal is shown in Figure 6. The maximum deformation at the brake pedal is 73.509 mm. Compared with the original design, the maximum deformation is reduced by 17.9%, and the optimization effect is obvious.
Figure 6. Deformation curve of brake pedal after preliminary optimization design

Figure 7. Acceleration curve after preliminary optimization design

(3) Acceleration analysis

After the lightweight design, the acceleration curve of the passenger compartment is shown in Figure 7, and the peak acceleration is 53.312g, which meets the occupant collision safety regulations and is reduced by 8.6% compared with the initial design.

After a preliminary lightweight design, it can be seen that while improving the collision safety performance of the frame, the material utilization rate is also improved.

5. Lightweight Design of FSEC Racing Frame Based on Response Surface Model

In the previous section, a preliminary lightweight design of the racing frame was made by changing the cross-sectional shape of the frame pipe fittings and the material of the pipe fittings. The influence of the thickness of the pipe fittings on the collision safety of the frame was not considered, and the thickness of the pipe fittings had room for weight reduction. Therefore, the thickness of each size of pipe is taken as the design variable to further lightweight the frame. On the premise of ensuring the crash safety of racing car frame, and considering the installation technology and material cost, the frame pipe fittings are divided into seven specifications, as shown in Figure 8.

Figure 8. Classification diagram of frame pipe fittings

The thickness of each specification of pipe fittings is taken as the design variable. In order to ensure the strength and stiffness of the frame structure, the thickness of main ring and front ring are not taken as design variables.

In this paper, the Latin hypercube test design method is used to select 36 sample points within the range of 6 variables. The data of these 36 sample points were substituted into the finite element model to calculate the maximum deformation at the brake pedal, peak cockpit acceleration, and frame mass.

(1) Establishment of response surface approximation model

The commonly used approximate models in engineering optimization problems mainly include response surface model, Kriging model and neural network model. These approximate models are compared in reference[13]. According to the comparison results, Response Surface Methodology(RSM) is used to construct the approximate model required in this paper[14]. RSM is an optimization method combining experimental design with mathematical statistics[15]. In this method, an explicit polynomial regression is constructed to approximate the implicit function between...
the output and the design variables. The quadratic polynomial response surface model is often used in practical engineering problems. The expression is as follows:

$$\hat{y} = \alpha_0 + \sum_{i=1}^{n} \alpha_i x_i + \sum_{i=1}^{n} \alpha_{i,i} x_i^2 + \sum_{i<j}^{n} \alpha_{i,j} x_i x_j$$

(1)

Where $\alpha$ is the unknown coefficient; $x_i$ is the $i$th design variable and $n$ is the number of design variables. The unknown coefficient $\alpha = [\alpha_1, \alpha_2, ..., \alpha_n]^T$ is usually calculated by the least square method. Finally, the fitting degree of the response surface to the responses is verified by determining factor $R^2$ in the analysis of variance. The expression is as follows:

Objective function: $\min (M)$;

design variable: $t_1, t_2, t_3, t_4, t_5, t_6$;

Restrictions: $A \leq 60g$;
$D \leq 71.6mm$;
$\min t_i \leq t_i \leq \max t_i$

(2)

Where $p$ is the number of design points; $\bar{y}, \hat{y}$, and $\bar{y}$ are the average values of the measured, predicted and measured values of the response respectively. The closer $R^2$ is to 1, it indicates that the better the fitting effect of the approximate model is. In general, if the determination factor $R^2$ is above 0.9, it is considered that the accuracy of the approximate model meets the requirements of optimal design.

The polynomial response surface method is a fast and efficient approximation method for solving such complicated dynamic problems as automobile collision. According to the selected sample points and their response values, a quadratic response surface model is used to fit the relationship between the peak acceleration of the cockpit $A / g$, the maximum deformation at the brake pedal $D / mm$, the mass of the frame $M / kg$, and the thickness $t / mm$. The response surface approximation model is shown in equations (3) to (5):

$$A = 121.43 - 55.19t_1 + 323.69t_2 - 114.36t_3 - 42.19t_4 + 11.87t_5 - 124.92t_6 + 12.66t_1t_2 + 8.23t_1t_3 + 2.27t_1t_4 - 14.25t_1t_5 + 14.43t_1t_6 + 71.77t_2t_2 - 139.63t_2t_3 - 22.39t_2t_4 - 25.77t_2t_5 + 31.07t_2t_6 + 54.87t_3t_3 - 3.57t_3t_4 + 15.5t_3t_5 - 34.21t_3t_6 + 3.22t_4t_4 + 47.43t_4t_5 + 13.5t_4t_6 - 59.41t_5t_5 - 10.05t_6t_6 + 56.64t_6t_6;$$

(3)

$$D = -969.41 + 110.77t_1 - 847.2t_2 + 580.95t_3 + 208.7t_4 + 181.7t_5 + 490.64t_6 + 65.27t_7 + 97.1t_1t_2 - 68.13t_1t_3 - 66.13t_1t_4 - 3.85t_1t_5 - 8.89t_1t_6 - 185.67t_2t_2 + 295.4t_2t_3 + 13.13t_2t_4 + 88.89t_2t_5 + 57.12t_2t_6 - 137.04t_2t_7 - 36.15t_2t_3 - 72.67t_2t_4 - 41.98t_2t_5 - 41.21t_2t_6 + 37.4t_2t_7 - 30.54t_3t_3 - 67.09t_3t_4 - 45.43t_3t_5 - 109.71t_3t_6;$$

(4)

$$M = 8.79 + 8.33t_1 + 3.76t_2 + 1.22t_3 + 1.5t_4 + 3.01t_5 + 1.15t_6 - 0.017t_1t_2 + 0.00028t_1t_3 + 0.006t_1t_4 - 0.0089t_2t_2 - 0.0084t_2t_3 + 0.0178t_2t_4 + 0.049t_2t_5 + 0.13t_2t_6 + 0.03t_3t_3 - 0.074t_3t_4 - 0.045t_3t_5 - 0.071t_3t_6 + 0.024t_3t_7 + 0.067t_3t_4 + 0.078t_4t_4 - 0.014t_4t_5 + 0.017t_4t_6 - 0.078t_5t_5 - 0.019t_5t_6 + 0.02t_6t_6 + 0.089t_6t_7;$$

(5)

The decision factors $R^2$ of the response surface approximation model are 0.974, 0.983, and 1.000, all of which are greater than 0.9, and the accuracy of the model meets the requirements of optimal design.

(2) Optimized design of frame pipe thickness

In the lightweight analysis of the frame based on collision safety, the optimization goal is to minimize the mass of the frame, to reduce the maximum deformation at the brake pedal by 20% after the original frame collision and the peak acceleration of the cockpit to be less than 60 g. The mathematical model of the optimization problem is as follows:
Objective function: \( \min \left( M \right) \);

design variable: \( \{ t_1, t_2, t_3, t_4, t_5, t_6 \} \);

Restrictions: \( A \leq 60 \text{g} \);
\( D \leq 71.6 \text{mm} \);
\( \min t_i \leq t_i \leq \max t_i \) \hspace{1cm} (6)

In this paper, a sequential quadratic programming algorithm is selected to find the optimal solution for lightweight frame. MATLAB is used to solve the optimization mathematical model. The optimal design variable solution is: \([t_1,t_2,t_3,t_4,t_5,t_6] = [1.414, 1.211, 3.431, 3.021, 1.388, 0.912]\), and the corresponding optimization results are \([A,D,M] = [47.775,67.534,39.108]\).

6. Verification Analysis of Optimization Results

In engineering practice, the thickness of the frame pipe is generally produced in units of 0.1 mm. Therefore, the optimal design variables are rounded to: \([t_1,t_2,t_3,t_4,t_5,t_6] = [1.4, 1.2, 3.4, 3.0, 1.4, 0.9]\), and the design variables after rounding are put into the finite element model of the frame as the optimization scheme for verification, and the corresponding response values are obtained through the simulation of the finite element model. The comparison of the peak acceleration curve before and after the optimization of the frame and the curve of the amount of deformation at the brake pedal are shown in Figures 9 and 10.

The approximate model prediction response value, finite element simulation response value of the optimization scheme and the initial design simulation result are compared, as shown in Table 3.

The following conclusions can be drawn from Table 3:

(1) The relative error between the response value of the response surface model and the finite element simulation model is within 5%, which verifies the accuracy of the response surface model;

(2) Compared with the original design, the optimized racing frame achieves a weight reduction of 14.38% based on a reduction in peak cockpit acceleration of 20.02% and a reduction in deformation at the brake pedal of 25.31%.

(3) The results verify the effectiveness of the lightweight design method for automobile crash safety structures based on multi-materials.

Table 3. Comparison of optimization results

| items                   | Initial design | Response surface model | Optimized Simulation value | Relative error | Optimization effect |
|-------------------------|----------------|------------------------|----------------------------|----------------|---------------------|
| Mass/kg                 | 45.439         | 39.107                 | 38.906                     | 0.52%          | 14.38%              |
| Peak acceleration /g    | 58.297         | 47.774                 | 46.627                     | 2.46%          | 20.02%              |
| Maximum deformation /mm | 89.511         | 67.534                 | 66.852                     | 1.02%          | 25.31%              |
7. Conclusions
1. This paper conducted a finite element analysis of the initial racing frame, evaluated the initial design, and replaced the frame material based on the analysis results, and proposed a multi-material frame structure.
2. A response surface model was established. Based on this, the thickness of each member of the racing frame was used as a design variable, the frontal impact safety performance parameters were used as constraints, and the minimum mass of the racing frame was used as the optimization goal to optimize the racing frame. The optimization work finally achieved a weight reduction of 14.38% based on a 20.02% reduction in peak cockpit acceleration and a 25.31% reduction in displacement at the brake pedal.
3. Based on the actual engineering situation, this paper proposes and establishes a lightweight design framework for automobiles based on collision safety, and realizes an optimized design that combines the lightweight design requirements of automobiles with the requirements of collision safety design. Provides an efficient optimization process for automotive lightweight design.

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