# Optimized Lightweight Frame for Intelligent New-energy Vehicles

Peipei Wu*

*Department of First, North China University of Water Resources and Electric Power, Zhengzhou, China, 450000*

Received April 19, 2023; Accepted May 19, 2023; Published June 2, 2023

In this paper, a joint optimization method based on multi-objective response surface approximation model and finite element simulation program is proposed to realize the lightweight optimization of new-energy vehicle frames. Under the premise of satisfying the constraints of strength, frequency and vibration, the thickness of different important parts is optimized to achieve the goal of minimizing the quality of intelligent vehicles. In order to obtain the stress distribution of each part and the vibration frequency of the frame, various finite element analyses of the intelligent vehicle frame are analyzed. In order to achieve optimization, this paper adopts the response surface method for multi-objective optimization. Sample data was generated by the central composite design, and the response surface optimization method was used to filter out 5 design variables that had a large impact on the frame. As a result, the weight of the frame was reduced from 25.05 kg to 19.86 kg, a weight reduction of 20.7%, achieving a significant weight reduction effect. This method provides important reference value and guiding significance for the optimization of frame and its lightweight. In this way, the design of the frame can be better optimized to make it lighter, thereby improving the performance of the smart car. At the same time, this method can also be applied to optimization problems in other fields to achieve more efficient and accurate optimization goals.

*Keywords: Intelligent new-energy vehicle, Vehicle frame; Finite element analysis; Lightweight; Optimization*

## Introduction

With the continuous development of intelligent new-energy vehicle technology, the importance of intelligent new-energy vehicle frames has been paid more and more attention. The lightweight design of the frame of the intelligent new-energy vehicle can not only improve the performance of the whole vehicle, but also reduce energy consumption and reduce environmental pollution. Therefore, it is of great theoretical and practical value to study the lightweight design of intelligent new-energy vehicle frames. The lightweight design of the frame of intelligent new-energy vehicles can be realized by various methods, such as material optimization, structural design optimization and process optimization. In this paper, a joint optimization method based on multi-objective response surface approximation model and finite element simulation program is proposed to realize the lightweight optimization of intelligent new-energy vehicle frames. This method can achieve the lightweight goal of intelligent new-energy vehicle frame by

*Corresponding author:* wupiepei0211@163.com

optimizing the thickness of different important parts under the premise of meeting the constraints of strength, frequency and vibration. These methods and tools provide useful references and guidance for the lightweight design of intelligent new-energy vehicle frames. The lightweight design of intelligent new-energy vehicle frame is an important research direction in the field of intelligent vehicles, which is of great significance for improving the performance of new-energy vehicles, reducing energy consumption and reducing environmental pollution.

Aiming at the lightweight research of the frame structure, Tang and Xia [1] improved the structural structure of the subframe, increased the safety factor of the frame, and verified the rationality of the side frame design. Zhang and Ran [2] proposed a lightweight optimization idea based on ant colony algorithm for frame structure design made of TC4 titanium alloy. Yu *et al.* [3] established a full-size finite element model of pure electric vehicles (PEV) and used the finite element method to realize the lightweight design of the frame. Feng *et al.* [4] has designed a lightweight fire truck frame based on Ansys software to reduce the mass of the frame, while meeting the strength requirements. Yang *et al.* [5] integrated four driving conditions (including full load bending conditions, torsional conditions, emergency braking and emergency steering) and used finite element analysis to optimize the lightweight design of the electric bus frame.

In this paper, the static analysis of the frame of intelligent new-energy vehicles is first carried out to understand its static mechanical properties. Then, the vibration characteristics of the intelligent vehicle frame at natural frequency were analyzed by modal analysis. Finally, this paper uses the method of random vibration analysis to study the vibration characteristics of intelligent vehicle frame in complex environment. In short, by studying the mechanical characteristics and lightweight analysis of intelligent vehicle frames, this paper successfully proposes a lightweight design scheme based on the multi-objective response surface method, which provides important reference value and guiding significance for the lightweight design of intelligent new-energy vehicle frames.

## Establishment of Frame Model

### Creation of 3D Model

For numerical simulation, a simplified analysis of the frame is carried out and a simple frame model is built. Due to the simplicity and versatility, a simple frame model was established using Solidworks software, as shown in Figure 1. The model contains only important parts of the frame (such as stringers and beams) as well as other necessary details like wheels and tires.

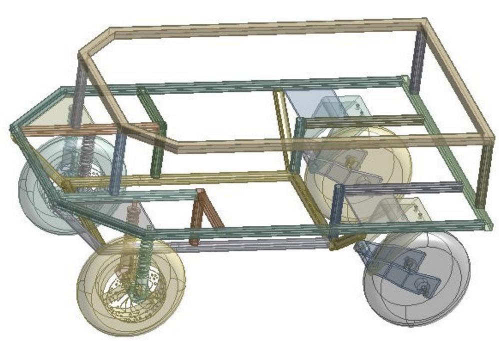


**Figure 1**. Full vehicle model

## Establishment of Finite Element Model

Table 1 lists some parameters of material attributes. Due to the complex structure of the frame, in order to reduce its mass, five representative parts were selected for local analysis. These parts are: the middle front steel pipe 1, the front right steel pipe 2, the front right steel pipe 3, the rear side cross steel pipe 4, and the upper whole circle steel pipe 5, as shown in Figure 2.

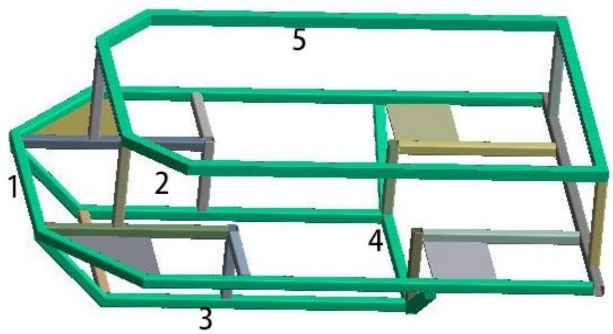



**Figure1.** Simplified frame

**Table 1.** Material attributes

| Material | Structural steel |
|---|---|
| Poisson's ratio | 0.3 |
| Elastic modulus/Pa | 2E+11 |
| density/(kg·m$^{-3}$) | 7850 |
| Yield strength/MPa | 250 |

# Finite Element Analysis of the Frame

## Static Analysis of the Frame

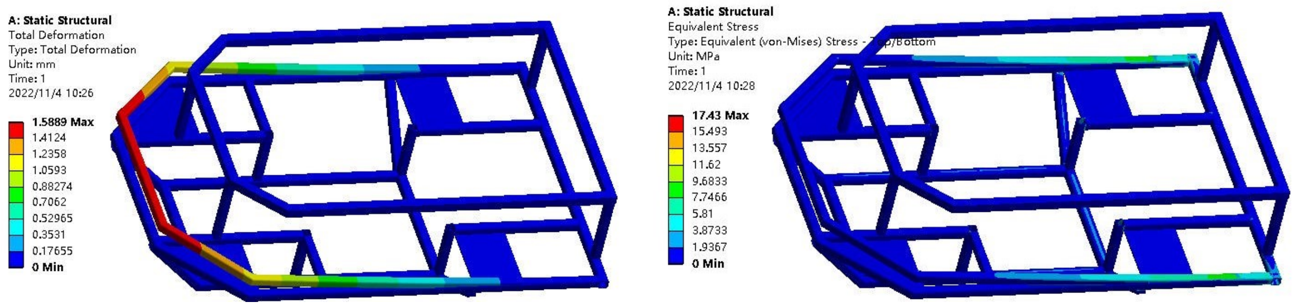
The static analysis of frames is an important research field, which has a wide range of applications in the field of intelligent vehicles. Static analysis refers to a method of analyzing and calculating the force situation of an object at rest or in uniform motion. It is necessary to divide the frame into several small units, and then analyze the force of the unit to obtain the force of the entire frame. It is also possible to perform calculations using traditional matrix methods, which are less efficient and are usually only used for preliminary design and estimation. In order to study the strength and deformation characteristics of the frame under load, the finite element method was used to analyze the statics of the frame, and the static characteristics of the frame under multiple working conditions such as bending and torsional conditions were considered.

### *Bending Conditions*

The frame is mainly statically loaded in bending conditions, and reasonable constraints are set to ensure that the model reflects the real situation well. Since the speed of the intelligent car is not too fast, the safety factor is selected as 1.5, and the allowable stress of the intelligent car frame can be obtained at this time as 120MPa. The constraints are shown in Table 2. The results of the finite element analysis are shown in Figure 3.

**Table 2.** Constraints under bending conditions

| Constraint points | Degrees of freedom restrictions |
|---|---|
| Left front wheel | X , Z |
| Left rear wheel | Z |
| Right front wheel | X ,Y , Z |
| Right rear wheel | Y , Z |




a Total deformation of bending b Bending and other effects

**Figure2**Static properties under bending conditions

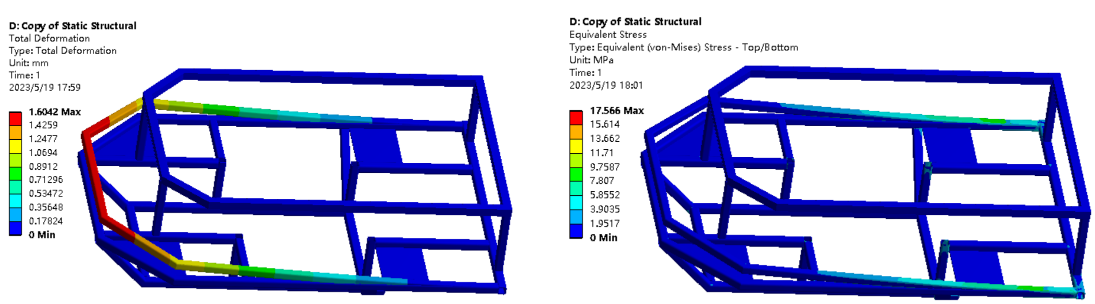
After calculation, the initial result is that under the bending moment condition of fully loaded intelligent car, the maximum frame equivalent force is 100.2 MPa, and the maximum frame total deformation displacement is 0.555 mm.

*Twist the Operating Conditions*

When the low-speed fully loaded intelligent vehicle is driving on a rough road, the four wheels will be in different planes, and the structural condition of the intelligent vehicle frame can be analyzed. The frame is mainly affected by torsional loads. In view of the occurrence of various situations, this paper selects a typical special case, that is, the right front wheel is raised 15 mm upwards and the left rear wheel is concave 15mm downward. The safety factor is selected as 1.2, and the allowable stress of the intelligent car frame can be obtained as 100 MPa. Table 3 lists the constraints, while the results are shown in Figure 4.

**Table 3.** Constraints under torsional conditions

| Constraint points | Degrees of freedom restrictions |
|---|---|
| Left front wheel | X, Y, Z |
| Left rear wheel | Z and Y 15 mm downwards |
| Right front wheel | X and Y upwards 15mm |
| Right rear wheel | Y |




a Total deformation b Equivalent forces

**Figure 4.** Static properties under torsional conditions

After calculation, the initial result is that under the torsional condition of fully loaded intelligent vehicle, the maximum frame equivalent force is 58.249 MPa, and the maximum frame total deformation displacement is 0.263 mm.

## Random Vibration Analysis of the Frame

The frame refers to the frame structure of the intelligent car, whose main role is to support the overall structure of the carrier, and must have sufficient strength and rigidity. The random vibration analysis of the frame is because the intelligent car will be randomly excited by different road surface conditions during driving, in this case, the frame will produce random vibration. When the excitation force is large or the long-term acceptance of some kind of excitation, it may promote the failure of the frame structure, so it is necessary for the frame to do random vibration analysis [6-9].

### *Modal Analysis*

The frame is a multi-degree-of-freedom vibration structure, so the modal analysis of the frame structure can be established through finite element analysis, and the vibration system of the frame can be further understood.

The natural frequencies of the first 6 stages of the frame are shown in Table 4, and the natural frequencies of the first order of the frame belong to the low frequency range, which is in line with the range of avoiding resonance frequencies [10-13]. The modal mode diagram of the frame is shown in Figure 5.

**Table 4.** Frame modal analysis results

| Order | Natural frequency/Hz | Order | Natural frequency/Hz |
|---|---|---|---|
| 1 | 14.062 | 4 | 62.386 |
| 2 | 25.581 | 5 | 71.960 |
| 3 | 36.417 | 6 | 82.357 |

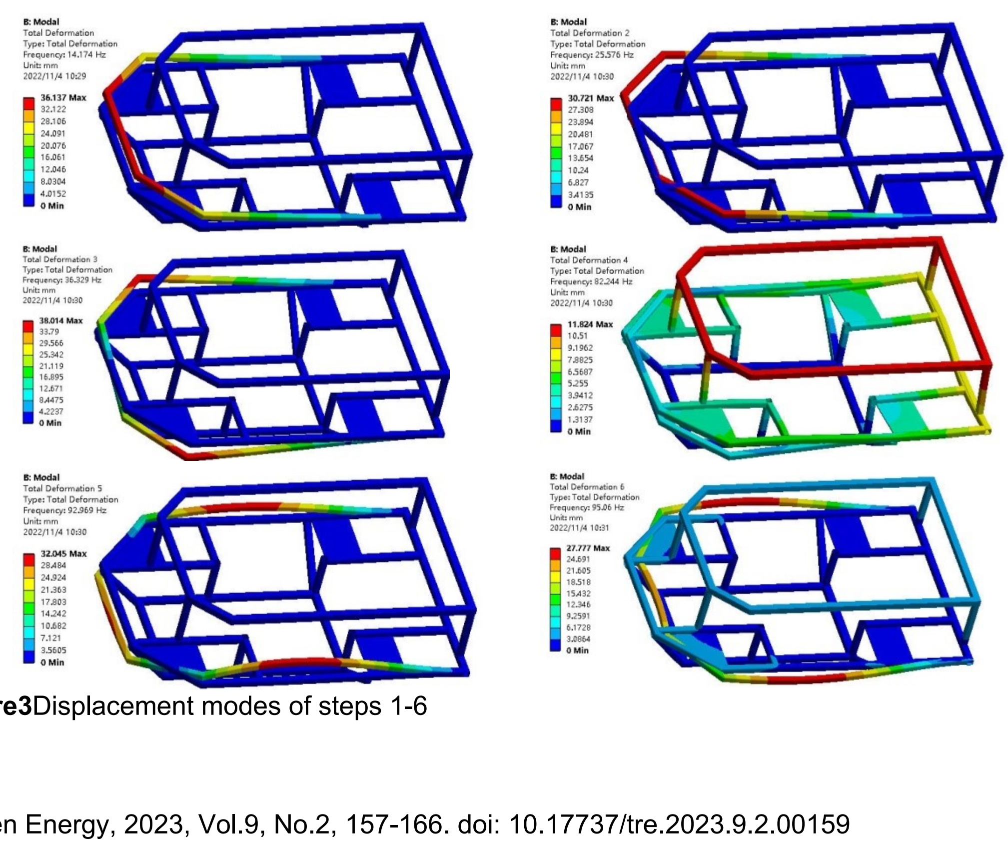



**Figure3**Displacement modes of steps 1-6

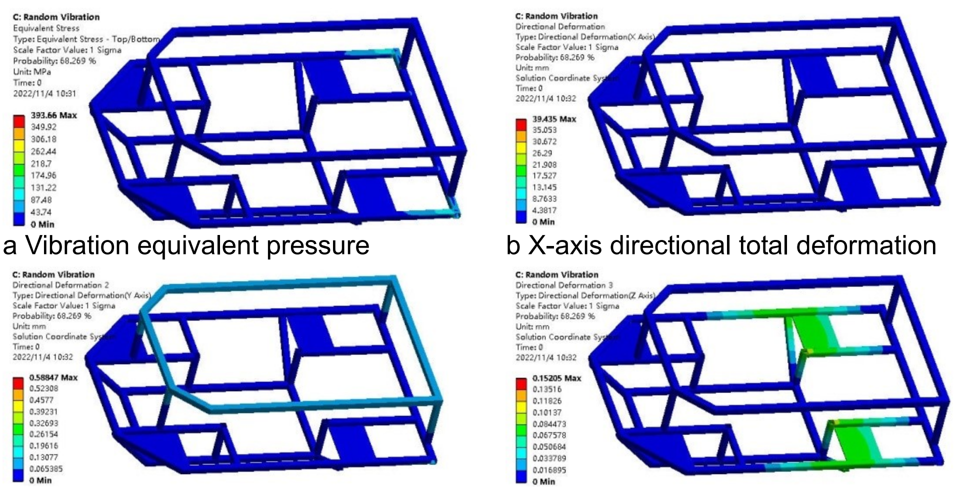
*Stochastic Vibration Analysis*

Random vibration is one of the important challenges faced by smart cars while driving. Therefore, the random vibration analysis of intelligent vehicles not only helps to improve the driving safety of intelligent vehicles, but also provides an important theoretical basis for future intelligent vehicle research.

Random vibration will affect the suspension system, control system and other aspects of intelligent vehicles, thereby affecting the driving stability and safety of intelligent vehicles. Therefore, random vibration analysis of intelligent vehicles can help to study the dynamic characteristics of automotive systems, identify vibration sources in systems, and evaluate the adaptability of vehicles to vibration environments. Finally, the results are evaluated and optimized to improve the adaptability of intelligent vehicles to random vibrations and improve the driving safety and comfort of intelligent vehicles [14]. Below are selected typical displacement power spectral densities that enable random vibration analysis. The four typical mode shapes of the smart car frame are shown in Figure 6.

**Table 4.** Class D pavement with displacement power spectral density (20 km/h)

| f(Hz) | $G_q(f)$ ($mm^2/Hz$) | f(Hz) | $G_q(f)$ ($mm^2/Hz$) |
|---|---|---|---|
| 1 | 163.810 | 11 | 1.354 |
| 3 | 18.201 | 22 | 0.338 |
| 5 | 6.552 | 44 | 0.085 |
| 8 | 2.560 | 66 | 0.038 |



a Vibration equivalent pressure b X-axis directional total deformation

c Y-axis directional total deformation d Z-axis directional total deformation

**Figure4.** Four typical mode shape diagrams

In short, the random vibration analysis of intelligent vehicles is of great significance to improve the driving safety and stability of intelligent vehicles. Scientists should attach importance to the research of random vibration analysis of intelligent vehicles, continuously improve the technical level and application scenarios, and explore intelligent vehicles as an important research direction in the field of modern transportation.

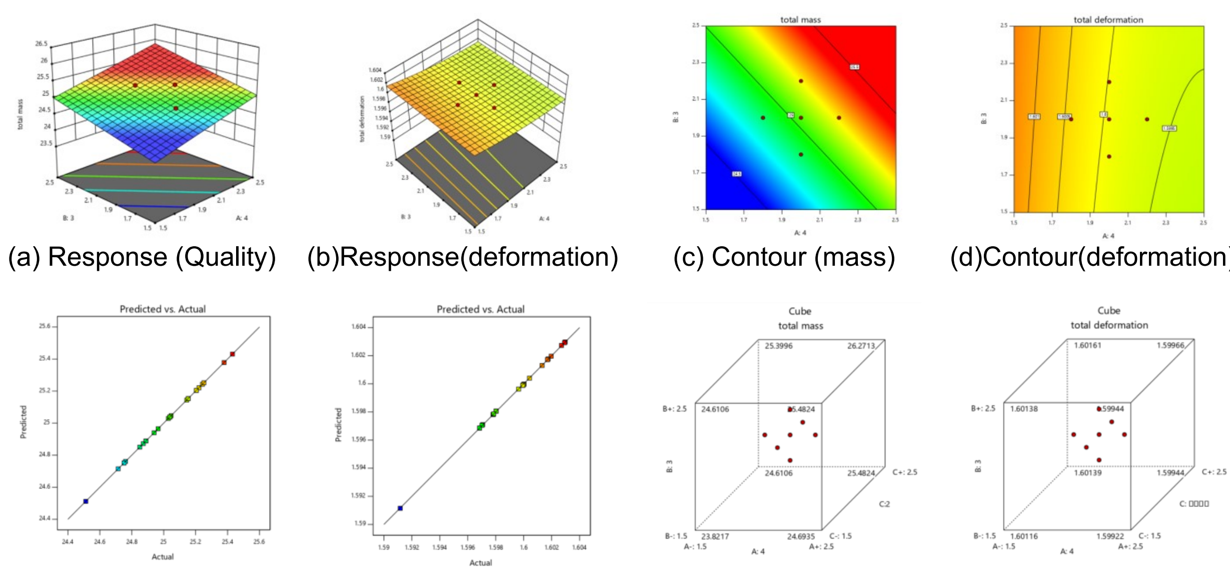
## Frame Lightweight Optimization Design

Frame lightweighting improves the fuel efficiency and performance of automobiles. We can use topology optimization to determine the optimal shape and finite element analysis to calculate the stress distribution of the frame. We can also use another optimization technique, which is parameter optimization. Parameter optimization can adjust parameters such as material selection, wall thickness and support structure. According to different design requirements to minimize the weight of the frame, aluminum alloy and carbon fiber also have high specific strength and specific stiffness, which can effectively improve the strength and stiffness of the frame.

In terms of structural design, a simplified structure should be adopted as much as possible to avoid excessive complexity. For example, unnecessary connections and traditional vertical pipe connection structures should be avoided in frame design. In addition, the use of hollow structure and multi-layer structure is also a common scheme in frame lightweight design.

### Response Surface Optimization Analysis

Through the central composite test design of each part of the frame, and the screening of the parameters by the F test method, the response surface equation of the thickness of each part and the parameters (such as stress, deformation and self-vibration frequency) was finally constructed. The equation of some parameters is shown in the following equation, and the response surface diagram is shown in Figure 7. Among them, d1, d2, d3, d4, and d5 in formulas (1) and (2) represented the middle front steel pipe 1, the right front steel pipe 2, the right front copper pipe 3, the rear horizontal steel pipe 4, and the upper full circle steel pipe 5, respectively (as shown in Figure 2).




(a) Response (Quality) (b)Response(deformation) (c) Contour (mass) (d)Contour(deformation)

(e)Forecast vs. Actual Chart (Quality) (f)Forecast vs. Actual Chart (Deformation) (g)Cube diagram (mass) (h)Cube diagram (deformation)

**Figure 7.** Response Surface Optimization Diagram

$$Total\ deformation = +1.48784 - 0.009484*d4 + 0.000220*d3 + 0.000228*d2 \\ +0.059409*d1 + 0.028771*d5 + 0.001886*d4^2 - 0.004064*d1^2 - 0.009368*d5^2 \quad (1)$$

$$Total\ mass = 11.48305 + 0.871769*d4 + 0.788938*d3 + 0.788938*d2 + \\ 2.67332*d1 + 1.65877*d5 \quad (2)$$

From Figures 7e~f, it can be seen that the response surface method is reasonable instead of finite element simulation, and has high accuracy.

## Results and Validation

Using the constructed response surface model instead of the finite element model for optimization iterations, the multi-objectives such as stress, deformation and total mass were taken into account for lightweighting analysis, and the multi-objective optimization solution was carried out using the optimization method to obtain the best solution for the thickness of the frame of the intelligent new-energy vehicle (as shown in Table 5). It can be seen that the mass of the steel tube 2, 3, 4 and 5 parts are all reduced by about 50%. The overall mass of the frame was reduced by 5.187 kg, a 20.71% reduction in mass. At the same time, the equivalent force before and after optimization was reduced by 4.13% and the first 6th order frequency was increased, reducing the possibility of frame resonance and indicating that the optimized frame is safer.

It can be seen that the optimized frame of the intelligent new-energy vehicle is obviously lighter and the thickness of the five components is more reasonable, which meets the requirements of strength, stiffness, modal and random vibration of each part while making full use of the material, reflecting the rationality of the proposed method.

**Table 5.** Comparison values before and after optimization

| **Initial value** | | **Optimize the value** | | | **Optimize before and after comparison /%** |
|---|---|---|---|---|---|
| | | Rsd value | Fem value | error/% | |
| steel tube1/mm | 2 | 1.596 | 1.596 | - | 20.2 |
| steel tube2/mm | 2 | 1.015 | 1.015 | - | 50 |
| steel tube3/mm | 2 | 1.003 | 1.003 | - | 50 |
| steel tube4/mm | 2 | 1.000 | 1.000 | - | 49.9 |
| steel tube5/mm | 2 | 1.000 | 1.000 | - | 50 |
| quality/kg | 25.047 | 19.872 | 19.86 | -0.06 | -20.71 |
| Static total deformation/mm | 1.553 | 1.585 | 1.589 | 0.25 | 2.32 |
| Static stress/MPa | 18.181 | 17.391 | 17.43 | 0.22 | -4.13 |
| First-order frequency | 14.062 | 14.152 | 14.174 | 0.16 | 0.80 |
| Second-order frequency | 25.581 | 25.589 | 25.576 | -0.05 | -0.02 |
| Third-order frequency | 36.417 | 36.441 | 36.429 | -0.03 | 0.03 |
| Fourth-order frequency | 62.386 | 84.836 | 82.244 | -3.06 | 31.83 |
| Fifth order frequency | 71.96 | 92.571 | 92.969 | 0.43 | 29.2 |
| Sixth-order frequency | 82.357 | 93.299 | 95.06 | 1.89 | 15.42 |
| Vibration stress/MPa | 24.992 | 12.585 | 13.200 | 4.89 | -47.18 |
| X-axis directional deformation/mm | 37.951 | 39.243 | 39.435 | 0.49 | 3.91 |
| Y-axis directional deformation/mm | 0.549 | 0.526 | 0.529 | -0.57 | 7.29 |

## CONCLUSIONS

(1) The central composite experimental design method and response surface optimization method are applied to the optimization and lightweight design of intelligent new-energy vehicle frame, effectively achieving the goal of structural lightweight.

(2) In order to improve the calculation efficiency, the central composite experimental design analysis is carried out by using finite element software before the response surface optimization, and the design variables that have a great influence on the total mass results of the frame are selected to participate in the subsequent optimization. Finally, the optimized frame achieves a reduction of 20.47% in the total mass of the intelligent frame, while ensuring the static and dynamic characteristics.

(3) The structural strength of the improved intelligent new-energy vehicle frame has been significantly improved, indicating that the structural optimization of the frame has good practical engineering application prospects and good reliability.

## CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

## REFERENCES

[1] Tang, P., & Xia, J. S. (2014). Finite element analysis of car's sub-frame. In *Applied Mechanics and Materials* (Vol. 651, pp. 733-737). Trans Tech Publications Ltd.

[2] Zhang, J., & Ran, W. (2021, May). Lightweight optimization design of a light electric commercial vehicle frame. In *Journal of Physics: Conference Series* (Vol. 1939, No. 1, p. 012038). IOP Publishing.

[3] Yu, L., Gu, X., Qian, L., Jiang, P., Wang, W., & Yu, M. (2021). Application of tailor rolled blanks in optimum design of pure electric vehicle crashworthiness and lightweight. *Thin-Walled Structures, 161*, 107410. doi: https://doi.org/10.1016/j.tws.2020.107410

[4] Feng, Q., Yu, S., Luo, J., & Chu, J. (2010, November). Research on lightweight design of vice-frame structure of fire-engine on basis of ANSYS. In *2010 IEEE 11th International Conference on Computer-Aided Industrial Design & Conceptual Design 1* (Vol. 2, pp. 1347-1350). IEEE.

[5] Yang, Z., Deng, B., Deng, M., & Sun, G. (2018). A study on finite element analysis of electric bus frame for lightweight design. In *MATEC Web of Conferences* (Vol. 175, p. 03049). EDP Sciences.

[6] Wang, S., Zheng, S., Feng, J., & Liu, X. (2013). Lightweight design for front sub-frame of a fuel cell vehicle. *Journal of Machine* Design, 30(2), 41-44.

[7] Luo, W., Zheng, Z., Liu, F., Han, D., & Zhang, Y. (2020, October). Lightweight design of truck frame. In *Journal of Physics: Conference Series* (Vol. 1653, No. 1, p. 012063). IOP Publishing.

[8] Yun, S. W., Go, S. H., Kim, H. G., & Yi-goo, K. (2018). Numerical Analysis of Deck Frame for Lightweight Trucks. *Journal of the Korean Society of Manufacturing Process Engineers, 17(3),* 127-133.
[9] Chen, Z., Wang, T., Zhao, Z., Shen, J., Zhen, D., & Gu, F. (2012, September). The lightweight design of a dump truck frame based on dynamic responses. In *18th International Conference on Automation and Computing (ICAC)* (pp. 1-5). IEEE.
[10] Wang, L., Yang, X., Lu, C., & Sun, X. (2012). Lightweight Design and Simulation of Vehicle Frame Based on FEM. *Modern Machinery, 2012(5),* 12-14.
[11] Sun, L., Tan, J., Jiang, C., & Chu, Z. (2010). Lightweight Study for Coach Body Frame under Multiple Loading Conditions. *Auto Mobile Science & Technology, 3*, 20-24.
[12] Han, K., Qu, X., & Fang, H. (2015). Lightweight Study of Frame Based on Sensitivity Analysis and Calculation of Dynamic Stiffness. *Journal of Hubei University of Automotive Technology, 29(4),* 21-25.
[13] Zheng, W., Lan, F., & Chen, J. (2016). Research on Topology Optimization and Lightweight Design for Frame Structure of FSAE Racing Car. *Chinese Journal of Automotive Engineering, 6(1),* 35-42.
[14] Chen, X., Lou, W., Jiang, Y., Yu, H., & Huang, Y. (2015). Static and Dynamic Performance Analysis and Lightweight Design of ATV Frame. *Journal of Chongqing University of Technology (Natural Science), 29(2),* 1-6.