Lightweight Optimization Design of a Light Electric Commercial Vehicle Frame

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Abstract. Aiming at the weight problem of a light electric commercial vehicle, a lightweight optimization idea is proposed, which is based on the design of the frame structure made of TC4 titanium alloy. Taken the strength, stiffness and stability of the longitudinal beam as the boundary constraints, and the minimum mass of the frame longitudinal beam as the objective function, the mathematical model was established, and the longitudinal beam size was optimized by ant colony algorithm. The influence of different materials on the strength and stiffness of the frame was analyzed from the bending and torsion conditions. The finite element model of the frame before and after optimization was established in ANSYS, and the static conditions before and after optimization were compared and analyzed. The results show that: under the constraint conditions, the frame weight of TC4 material is reduced from 122kg before optimization to 103kg after optimization, which is 15.5% less than that before optimization, and the stress and deformation of the optimized frame meet the service conditions, which has great advantages for reducing the vehicle weight and realizing the lightweight purpose.

1. Introduction
Lightweight optimization design of frame is one of the effective means to reduce the weight of electric vehicle [1]. Frame optimization methods usually include size optimization, topology optimization and structure optimization. Modern optimization algorithms mainly include simulated annealing algorithm, neural network optimization algorithm, genetic algorithm and ant colony algorithm [2] which suitable for different applications. In recent years, ant colony algorithm has been paid more attention in the field of mechanical optimization design [3]. Taking a light electric commercial vehicle frame as the research object, according to the load and size of the frame, ant colony algorithm is applied to optimize the size of the longitudinal beam section of TC4 light commercial vehicle frame, so as to obtain the optimal size to meet the stiffness, strength and stability, and then complete the design of other parts to realize the lightweight design of the frame.

2. Frame design and load treatment
2.1. Frame structure and parameter design
Considering that the target frame is not only simple in structure, but also low in process requirements, and has strong bearing capacity and torsional stiffness, the main body of the frame adopts the side beam structure. The dimension parameters of other members are shown in Table 1.
### Table 1
Frame component dimension parameters

| Component | Section shape | Size/mm                          |
|-----------|---------------|----------------------------------|
| Stringer  | Rectangle     | Total length 4200, Section width 110, Section thickness 8 |
| Beam      | Circular      | Ø40, Minimum width 840, Maximum width 1000 |

2.2. Load size and load form

In the finite element analysis, the load forms on the model are concentrated load and uniform load respectively [4]. The load on the frame is shown in Table 2.

| Load name         | Load value /N | Loading position | Direction |
|-------------------|---------------|------------------|-----------|
| Members           | 1300          | Third crossbeam  | X         |
| Drive motor       | 730           | Second crossbeam | X         |
| Power battery     | 1200          | Third crossbeam  | X         |
| Full load of goods| 4000          | Evenly distributed to the crossbeams(7th–9th) | X |
| Body weight       | 4000          | Evenly distributed on the two longitudinal beams | |

(Note: X - vertical down)

3. Frame rail optimization

3.1. Mathematical model

3.1.1. Design variable

![Figure 1: Longitudinal beam section](image)

The longitudinal beam is the key component to ensure the safety of the frame, its size and shape directly affect the strength and stiffness of the frame and the cost of the frame, and it is an important object of lightweight optimization. Taking the cross-section size of frame longitudinal beam $x_1$ and $x_2$ as the optimization parameters, the cross-section of longitudinal beam is shown in Figure 1, $x_1$ and $x_2$ the optimization range of parameters is shown in Table 3.

| Optimization parameters | Original size | Optimization scope |
|-------------------------|---------------|--------------------|
| $X_1$/mm                | 8             | 7-9                |
| $X_2$/mm                | 110           | 100-120            |

3.1.2. Optimization objective

The purpose of optimization is to reduce the weight of the target frame. The method is to change the structure size of the longitudinal beam, find the optimal cross-sectional area of the longitudinal beam, and then reduce the weight of the target frame. The objective function is as follows,

$$f(x) = \rho AL$$

In the above formula, $f(x)$ is the mass of a longitudinal beam; $\rho$ is the density of the longitudinal beam; $A$ is the cross-sectional area of a longitudinal beam; $L$ is the length of a longitudinal beam.
3.1.3. Optimization of boundary conditions
Under the constraints of longitudinal beam design variables \( x_1, x_2 \), it must be ensured that the maximum bending stress of the frame does not exceed the limit value of the allowable stress. Its expression is as follows,

\[
\sigma_{\text{max}} \leq [\sigma]
\]

In formula (1), \( [\sigma] = \frac{836}{1.4} = 597 \text{MPa} \), 1.4--- safety factor;
The maximum bending stress of the frame \( \sigma_{\text{max}} \) can be calculated by the following formula,

\[
\sigma_{\text{max}} = \frac{M_{\text{max}}y_{\text{max}}}{l} = \frac{M_{\text{max}}x_2}{2l} \quad \text{l} = \frac{110x_2 - (110 - 2x_1)(x_2 - 2x_1)^3}{12}
\]

In formula (2), \( M_{\text{max}} = 1.88 \times 10^6 \text{N/mm} \)
Can get,

\[
h_3(x) = 1 - \frac{[\sigma]}{\sigma_{\text{max}}} \leq 0
\]

The maximum deflection of the longitudinal beam shall not exceed the allowable deflection, its expression is as follows,

\[
W_{\text{max}} \leq [W]
\]

In formula (5) , \( [W] = \frac{L}{400} = 10.5 \text{mm} \);

\[
W_{\text{max}} = \frac{FL^3}{48EI}
\]

In formula (6), \( L \) is length of longitudinal beam, \( L=4200 \text{ mm} \); \( F \) is load on a longitudinal beam, \( F=2000 \text{N} \);
Can get,

\[
h_4(x) = 1 - \frac{[W]}{W_{\text{max}}} \leq 0
\]

The bending stress of frame rail should be less than the yield critical stress, its expression is as follows,

\[
\sigma_{\text{max}} \leq \sigma_{\text{cr}}
\]

The critical yield stress is calculated by the following formula,

\[
\sigma_{\text{cr}} = \frac{\pi^2 Eli}{(h_i)^2 A}
\]

Can get,

\[
h_5(x) = 1 - \frac{\sigma_{\text{cr}}}{\sigma_{\text{max}}} \leq 0
\]

3.2. Realization of ant colony algorithm based on MATLAB
Ant colony algorithm is a probabilistic algorithm for finding optimal path, and it is also a swarm intelligence algorithm [5]. The basic steps of ant colony algorithm are as follows,

1. \( \mu_c = 0 (\mu_c \) is the number of iteration steps), initialization of pheromone \( \omega_{ij} \) and \( \Delta \omega_{ij} \). Place \( m \) ants square on \( n \) vertices;

2. The initial starting point of each ant is placed in the current solution set \( Z_k(k = 1, \ldots, m) \). For each ant \( k (k=1, \ldots, m) \), it moves to the next vertex \( j \) according to the probability \( p_{ij}^k \), and the vertex \( j \) is placed in the current solution set;

3. Calculate the objective function value \( Z_k(k = 1, \ldots, m) \) of each ant and record the current best solution;

4. The ant trajectory is modified according to the updating equation;

5. For the arc of each side, do the following,

\[
\Delta \omega_{ij} = 0, \quad \mu_c = \mu_c + 1;
\]

6. If \( \mu_c < \) predetermined iterative algebra, go to step 2, continue the cycle.
Based on its characteristics, ant colony algorithm is selected as the optimization algorithm, and the longitudinal beam of the frame is taken as the target object.
Table 4 Part of parameter setting of ant colony algorithm

| Parameter                  | Values / Type |
|----------------------------|---------------|
| Ant numbers                | 300           |
| Ant movement times         | 80            |
| Pheromone volatilization coefficient | 0.9        |
| Transition probability constant | 0.2       |

After 80 iterations of optimization, the optimization results are shown in Figure 2. For the convenience of calculation, $x_1$ is taken as 7mm, $x_2$ is taken as 101mm. The comparison of parameters before and after optimization is shown in Table 5. After optimization, the cross-sectional area of the longitudinal beam is reduced by 15.49%; the weight of the frame longitudinal beam before optimization is 122kg, and the weight of the frame longitudinal beam after optimization is 103kg, the weight of frame rail after optimization is improved by 15.5%. And it is easy to verify that the optimized longitudinal beam structure size meets the variable constraints.

Table 5 Comparison of parameters before and after frame optimization

| Parameters                              | Before optimization | After optimization |
|-----------------------------------------|---------------------|--------------------|
| Size $x_1$/mm                           | 8                   | 7.0032             |
| Size $x_2$/mm                           | 110                 | 100.7080           |
| Cross sectional area of longitudinal beam $A$/mm$^2$ | 3264               | 2758               |
| Weight of longitudinal Beam W/kg        | 122                 | 103                |

4. Static characteristic analysis of frame before and after optimization

4.1. Material properties and finite element model

Simultaneous interpreting of TC4 has obvious advantages compared with traditional Steels: low density, good strength ratio, excellent corrosion resistance, high economy and impact resistance [6]. The mechanical properties of TC4 are shown in Table 6.

Table 6 Mechanical properties of TC4

| Material | Yield limit(MPa) | Elastic modulus(N/mm$^2$) | Density(kg/m$^3$) | Poisson's ratio |
|----------|------------------|---------------------------|-------------------|-----------------|
| TC4      | 836              | $1.09\times10^5$          | 4450              | 0.3             |

The frame model is built on CATIA platform, saved as STP format, imported into ANSYS Workbench platform, and the material is set. Because the parts of the frame are welded, riveted and bolted, the contact type of the parts is set to bonded. Because the frame model is a simplified model and has no complex connection, automatic mesh generation is adopted. The partition unit is 20 mm, and the frame generates 192114 nodes and 105297 units. The finite element model of TC4 light commercial vehicle frame is shown in Figure 3.
4.2. Static characteristic analysis

4.2.1. Simulation conditions

Static analysis of frame is the process of analyzing the response of frame under different loads [7]. The dynamic load of a car in motion will affect the frame, so a dynamic load coefficient should be introduced. Because the target frame is suitable for vehicles with moderate speed and mainly driving on urban roads, under different working conditions, the force of the frame is different, and its dynamic load coefficient is also different. According to the influence of dynamic load on the frame, the dynamic load coefficient of the frame is 2.5 under bending condition and 1.1 under torsion condition. According to the principle of static equivalence, the equivalent load of each component is applied to the corresponding position, and the frame boundary conditions are shown in Table 7.

| Position          | Degree of freedom constraint in bending condition | Degree of freedom constraint in torsion condition |
|-------------------|--------------------------------------------------|-------------------------------------------------|
| Right-front wheel | Z,X                                              | X,Y,Z                                           |
| Right-rear wheel  | X                                                 | X,Y                                             |
| Left-front wheel  | X,Y,Z                                             | X,Z                                             |
| Left-rear wheel   | Y,X                                               | Release all degrees of freedom                  |

(Note: release all 4 rotational degrees of freedom)

(a) Deformation diagram of TC4 frame under bending condition before optimization
(b) Stress diagram of TC4 frame under bending condition before optimization
(c) Deformation diagram of optimized TC4 frame under bending condition
(d) Stress diagram of optimized TC4 frame under bending condition

Figure 4 Bending condition of TC4
4.2.2. Bending condition

Full load bending condition is a common working condition, which simulates the stress distribution and deformation of the vehicle under full load and vertical load from the ground [8]. It is constrained according to the frame boundary conditions in Table 7 and loaded after multiplying the equivalent load by the dynamic load coefficient. The bending condition of TC4 material is obtained as shown in Figure 4.

4.2.3. Torsion condition

Torsion condition is a very dangerous condition. When the car is driving on uneven road, due to the uneven force on the longitudinal beam of the frame, when a certain wheel is raised or suspended, the frame is in the phenomenon of asymmetric support [9]. Taking the left rear wheel suspension as an example, the ability of the frame to resist torsion and deformation is analyzed when the vehicle is fully loaded. According to the frame boundary conditions in Table 5, the equivalent load is multiplied by the dynamic load coefficient, and then the TC4 torsion condition is obtained, as shown in Figure 5.

(a) Torsional deformation diagram of TC4 frame before optimization
(b) Stress diagram of TC4 frame under torsion condition before optimization
(c) Torsional deformation diagram of optimized TC4 frame
(d) Stress diagram of TC4 frame under torsion condition before optimization

Figure 5 TC4 torsion condition

4.2.4. Working condition analysis and discussion

The deformation of the frame mainly occurs at the rear end, which is mainly due to the location of the goods and the large load. It can be seen from the cloud images that they all occur in the direction of X, the maximum displacement before optimization is 3.74mm, and the maximum displacement after optimization is 4.82mm. The displacement increases by 28.8%, but it is less than the allowable deflection. The optimized frame meets the stiffness requirements.

Most of the stress values of the frame are small. Before optimization, the maximum stress of the frame is 132.53MPa, and after optimization, the maximum stress of the frame is 133.14MPa, and the stress increases by 0.46%, but they are less than the allowable stress, so the strength requirements are met after optimization.

Under the torsion condition, it can be seen that when the left rear wheel is suspended, the maximum deformation of the frame appears on the left side of the cargo box, and the maximum stress appears on the right rear wheel, which is in line with the torsion condition and the actual situation. The maximum displacement is 5.73mm before optimization and 6.84mm after optimization. The displacement increases by 19.3%, which are less than the allowable deflection. The optimized frame meets the stiffness requirements.
Most of the stress of the frame is small. The maximum stress of the frame before optimization is 132.15MPa, and the maximum stress of the frame after optimization is 145.30MPa. The stress increases by 9.95%, which are less than the allowable stress and meet the strength requirements.

5. Conclusion
(1) Taking the TC4 titanium alloy light-duty electric commercial vehicle frame as the research object, the longitudinal beam section of TC4 light-duty commercial vehicle frame is optimized by ant colony algorithm. The weight of TC4 frame is reduced from 122kg before optimization to 103kg after optimization, which is 15.5% less than that before optimization.

(2) After optimization, the cross-section size of the frame rail is found out through 80 iterations of ant colony algorithm, which shows that ant colony algorithm has good convergence and search ability in the optimization of frame size, and has certain robustness and parallel computing ability in solving nonlinear constraint problems.

(3) Before optimization, the maximum displacement and stress of the frame are 5.73mm and 132.53MPa respectively; after optimization, the maximum displacement and stress are 6.84mm and 145.30MPa respectively. Although the maximum displacement and maximum stress of the optimized frame are increased, they meet the requirements of material and design.

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