Topology optimization design of high-speed train body section based on optistruct

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Abstract

High-speed trains are important for accelerating the development of the regional economy. Realizing the lightweighting of high-speed trains has always been a goal pursued by designers. According to the principle of the topology optimization of realizing reasonable distribution of regional material, uses OptiStruct density method and the control method of the minimum members size for its lightweight design. Under the condition of ensuring that the stress, displacement and other constraints are met, an optimized structure of the distribution of the cross-section ribs is obtained. Comparing the optimized structure with the existing car body section rib structure, the analysis results show that the optimized structure weight reduction is 9.5%, which provides a theoretical reference for subsequent related engineering design.

Keywords

High-speed trains; train section; lightweight; topology optimization; OptiStruct.

1. Introduction

For the optimization of mechanical structure, topology optimization breaks through the limitations of traditional optimization methods in terms of size and shape, with higher level, more comprehensive design and closer to the original design intention [1]. According to the given external load and constraint conditions, the material can be reasonably distributed in the given optimization area under the premise of meeting various indexes such as stiffness and strength, so as to achieve the goal of weight reduction. In the initial concept stage, topological optimization determines the optimal topological optimization form of the structure through the optimal force transfer path inside the material, so as to guide the size allocation and shape determination of the global structure at a higher level, which will be greatly promoted and developed in the future.

2. Research status of topology optimization

Topology optimization can be divided into discrete topology optimization and continuum topology optimization according to the structure of the research object [2]. Objects for topology optimization of discrete body, such as frame structure, truss, membrane, etc. Objects of continuum topology optimization, such as two-dimensional plates and shells, three-dimensional entities. Topology optimization of discrete structures began to develop from the truss theory proposed by Michell[3] in 1904. Michell's theory can only be used in a single working condition and depends on the selection of appropriate strain fields. It was not until 1964 that Dorn, Gomory and Greenberg et al proposed the representative base structure method [4]. Later, Schmit expressed the structural optimization problem as a mathematical programming problem, which was solved by mathematical programming algorithm and became an important milestone in the field of structural optimization [5]. Xu Suqiang and Xia Renwei introduced genetic algorithm into trusses and conduct new explorations of topological methods [6]. In recent years, the pursuit of speed in aerospace, emus, vehicles and other fields requires the structure quality to be reduced as much as possible, which greatly promotes the development of topology optimization theory of continuum structure.

The commonly used topological expression forms and material interpolation model for topology optimization include: variable thickness method, homogenization method, variable density method, etc. The basic theory of the homogenization method is relatively rigorous, but the topology optimization algorithm based on it has many design variables, and the workload of optimization iterative calculation is very large. At present, it is generally used to solve the reverse problem and the theoretical research of topology optimization, and to solve the optimization design problem of material microscopic cells [1]. By establishing the relationship between element density and elastic modulus, the variable density method reduces the optimization design variables and simplifies the optimization solution process. It is the most convenient and promising topological optimization method in engineering.

In recent years, topology optimization has been developed rapidly, and it has been applied in aerospace, automobile and other fields. For example, Wu Xiuchun, Zheng Wenqiang [7] et al. used topology optimization method to optimize the design of bus body, so as to improve the performance of car body skeleton and reduce the quality.

Density method is adopted in this paper. Density method is to assume a material in many of the finite element cell.the material density within a single finite element cell is certain, but different finite element cell material density is different. The functional relationship between physical parameters of finite element and material density was established through mathematical model, and the ratio of the density of a single finite element to the density of raw materials was taken as the design variable. Finally, the optimization result was obtained through the selection of 0 ~ 1 threshold. The density method can use the volume and response of the structure, such as flexibility, displacement, frequency, etc. as the design target. The optimized volume ratio of the structure and the overall response of the structure, such as flexibility, displacement and frequency, are set as constraints. Local structural responses, such as stresses, can also be used as constraints. The specific expression is as follows:

$$\text{Find：} \mathrm{X} = \{x_1, x_2, \cdots, x_e\}^T \in R^N, \mathrm{e} = 1, \cdots, \mathrm{N}$$

$$\text{minimize：} \mathrm{C} = U^T K U = \sum_{e=1}^{N} U_e^T K_e U_e = \sum_{e=1}^{N} (x_e)^p U_e^T K_e U_e$$

$$\text{Subject to：} \mathrm{V} = \mathrm{f}\, V_0 = \sum_{e=1}^{N} X_e V_e \le V^*$$

$$\mathrm{F} = \mathrm{KU}$$

$$g_{(X_e)} - g_{(0)} \le 0$$

$$h_{(X_e)} = 0$$

Among them: $\rho_i = x_e \rho_0$, $E = (x_e)^p E_0$(it can be used in computing), $K_e = (x_e)^p K_0$. ρ_0,E_0, K_0 are respectively the density, elastic modulus and stiffness matrix of the initial element of the structure. ρ_i,E, K_e are respectively the density, elastic modulus and stiffness matrix of the structural element after optimization. P is the penalty factor, F is the force vector, and C is the overall compliance of the structure, U is the displacement column matrix, F is the optimized volume ratio. $g_{(X_e)} - g_{(0)} \le 0$, $h_{(X_e)} = 0$ are engineering constraints.

3. The optimization of emu body

In recent years, China's emu has developed rapidly. At present, railway designers have optimized the train body from many aspects.

For example, Li Ming, li minggao, li guoqing et al. [8] applied genetic algorithm to analyze the aerodynamic performance optimization of the head of the train driven by parameterized driving, carried out the optimization design of the key control variables related to aerodynamic characteristics of the locomotive, and proposed the aerodynamic shape of the head with better comprehensive performance.

For example, Hai bangjun [9] studied aluminum alloy car body from the aspects of car body structure, extrusion profile section form, determination principle of car body material and welding seam design principle. Li shiming [10] established the finite element simulation through the mechanical requirements and strength indexes of various parts of the vehicle body and other indicators, and verified the design of the car body meets the requirements of use.

For example, Zhou weixu, li zeyu et al. [11] compared and analyzed the advantages and disadvantages of CRH2, CRH3 and CRH5 vehicle body sections from the perspective of vehicle body section optimization, and combined with the better aerodynamic shape of model 3 vehicle and the more reasonable rib plate layout of model 5 vehicle, and designed a new vehicle body section comprehensively. Cai Shunyin, Chen shujuan [12] et al. designed the section through the selection and design of the profile, the connection mode of the profile, and the optimization of the size and included Angle of the reinforcement plate. Xie suming, wang siyang [13] et al. summarized the main load conditions and basic requirements for performance evaluation of the structural design of aluminum alloy body of high-speed emu based on relevant standards at home and abroad, and studied the influence of the typical cross-section shape of the body on the rigidity of the body.

At present, the optimization of the body section is more from the aerodynamic shape, profile selection, profile connection process, internal steel plate size and Angle design, etc. The traditional layout of the internal stiffeners of the train body is more based on the experience accumulated by the designers in the design of the car body, no specific quantitative standard is formed, and the optimal distribution of the internal stiffeners along the force transmission path is less based on the external stress conditions of the car body, which leads to the excessive density of the internal stiffeners in local areas and the redundancy.

In this paper, according to the railway boundary conditions, the maximum area of the external wall of the vehicle is obtained by subtracting the safety margin. According to the principle of space maximization inside the train determine the maximum area of the interior wall of the train. These two areas form the envelope of the body wall. The existing drum section is placed in the enveloping region, so that the section is enveloped in all aspects, then used topology optimization to find the reasonable distribution of internal stiffeners in the section. The reasonable distribution of the rib plate can be solved with the topological solution of the Optistruct software, and finally the goal of weight reduction of the body is achieved.

4. Establish topology optimization model

In this paper, a topological optimization model is established based on the aluminum alloy train body of a certain type of hollow extruded profile in CRH series.

4.1 Grid division

Train Body section model is based on partial data and relevant data of a certain model [14]. Because of the train body being symmetrical, and does not consider the influence of the train body windows and doors, the 1/2 plane model is established. In the HyperMesh software, the mixed triangle and quadrilateral elements are selected to conduct finite element mesh processing for the optimized model. After mesh division, the model has a total of 155,541 nodes and 152,863 elements, among which 152,326 quadrilateral elements and 537 triangular elements.

4.2 Materials and properties

The body of emus is welded from aluminum alloy hollow extruded profiles, so Al is selected as the material. In the actual production process of the train body, the roof, side wall and floor of the train body are often selected as the 6005AT6 model in aluminum (The actual production of the train body may be more than one aluminum alloy profile), so select its properties as the parameter setting criteria.

Mechanical performance parameters: density:$\rho = 2.7 \times 10^3$ kg/m^3, elasticity modulus: $E = 6.9 \times 10^4$ MPa, Shear modulus (mean value): $G = 24650$ MPa, Poisson's ratio: $\mu = 0.34$. The values are input into the HyperMesh according to the dimensional unification principle. MAT1, namely isotropic material, was selected from the HyperMesh material library.

4.3 Setting of working conditions

4.3.1 Constraints imposed

The constraints of topology optimization are similar to those of static analysis. The topological optimization in this paper is to seek the optimal reinforcement plate distribution in the vehicle body section. In order to prevent the displacement of the vehicle body section under external load, the acting position should be determined according to the actual situation. In this paper, according to the actual processing of the car body, the side wall and roof are welded by five extruded profiles, and the floor is welded by six profiles.

4.3.2 Load establishment

In the process of the train running, the body of emus is under complex and comprehensive road conditions, and there are a relatively large number of verification conditions for the train body, including 16 accumulative ones. Most of the working conditions are the verification of the longitudinal strength, stiffness and vertical bending of the vehicle body, which is relatively weak in relation to the verification of the vehicle body plane model. Therefore, this paper will not elaborate further. The vehicle body is subjected to different loads in vertical and horizontal direction. In this paper, different working conditions are effectively combined to make the vehicle body assume the worst working conditions. Through the optimization of the vehicle body section under the worst working condition, the goal of section optimization under different working conditions is met. The loading conditions are shown in table 1, and apply each load to the corresponding part of the vehicle body in a corresponding way. The constraints and loading conditions under various working conditions are shown in figure 1.

Tab 1 Load cases

Name	Vehicle roof	Mass of Side walls	Floor load	Baggage holder	Table	Crosswind
Standard load	Support the 100 kg of people walking	Take an average of 1.35T between 1.1 T and 1.6 T	There are five seats in each row	No	Bear 100 kg	Unit area wind pressure 540Pa
Maximum payload	Support the 100 kg of people walking	Take an average of 1.35T between 1.1 T and 1.6 T	There are 5 seats in each row and 4 people per square meter in the middle aisle	Per square meter bear 60 kg	Bear 100 kg	Unit area wind pressure 540Pa

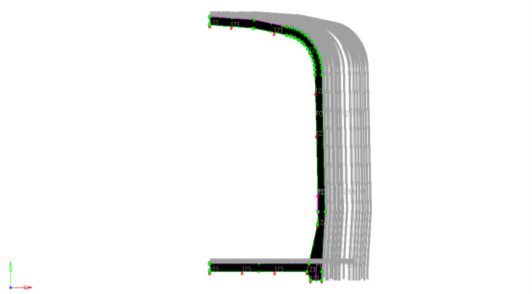
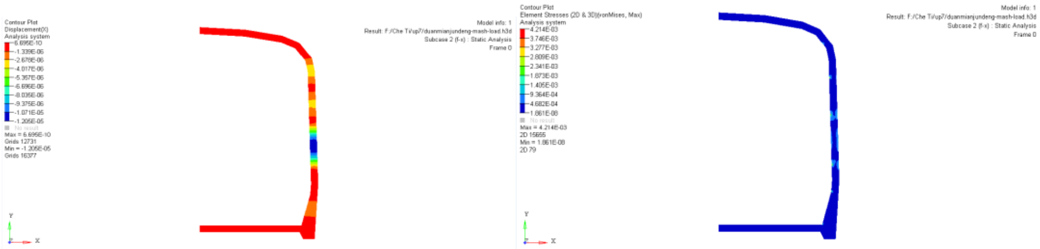


Fig1 load application

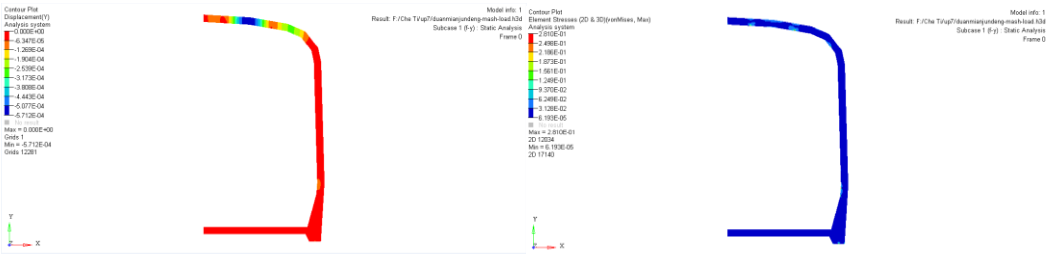
5. Static performance calculation and analysis

The topological optimization theory of Optistruct in Hyperworks adopts density method. Its processing principle is as described above. In the end, less important materials are discarded through the selection of different thresholds, so as to achieve efficient use of materials and realize lightweight design [2].

Optistruct solver solves the section with set load and constraint to obtain the displacement and stress cloud diagram of the vehicle body section under the worst combined working conditions. Since the forces acting in the X and Y directions are negative, the displacement in the X and Y directions is selected as the data source (the X and Y orientations are shown in the figure). The maximum displacement in the negative X direction is 1.2×10^{-5}mm, and the maximum stress is 4.214×10^{-3} MPa. The maximum displacement in the negative Y direction is 5.712×10^{-4} mm, and the maximum stress is 2.810×10^{-1} MPa. The statistical value of the train body mass by software is 1.660kg. The cloud diagram of displacement and stress is shown in figure 2.



Displacement in X direction Von-Mises stress in X direction



Displacement in X direction Von-Mises stress in X direction

Fig2 Displacement and Von-Mises stress on body section structure

6. Topology optimization of the train body section

6.1 Parameter setting in the train body section model optimization

The function key in the Optimization panel is used for parameter Settings for topology Optimization analysis. In the optimization process, the relative density of materials in the section area is taken as the design variable, the load and limit in the combined working condition of the vehicle body are taken as the constraints, and the volume (i.e., mass) of the section is taken as the optimization objective. The topology panel defines design variables, such as selecting PSHELL unit, selecting each optimization point as the topological response object in "responses", taking the displacement of each optimization point as the constrained displacement response in "dconstraints", and setting the volume as the target for topology optimization in "objective". Since there are many forces in combined working conditions, and the forces in different parts are different in size and manner, different thresholds are adopted to extract the optimization results in the roof, side wall and floor. After topology parameter setting is completed, Optistruct is used for calculation and solution, and the results are observed in the postprocessor HyperView[16]. After a total of 80 iterations, the material distribution of each part is obtained as shown in the figure below: the roof is shown in figure 3, the side wall is shown in figure 4, and the floor is shown in figure 5.

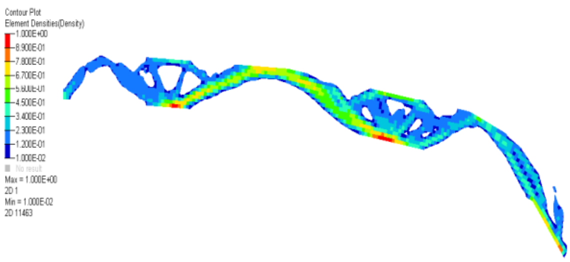


Fig3 Vehicle roof optimization results

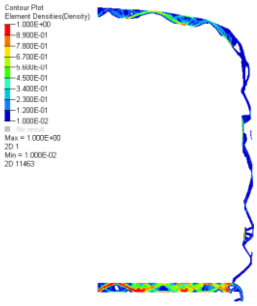


Fig4 Side wall optimization results

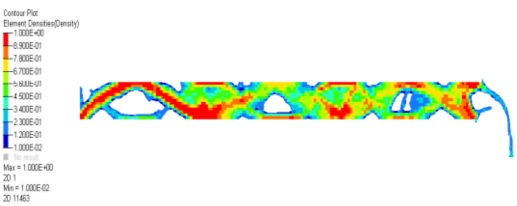


Fig5 Floor optimization results

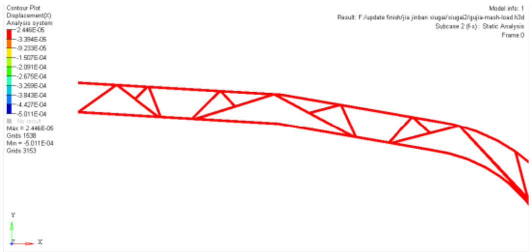


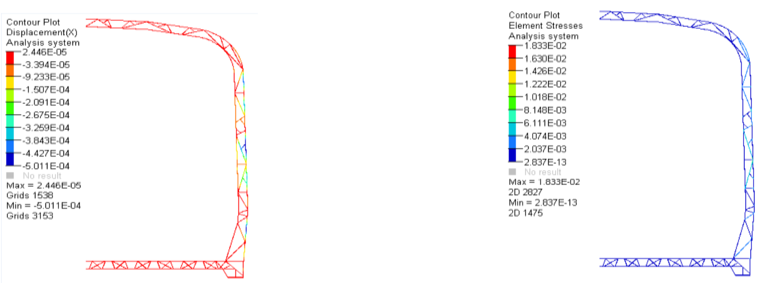
Fig6 optimized model of vehicle roof rib plate

6.2 A model of the train body section stiffeners after optimized

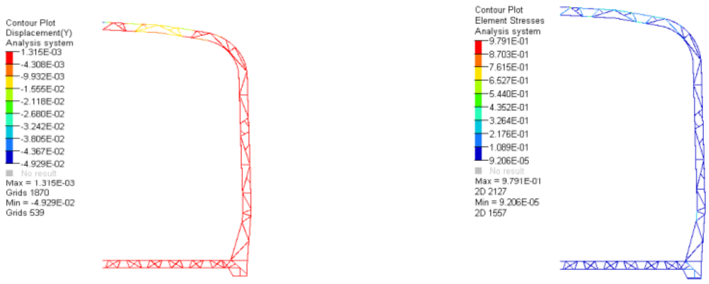
Taking the roof of the car as an example, the optimization results of the roof internal rib plate can be seen in figure 3. According to the location information provided in the HyperView, the optimized rib plate is arranged between the inner and outer walls of the roof, and the optimized cross-section of roof rib plate shown in figure 6 can be obtained. The cross-sections of the rib plates of the side walls and floors shall follow the same method.

6.3 Static analysis of the optimized vehicle body section

The distribution of the material of the rib plate of the train body after the topological optimization was analyzed.At the same time, the optimization section model of vehicle body was established according to the parameter setting in the earlier stage. Finite element analysis is carried out on the optimized car body section.The vehicle body load and constraint combination conditions were set to be the same as before the optimization, and the static analysis was carried out. The results obtained after the solution are as follows: the maximum displacement in the negative X direction is 5.011×10^{-4}mm, and the maximum stress is 1.833×10^{-2} MPa. The maximum displacement in the negative Y direction is 4.929×10^{-2} mm, and the maximum stress is 9.79×10^{-1} MPa MPa. The statistical value of the train body mass by software is 0.4512kg. The cloud diagram of displacement and stress is shown in figure 7.



a) Von-Mises stress in Y direction b)Von-Mises stress in X direction



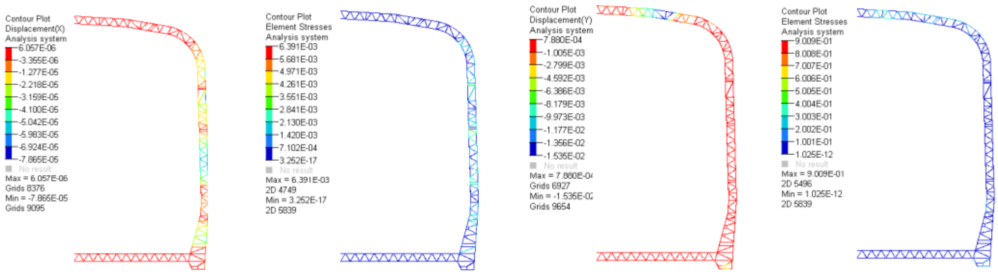
c)Displacement in X direction d)Displacement in Y direction

Fig7 Displacement and Von-Mises stress on body section structure

7. Result analysis

7.1 Static analysis of traditional train body

According to the partial data and relevant data of the enterprise, the static analysis of the traditional train body is carried out. Among them, the constraints and loads imposed on the existing train body are the same as the optimized vehicle body. The result is as follows: the maximum displacement in the negative X direction is 7.865×10^{-5}mm, and the maximum stress is 6.391×10^{-3} MPa. The maximum displacement in the negative Y direction is 1.535×10^{-2} mm, and the maximum stress is 9.009×10^{-1} MPa MPa. The statistical value of the train body mass by software is 0.4991kg kg. The cloud diagram of displacement and stress is shown in figure 8.



a) Displacement in X direction b) Von-Mises stress in X direction c) Displacement in Y direction a) Von-Mises stress in Y direction

Fig 8 Displacement and Von-Mises stress on body section structure

7.2 Comparative analysis of results

The static mechanical properties at each stage of the section were compared and analyzed, and the results are shown in table 2.

Tab2 Comparison and analysis

Name	Traditional vehicle Cross section	Existing vehicle Cross section	Optimized vehicle Cross section
Maximum displacement in the negative X direction /mm	$1.2e^{-5}$	$7.865e^{-5}$	$5.011e^{-4}$
Maximum stress in the negative X direction /Mp	$4.214e^{-3}$	$6.391e^{-3}$	$1.833e^{-2}$

Maximum displacement in the negative Y direction /mm	$5.712e^{-4}$	$1.535e^{-2}$	$4.929e^{-2}$
Maximum stress in the negative Y direction /Mp	$2.81e^{-1}$	$9.009e^{-1}$	$9.79e^{-1}$
quality /kg	1.660	0.4991	0.4512

It can be seen from table 2 that the displacement and stress of the optimized section are both increased in the X direction and slightly increased in the Y direction, and the stress is basically flat, but both are within the acceptable range. Under this condition, the optimized section can achieve a weight reduction of 9.5% compared with the traditional section.

8. The conclusion

In this paper, the finite element software HyperMesh is used to build the vehicle body section model, and the density method of OptiStruct software is used to solve the topology of the vehicle body section that under combined working conditions, so as to optimize the layout of the internal rib plate of the vehicle body. On the basis of the optimization results, a new scheme for the distribution of the rib plate of the vehicle body is proposed, which provides a reference for the design of the distribution of the gluten plate of the vehicle body section of the emu.

According to the optimization results, it can be seen that the topologically optimized section achieves a weight reduction of 9.5% compared with the traditional section. However, the comparison between the two was only based on the plane problem. The optimized rib plate was not extended to the longitudinal section of the whole vehicle body. Because the actual vehicle body still has gaps such as window opening and air conditioning opening in the longitudinal direction, it is not possible to simply apply the rib plate layout of topological optimization of local section to the whole longitudinal vehicle body. Such a longitudinal car body is quite different from the actual vehicle body in terms of strength, torsion and other indicators verification. In the later stage, the longitudinal topology optimization and the section topology optimization are combined to realize the optimization of the vehicle under the premise of meeting the indexes of strength and torsion.

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