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RESEARCH ON MODAL CHARACTERISTICS OF SHANGHAI METRO VEHICLE CAR BODY

Abstract. *This article takes the head vehicle body of Shanghai Metro Line 13 as the research goal, through the finite element analysis of the vehicle body, to view the structural characteristics of various parts of the car body. First of all, look at the relevant parameters of the car body, analyze its structure, save some parts that have little effect on the results, reasonably simplify the car body structure, and use UG to draw a simplified 3D head car model. The model was imported into the finite element analysis software Hyper Mesh, which was divided into grids, defined materials, defined units, and unit-giving materials. The analysis order and analysis mode were determined, and the modal analysis of the vehicle body structure was performed to see the results of the modal analysis. The body vibration pattern and natural frequency under different orders are obtained. Analysis and statistics can provide the theoretical basis for the optimization and design of the body structure.*

Keywords: Subway body; UG model; finite element model; modal analysis

Problem statement

The Shanghai Metro Line 13 vehicles use a large-surface-all-welded A-type aluminum alloy body. The materials are mainly made of aluminum alloy extruded profiles 7005 T6 and 6005A T6, and the car body material parameters are shown in Table 1. They have corrosion resistance and low density. Anti-stretch extrusion and other advantages. According to the structural parameters of the car body, it can be found that most of the material of the car body is an extruded aluminum alloy profile, and the material properties are excellent. Therefore, being selected by a large area of metro vehicles can greatly reduce the weight of the car body [1].

*Table 1 – **Body aluminum alloy material parameters***

Material used	Elastic Modulus / MPa	Poisson's ratio	Elastic limit / MPa		thickness / mm
			Non-welded area Weld area		
EN AW-6005A T6	6.9e4		225	146.0	T ≤ 5
			215	140.0	5 <t≤ 10
			200	130.0	10 < t ≤ 25
			210	136.5	2≤ t ≤25
EN AW-7005 T6	7.1e4	0.33	290	232.0	t ≤ 40

The design speed of the Shanghai Metro Line 13 is 80km/h. The type A subway car used is shown in Table 2 below.

*Table 2 – **Body structure and technical parameters***

Design speed / (KM/h)	80
Single compartment length (header)/mm	23600
Single car length (without car)/mm	22000
Width/mm	3000
Maximum outside height of the vehicle/mm	3800
Guest room height/mm	2100
Capacity/person	310
Gauge/mm	1435
Vehicle distance/mm	15700
Coupler center line height/mm	720
Fixed wheelbase/mm	2500
Quality/t	36

The head of the Shanghai Metro Line 13 headstock adopts a hollow double-layer structure. On the basis of two aluminum alloy plates, a sandwich layer is built inside, which can save material costs and meet technical strength requirements. From the structural point of view, the head car is mainly composed of a roof, side walls, end walls, a chassis, and a driver's cabin. The hollow sections are welded to form an integral whole with a strong overall rigidity and strong compressive performance characteristic [2].

The establishment of car body geometry model

In this paper, the Shanghai Metro Line 13 subway vehicle head vehicle as the research object, using the head vehicle's original data and model for UG simulation drawing. Due to the complexity of the actual car body model, the actual complexity of the car body is more than expected. If the actual model of the car body is completely drawn, it is very time-consuming and does not make much sense. The car body model is simplified and not processed. In the case of affecting the overall structural characteristics of the car body, unnecessary parts are omitted, only the main part of the car body is retained. The car body model thus obtained has met the test requirements and standards, and the simplification can greatly reduce the cost of modeling time. Model it in three dimensions. The modeling process is as follows:

1. Use the "difference" command to draw the overall body shell model;
2. Car body doors and windows and roof air conditioning position and other operations, get a preliminary body model;
3. Detailed processing and modification of the body model to obtain the final body model [3].

Firstly, through the original car body data, two overlapping cuboids are reasonably drawn. Through the “difference” command, the shell-like structure of the two ends of the vehicle body can be obtained. By drawing the shapes of the doors and windows at corresponding positions on both ends of the cuboid, the corresponding model is also obtained by finding the “difference”.

Considering the installation of air conditioning equipment on the roof of the vehicle body, the vehicle body model should be further operated. The air conditioning position housing at both ends of the vehicle roof and the position of the roof of the cab room should be removed. Taking into account the installation position of the roof to reserve the connection part, add the driver's room floor part, and carry out detailed processing of the roof and other components, and finally get the body model shown in Fig. 1 [4].

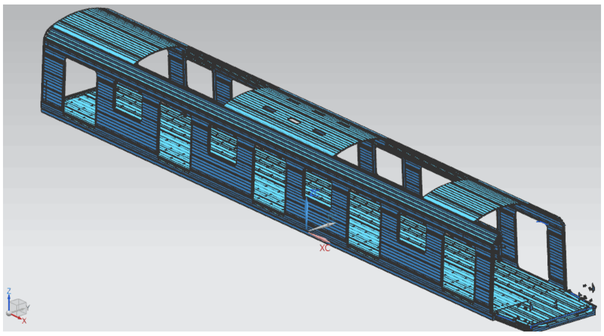


Figure 1 – Body simplified model

Establishment of a car body finite element model

This topic is based on the analysis of the headliner structure of the Shanghai Metro Line 13 heading. Therefore, we need to import it into the finite element analysis HyperMesh software based on the geometric model previously established in the UG software, as shown in Fig. 1. Meshing in HyperMesh. Among them, the division of the grid is an extremely important step, using a powerful automatic network. After the free division mesh is set up, it can be automatically divided, and the mesh quality is high and the operation is simple.

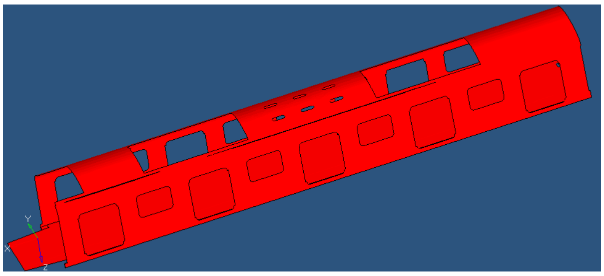


Figure 2 – Vehicle body model imported into HyperMesh

This article divides the four steps of the grid process:

1. choose to divide the grid tool;
2. select the panel mode;
3. select the unit standard;
4. select the algorithm.

The mesh is divided into free meshes. The panel mode selects size and bias. The unit influences the accuracy of the calculation. In general, the smaller the mesh is, the better the calculation accuracy is, and the calculation result is more accurate toward the true value. However, if the number of grids is too large, the density of the grids will continue to increase, and the calculation accuracy will not be greatly improved. However, the calculation time will be greatly increased, which will lead to a large increase in computational costs, which can be said to be unnecessary [5]. Therefore, the choice of grid size should be combined with a rational analysis of economics, where the unit size is 50mm and the type of hybrid unit is divided. The details of the car body grid that has been divided are shown in Fig. 3.

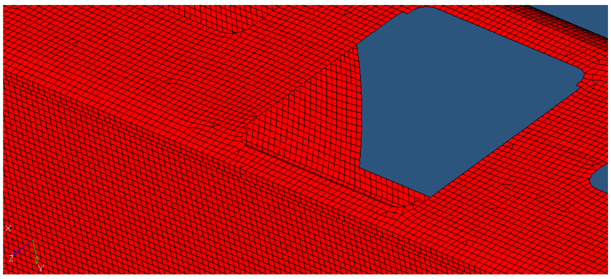


Figure 3 – Meshed body detail

The theoretical basis of modal analysis

Modal analysis is also called eigenvalue analysis. It uses linear analysis to solve frequency eigenvalues and modal eigenvectors. Through analysis and processing of the finite element model, the modal analysis obtains an analysis method of its inherent characteristics and plays an important role in the actual simulation analysis process. The subject vehicle body uses the form of undamped free vibration. Its basic principle is analyzed as follows [6].

Typical equations of motion for undamped structure free vibration:

$$[M]\{\&X\}+[K]\{X\}=\{0\} \quad (1)$$

In the formula, [M] -the mass matrix; {&X}-acceleration vector; [K]-stiffness matrix; {X}-displacement vector.

If the structure is vibrating with a fixed pattern and frequency, That is:

$$\{X\}=\{\phi\}\sin(\omega t+\varphi) \quad (2)$$

Then there: $\{\&X\}=-\omega^2\{\phi\}\sin(\omega t+\varphi)$ (3)

Substituting the above formula into subform 1, we get the equation:

$$([K]-\omega^2[M])\{\phi\}=\{0\} \quad (4)$$

Although $\{\phi\}=\{0\}$ is a solution, this solution does not show that all particles are in a static state. In order to obtain a non-zero solution, the following formula must also be satisfied:

$$\det([K]-\omega^2[M])=0 \quad (5)$$

The above equation 4 is called the characteristic equation of the structural vibration. The eigenvalue of the equation is ω_i^2. The regression characteristic equation is to find the characteristic vector $\{\phi_i\}$ corresponding to the characteristic value. The vibration frequency of the structure is the square root of the characteristic value ω_i, and the mode shape vector of the structure is the feature vector $\{\phi_i\}$. Using the finite element software HyperMesh for modal analysis, the vibration modes and natural frequencies of the vehicle body with different orders can be obtained. This provides a theoretical basis for structural optimization and structural rigidity in order to better understand structural features and structural stiffness [7].

Structural Mode Shape Analysis of Vehicle Body Structure

This topic uses modal analysis with HyperMesh. The basic process is as follows

1. Define material properties: Create materials, input Poisson's ratio, modulus of elasticity, density parameters;
2. Define cell attributes: Select the cell type as shell element;
3. Give the unit attributes to the material;
4. Define the modal order and frequency range;
5. Select the analysis mode, select modal analysis here;
6. Create a control card, set for different needs;
7. Solve and view the results.

After setting the above parameters and other settings, the finite element model of the car body is solved and analyzed. After the calculation is completed, check the modality of the car body. The natural frequency and mode shape of the 40th mode are as follows:

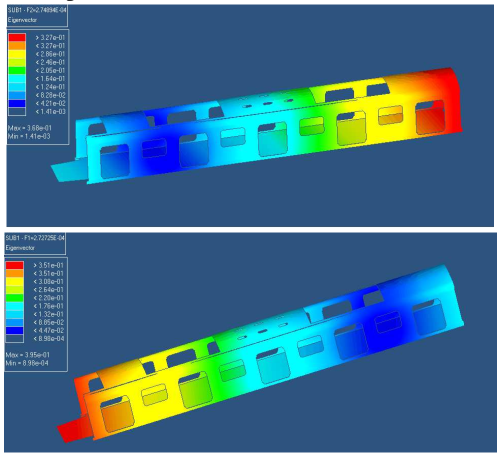


Figure 4 – 1st and 2nd Body Shapes

The first and second vibration modes are local deformation modes of the vehicle body, and the vehicle body exhibits rigid body characteristics, which has little effect on the vibration characteristics of the vehicle body. The first vibration mode is a local deformation of the front end, and the vehicle body makes a nod vibration around the rear end. The second-order vibration mode is just the opposite. The local deformation of the rear end causes the body to vibrate around the front end [8].

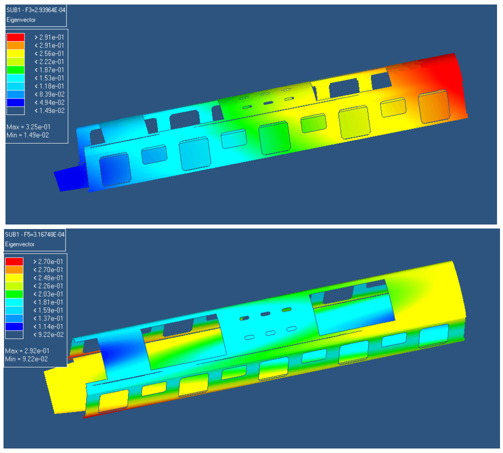


Figure 5 – Body 3rd and 4th vibration pattern

The 3rd and 4th vibration modes are the local deformation modes of the vehicle body, and the vehicle body shows the rigid body characteristics, which has little effect on the vibration characteristics of the vehicle body. The third vibration mode is the local deformation of the rear end, and the vehicle body shakes around the front end. The 4th vibration mode is just the opposite. It is a local deformation of the front end. The body oscillates around the rear end. The vibration pattern is very similar to the first two orders.

The fifth-order vibration mode is already an overall deformation, but it still exhibits the characteristics of a rigid body, and has little influence on the vibration characteristics of the vehicle body. The sixth-order vibration mode is a local deformation, showing the characteristics of a rigid body, and the effect of vibration characteristics is also very small.

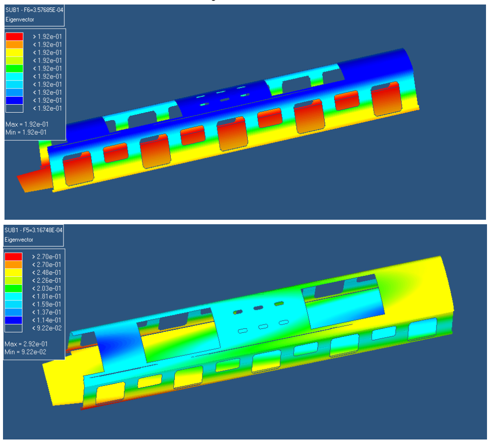


Figure 6 – The 5th and 6th vibration pattern of car body

The 5th vibration mode is the overall body deformation, but the difference in the deformation of each part is very small, the body does roll vibration. The sixth-order vibration mode is just the opposite [9]. It is a local deformation of the front end. The deformation of the lower part of the chassis and the side wall of the car body is relatively large, and the body of the vehicle is oscillating horizontally.

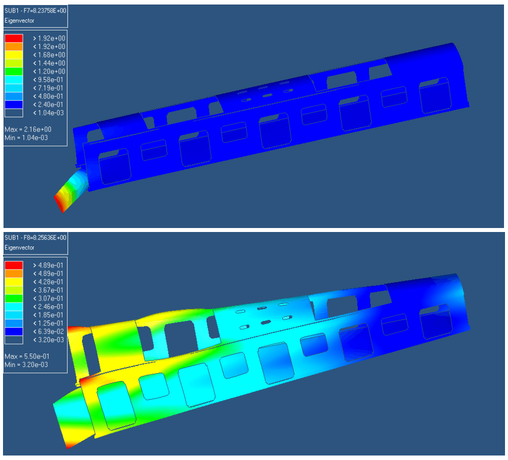


Figure 7 – The 7th and 8th vibration pattern of car body

The seventh-order vibration mode is a local deformation mode, and the vehicle body shows a rigid body characteristic, which has little effect on the vibration characteristics of the vehicle body. The vibration mode is the distortion of the driver's cab position of the chassis of the vehicle body, and the remaining places are only slightly deformed, and the natural frequency produces 4 orders of magnitude change.

The eighth vibration mode is a local mode and has little effect on the vibration characteristics of the vehicle body. For the first time, the body showed the characteristics of a flexible body. This is the boundary between the rigid body and the flexible body. The front end of the body is made into a rhombic vibration.

The 7th and 8th vibration modes have very important significance for the study of the vibration characteristics of the vehicle body. The 7th order produces an order of magnitude increase in the natural frequency, and the 8th order mode exhibits a flexible characteristic [10].

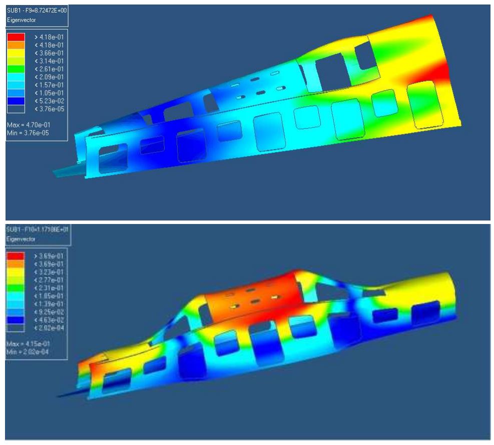


Figure 8 – The 9th and 10th vibration pattern of car body

The ninth vibration mode is the local deformation mode of the vehicle body, and the rear end of the vehicle body is strongly deformed. The rear end is made into a rhombic vibration mode, which has little effect on the vibration characteristics of the vehicle body.

The 10th-order vibration is a local deformation mode. The front, middle, and rear ends of the roof are strongly deformed. The front and rear ends of the roof are in phase with each other, and the middle portion of the roof is in phase opposition. The body is partially bent and deformed. The impact is small.

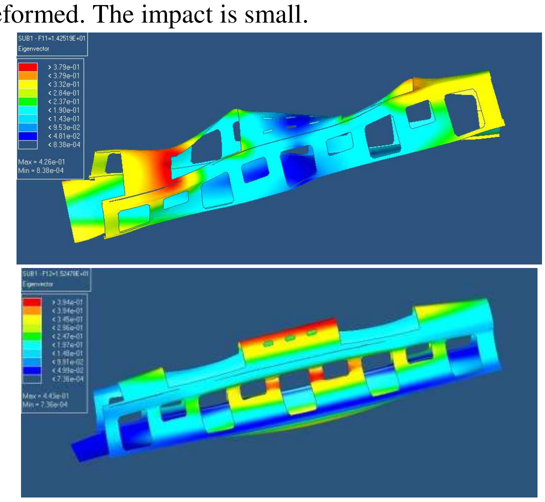


Figure 9 – The 11th and 12th vibration pattern of car body

The 11th vibration mode is the overall deformation mode of the car body. The torsional vibration of the car body is subject to a first-order torsional vibration, which has a great influence on the vibration characteristics of the car body. During the actual operation, if the vibration is close to 14.2519HZ, the car body is prone to severe vibration. This is the "resonance", which should be avoided during operation to prevent the occurrence of danger. This has great influence on the vibration characteristics of the vehicle body.

The 12th-order vibration-type body deformation mode, body vibration as a first-order vibration, a great impact on the body vibration.

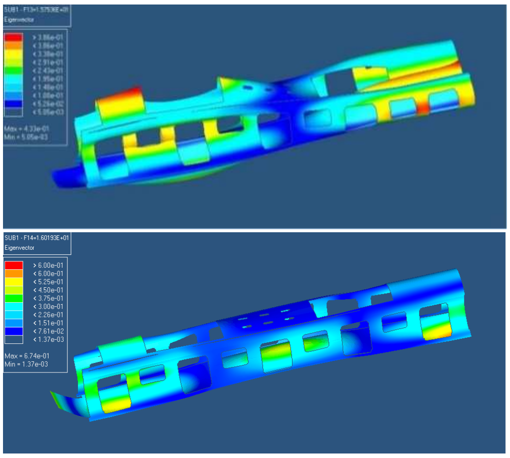


Figure 10 – The 13th and 14th vibration pattern of car body

The 13th vibration mode is the overall deformation mode of the vehicle body. The front and rear ends of the vehicle body are strongly deformed, and the front and rear ends perform the respiratory vibration mode. The vibration at both ends is reversed, which has a great influence on the vibration characteristics of the vehicle body.

The 14th vibration mode is the overall deformation mode of the car body. The front, middle and rear parts of the car body are strongly deformed. The front and rear ends of the car body are subjected to respiratory vibration, vibration is in phase, the middle of the car body is made respiratory vibration, and the middle deformation occurs. The smaller deformation and opposite phase at both ends have greater influence on the vibration characteristics of the vehicle body.

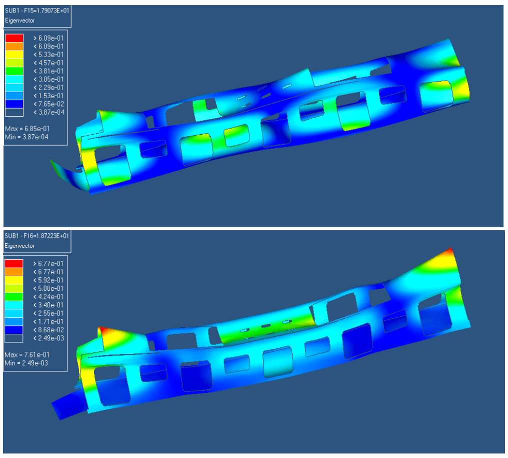


Figure 11 – The 15th and 16th vibration pattern of car body

The 15th vibration mode is the overall deformation mode of the vehicle body. The body is divided into four sections of local deformation. The direction of vibration from each of the adjacent two sections from the front end to the rear end is opposite, and the vibration form is respiratory vibration.The impact on vehicle body vibration characteristics is greater.

The 16th vibration mode is the local deformation mode of the vehicle body. The front, middle and tail ends of the vehicle body are strongly deformed. The front and rear ends of the vehicle body undergo respiratory vibration, and the vibrations are in phase with each other. The center of the vehicle body makes respiratory vibration, and the vibration is inverted. The deformation of the body frame is very small, which has little effect on the vibration characteristics of the vehicle body.

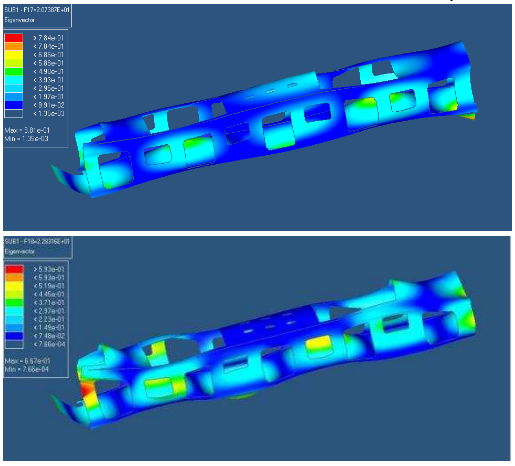
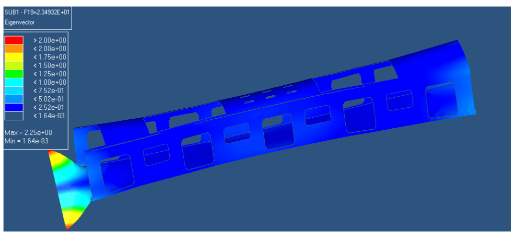


Figure12 – The 17th and 18th vibration pattern of car body

The 17th vibration mode is the overall deformation mode of the vehicle body. The body is divided into five segments with strong local deformation. The vibration manifests itself as respiratory vibration. The adjacent two segments are in opposite phase, and the deformation of the undercarriage is greater than the deformation of the sidewall and roof. The impact on the characteristics of the car body is greater.

The 18th vibration mode is the overall deformation mode of the car body. The car body is divided into six segments with strong local deformation. The vibration manifests itself as respiratory vibration. The adjacent two segments are in opposite phase, and the first, second, fifth and sixth segment deformations are obvious. The deformation of the roof of the 3rd and 4th sections is very small, which has a great influence on the vibration characteristics of the vehicle body.



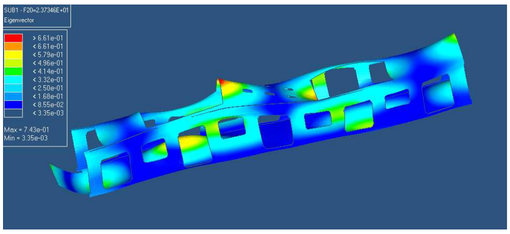


Figure 13 – The 19th and 20th vibration pattern of car body

The 19th vibration mode is the local deformation mode of the vehicle body. The chassis of the driver's cab is strongly deformed and the vibration manifests as torsional deformation, which has little effect on the vibration characteristics of the vehicle body.

The 20th vibration mode is the overall deformation mode of the car body. The car body is divided into four segments with obvious local deformation. The vibration manifests itself as respiratory vibration. The vibrations of two adjacent segments are in antiphase, and the deformation in the middle two segments is greater than the deformation in both ends. The effect of vibration characteristics is greater [11].

*Table 3 – **20th-order modal frequency and mode statistics***

Order	frequency /Hz	Modal Shape
1	2.72725E-4	Front-end deformation + end point
2	2.74894E-4	Backend deformation + nodding around the front end
3	2.93964E-4	Rear end deformation + shaking around the front end
4	3.03055E-4	Front end deformation + shaking around the back end
5	3.16748E-4	Overall deformation + roll
6	3.57685E-4	Base frame, side wall lower half deformation + yaw
7	8.23758	Distortion of driver's cab chassis
8	8.25636	Body front breathing
9	8.72472	Rear body breathing
10	11.7186	Roof front, middle (inverted), rear end deformation + local bending
11	14.2519	First-order twist
12	15.2478	First-order breathing
13	15.7536	Front and back breathing (inverted)
14	16.0193	Front-end, middle (inverted), back-end breathing
15	17.9073	Four breaths (adjacent inversion)
16	18.7223	Front-end, middle (inverted), back-end breathing
17	20.7387	Five breaths (adjacent inversion), only strong deformation of the chassis
18	22.8316	Six breaths (adjacent inversion)
19	23.4932	Distortion of driver's cab chassis
20	23.7346	Four breaths (adjacent inversion)

Conclusions

1. The 6th order vibration of the vehicle body shows rigid vibration, the vibration frequency is very small, the deformation is very small, and it cannot be considered in the actual design and analysis of material stiffness.

2. At the beginning of the 7th order, four orders of magnitude change occur in the vibration frequency. Attention should be paid to this node during design. Most of the orders of the 8th order and later have a large local or overall deformation, and the car body design needs to pay attention to analysis.

3. The 11th-order vibration is a first-order torsion, which has a great influence on the vibration characteristics of the vehicle body. During the actual operation, if the vibration is close to 14.2519HZ, the vehicle body is prone to severe vibration. This is the “resonance” and it is necessary to run Take care to avoid the danger. The 12th-order vibration-type body deformation mode, body vibration as a first-order vibration, a great impact on the body vibration. These two-step vibrations require special attention in the body design.

4. The subsequent frequencies exhibit different vibrations. The actual process is analyzed individually.

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ДОСЛІДЖЕННЯ МОДАЛЬНИХ ХАРАКТЕРИСТИК ВАГОНІВ МЕТРО МІСТА ШАНХАЙ

Анотація. *Ця стаття розглядає переважно вагони Шанхайської лінії метро № 13 як мету дослідження за допомогою аналізу кінцевих елементів кузова, щоб переглянути структурні характеристики різних частин кузова. Перш за все, подивітися на відповідні параметри кузова, проаналізувати його структуру, зберігти деякі деталі, які мало впливають на результати, доцільно спростити структуру кузова автомобіля та використовувати UG, щоб намалювати спрощену 3D-модель вагону. Модель була імпортована в програму аналізу кінцевих елементів HyperMesh, яка була розділена на сітки, визначені матеріали, визначені одиниці та одиничні матеріали. Визначено режим замовлення та аналізу, а також модальний аналіз структури кузова транспортного засобу, щоб побачити результати модального аналізу. Отримано вібраційний візерунок тіла та природна частота підрізними порядками. Аналіз та статистика можуть забезпечити теоретичну основу для оптимізації та дизайну структури.*

Ключові слова: корпус метро; Модель UG; модель кінцевих елементів; модальний аналіз

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