Research on Lightweight Design and Finite Element Analysis of a 9 Meter Bus Body Frame

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Abstract: The finite element model of a 10 meter bus body frame is built in Hypermesh software. The static force and modes of bus body frame under four typical working conditions are calculated by Nastran solver. The simulation of results show that the strength, stiffness, low natural frequency and vibration mode of bus body frame satisfy design requirement, and have enough potential reserve. Under the premise of ensuring the strength, stiffness and modal characteristics of bus body, the bus structure and dimensional parameters of parts are optimized to realize the lightweight design of bus body frame. The weight reduction rate of the optimized body frame is 10.57%, which verifies the feasibility of the optimized scheme.

1. Introduction
With the increasing shortage of global energy and manufacturing costs, the lightweight design has become the mainstream design of automobile manufacturers [1]. The weight of the bus body accounts for 30%-40% of the whole vehicle, but the cost exceeds 50% of it [2]. According to statistics, the total weight of the vehicle reduces by 10%, fuel consumption can be reduced by 6%-8% [3]. The lightweight design of passenger car is great significance.

There are three main ways to reduce the weight of body structure. 1) Using a more rigid structure and reasonable selection of plate thickness to reduce the frame weight. 2) Replace traditional low-strength steel with lightweight materials. 3) Update the manufacturing and connection process of skeleton parts [4]. There have been many research results in the lightweight design of body structure using finite element analysis method [5]. In this paper, we have fully studied the technical achievements of lightweight at domestic and abroad. The FEA (finite element analysis) model of the 9 meter bus body frame is established in Hypermesh. Its static and modal characteristics are solved by Nastran software. The simulation results show that the body frame strength, stiffness, low-order modal frequency and mode shape have a large margin reserve. So the body structure and the dimensional parameters of parts are optimized. The feasibility of the scheme is verified by comparing the simulation results of original and lightweight model.

2. FEA model and methods
In the case of guaranteed calculation accuracy, the bus skeleton is appropriately simplified. Some non-bearing parts, functional parts, all fillet and partial holes are deleted. The body frame is meshed by shell element in Hypermesh. The mesh size is 15mm. The FEA model of the bus structure is shown in
Fig1. The total elements are 407779. The triangle mesh is 1956 which accounts for 0.48%. It meets the accuracy requirements.

![Fig1 FEA model of bus structure](image)

The load of the bus body frame consists of bus skeleton mass, non-structural mass, equipment mass and passenger mass. Skeleton mass is calculated by FEA software. The mass of non-structural parts are simulated by mass element. The mass of equipment is applied with a mass element at its center of mass, and then distributed on the corresponding nodes of the body structure in the form of RBE3. The passenger mass is distributed on the body structure and the chassis frame. The mass of the bus main components is shown in Table 1.

| Name                  | Mass/kg |
|-----------------------|---------|
| Non-structural mass   | 1172.7  |
| Equipment mass        | 3589    |
| Passenger mass        | 2400    |
| Bus body Frame mass   | 2594.6  |
| Total mass            | 9756.3  |

3. Results and discussion

Under the four typical working conditions, the maximum Von.Mises stress of the body frame is shown in Table 2. The maximum deformation of the body frame is shown in Table 3.

| Assembly    | Bending/MPa | Torsion/MPa | Swerve/MPa | Brake/MPa |
|-------------|-------------|-------------|------------|-----------|
| Dash        | 79.2        | 83.25       | 108.5      | 89.89     |
| Back wall   | 24.5        | 55.3        | 60.5       | 32.8      |
| Left side wall | 135.7       | 125.3       | 123.4      | 101.3     |
| Right side wall | 137.2       | 79.3        | 112.3      | 105.7     |
| Headliner   | 40.84       | 60.32       | 43.78      | 31.97     |
| Reinforcement | 135         | 110.5       | 105.6      | 110.5     |
| Body frame  | 143.5       | 180.6       | 139.5      | 102.5     |

| Case       | Location                        | Maximum displacement/mm |
|------------|---------------------------------|--------------------------|
| Bending    | The bottom of body frame and reinforcement | 3.00                     |
| Torsion    | The window of left door         | 14.69                    |
| Swerve     | The middle of headliner         | 10.57                    |
| Brake      | The connection panel of reinforcement | 6.09                     |

It can be seen from Table 3 that the maximum displacement of the bus appears in the limiting torsion condition. Its value is 14.69mm which is less than the design value of 20mm. In summary, the strength and stiffness of the bus body meet design requirements. It has a large safety margin, so it can be optimized design.

The free mode of the body frame is calculated by Nastran software. The first ten-order elastic body modes are extracted (Regardless of the first six-order rigid body modes, which have no reference
significance). Their natural frequencies and mode shapes are shown in Table 4.

### Table 4 The first ten natural frequencies and mode shapes

| Order | Frequency/Hz | Displacement/mm | Mode shape description                |
|-------|--------------|-----------------|---------------------------------------|
| 1     | 8.02         | 1.92            | Back wall torsion                      |
| 2     | 8.50         | 1.64            | First-order vehicle torsion            |
| 3     | 13.52        | 2.25            | Second-order vehicle torsion           |
| 4     | 14.3         | 1.91            | First-order vehicle Y bending          |
| 5     | 15.28        | 2.32            | First-order headliner bending          |
| 6     | 15.98        | 4.01            | Second-order headliner bending         |
| 7     | 20.52        | 1.95            | Second-order vehicle Y bending         |
| 8     | 20.71        | 3.91            | Third-order headliner bending          |
| 9     | 21.10        | 2.12            | Bending and torsion combination        |
| 10    | 21.63        | 2.45            | First-order vehicle Z bending          |

The main vibration sources of bus body frame are uneven road surface, engine operation, the local vibration caused by the unbalanced rotating parts such as wheels. The ground excitation frequency is generally below 3Hz on highway; the frequency range caused by the unbalance of the transmission shaft is 33-36Hz; the frequency caused by the engine is above 35Hz (idle speed is 750r/min). The first ten-order modal frequency range of the body frame is 8-22Hz. It avoids the above-mentioned vibration source frequency and is not resonance phenomenon, so the modal frequency of the body frame is reasonable.

### 4. Lightweight design and simulation

The principle of lightweight: (1) The mass of components account for a large proportion of the whole vehicle; (2) The components have little effect on the strength and stiffness of the whole vehicle. According to the principle of lightweight and Table 2, it can be found that the roof stress is relatively small under the four typical working conditions. There is a large lightweight margin. The roof stress is the largest under the limiting torsion condition, its value is 60.32 MPa and safety factor is greater than 3. Its stress is shown in Figure 2. The stress values of other working conditions are all less than 45 MPa, and the safety factor is greater than 4, so the roof structure can be boldly lightened. The before and after of lightweight structure is shown in Figure 3.
It can be seen from Figure 2 that the maximum stress is mainly concentrated on 9 beams and air-conditioner mounting bracket under the limiting torsion condition. The stress is relatively small in the remaining areas. It can be seen from Figure 3, the lightweight area 1 removes 2 longitudinal stiffeners, the lightweight area 2 removes the 14 longitudinal beams between the reinforcing plates, and the lightweight area 3 removes 4 longitudinal short beams. At the same time, the cross section of other longitudinal beams can be changed from the original 50mm×40mm×1.75mm to 50mm×40mm×1.5mm.

It can be seen from Table 4 that the stress of the left side wall and right side wall are small except in the limiting torsion state. In the four working conditions, the left side body and right side body are subjected to relatively large forces, so only the cross-section size of the stiffener under the window is changed from the original 50mm×40mm×2mm to 50mm×30mm×2 mm.

It can be seen from Table 4 that the stress of the dash is relatively even under the four conditions. The door area of dash is not designed to be lightweight in order to keep the door open in the event of accident. The optimized area is mainly concentrated on the stiffener under the front of the bus, and its thickness is changed from 3mm to 2.5mm. The force of back wall is small under the four working conditions. Under the premise of keeping its structure unchanged, the cross section size of the connecting parts are changed from 50×40mm×2mm to 50mm×30mm×1.5mm.

The mass of frame and reinforcements accounts for about 65% of body frame. According to the principle of lightweight, it is the object of key lightweight design. It can be seen from Table 4 that the frame and reinforcements have greater stress under the four working conditions, but the maximum stress is concentrated on the middle and rear of frame. The main reason is that the engine and gearbox of the car are located in this area. Therefore, the section size of rear frame is kept unchanged in the lightweight design. The thickness of front longitudinal beam connecting plate is changed from 7mm to 5mm. The thickness of Front longitudinal beam reinforcement is changed from 7mm to 4mm. The outer periphery of the trunk is removed. The thickness of the body beam is changed from 6mm to 5mm. The thickness of luggage reinforcement is changed from 5.5mm to 4.5mm.

According to the results of the static analysis and modal analysis, and combined with the principle of lightweight, the lightweight results of parts are shown in Table 5.

| Assembly name | Weight before lightweight/kg | Weight after lightweight/kg | Reduce weight/kg |
|---------------|-------------------------------|----------------------------|-----------------|
| Dash          | 168                           | 160.75                     | 7.25            |
| Back wall     | 105                           | 95.2                       | 9.8             |
| Left side wall| 156                           | 145.31                     | 10.69           |
| Right side wall| 156                         | 145.31                     | 10.69           |
| Headliner     | 325                           | 275.4                      | 49.6            |
| Reinforcement | 308.9                         | 287.3                      | 21.6            |
| Frame assembly| 1394.5                        | 1228.1                     | 166.4           |
| Bus skeleton  | 2613.4                        | 2337.37                    | 276.03          |

It can be seen from Table 5 that the weight of bus skeleton is reduced from 2613.4 kg to 2337.37 kg. The weight is reduced by 276.3 kg, and the percentage is 10.57%.

According to the results of lightweight design, the FEA of body frame is rebuilt in Hypermesh. The constraint and load of each working condition are the same as original model. The result is solved by Nastran software. Comparing original and new model under four typical working conditions, the strength result and stiffness result of bus skeleton are shown in Table 6-7. The maximum stress and displacement are shown in Figure 4-5 under limiting torsion working condition.

| Case    | The maximum V on. Mises stress /MPa |
|---------|-------------------------------------|
| Bending| 143.5 | 160.6 | 11.92% |
Torsion | 180.6 | 240 | 32.89%  
Swerve | 139.5 | 145.3 | 4.16%  
Brake | 110.5 | 121.2 | 9.68%  

Table 7 Comparison of body frame stiffness

| Case | The maximum displacement /mm | Original model | Lightweight model | Rate of change |
|------|-------------------------------|----------------|-------------------|----------------|
| Bending | 3.00 | 3.2 | 6.67%  
Torsion | 14.69 | 18.33 | 24.78%  
Swerve | 10.57 | 9.34 | -11.64%  
Brake | 6.09 | 5.77 | -5.25%  

It can be seen from Table 6 that the stress of lightweight model increases under four typical working conditions. The value is less than the yield stress of the material which meets the design requirements. It can be seen from Table 7 that the deformation increases greatly under limiting torsion condition. The value is 18.33mm which is less than the design given value 20mm. The deformation changes are small in other working conditions. The analysis results verify the feasibility of the lightweight design.

The Lanczos method is used to analyze the modal of the body frame. The first ten elastic modal frequencies and vibration modes are obtained. The comparison of the modal characteristics between original model and lightweight model is shown in Table 8. The comparison of the first bending and torsion modes of the vehicle is shown in Figure 6-7.

Table 8 Modal characteristics of body frame

| Order | Original model | Lightweight model | Rate of change |
|-------|----------------|-------------------|----------------|
| 1     | 8.02           | 8.32              | 3.74%          |
| 2     | 8.50           | 8.95              | 5.29%          |
| 3     | 13.52          | 13.98             | 3.40%          |
| 4     | 14.3           | 14.92             | 4.33%          |
| 5     | 15.28          | 15.99             | 4.64%          |
| 6     | 15.98          | 17.06             | 6.76%          |
| 7     | 20.52          | 20.51             | -0.05%         |
8 20.71 21.20 2.37%
9 21.10 21.65 2.61%
10 21.63 22.56 4.30%

\( a \) Original model \( b \) Lightweight model

Fig 6 Comparison of torsion vibration modes of first-order vehicle

\( a \) Original model \( b \) Lightweight model

Fig 7 Comparison of Y direction bending vibration modes of first-order vehicles

In summary, by comparing the strength, stiffness and the first ten modal frequencies and mode shapes of the body frame between original model and lightweight model, it can be seen that the lightweight results meet design requirements, which verifies the rationality of the design scheme.

5. Conclusions
Through the dynamic and static analysis of the original model, it can be known that the strength, stiffness and modal frequency of body frame meet the design requirements. There is a large margin. The dimension parameters of the body frame and parts are optimized under the premise of ensuring the strength, stiffness and modal characteristics. Comparing the performance of the body frame between original model and lightweight model, the results show that the strength, stiffness and modal frequency meet the requirements. The weight reduction is 276.4 kg, and reduction rate is 10.57%. The weight reduction effect is obvious, which verifies the feasibility of the lightweight scheme.

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