A COMPARATIVE STUDY ON STRENGTH OPTIMIZATION OF BATTERY TRAYS FOR NEW ENERGY VEHICLES BASED ON MATERIAL LIGHTWEIGHTING

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Abstract - Against the backdrop of the vigorous development of the new energy vehicle industry, the performance of battery trays is directly related to the safety and stability of vehicles. In accordance with standards such as GB/T38031-2025 "Safety Requirements for Traction Power Batteries of Electric Vehicles", this study aims to enhance the static strength and modal performance of the battery tray. Through finite element analysis, the main frame of the primary battery pallet based on Q235 steel was simulated under static working conditions. The results show that the maximum stress of the original structure is 190.54MPa, which is lower than the yield limit of Q235 at 235MPa, the safety factor is 1.23, and the static strength meets the standard. However, the first-order natural frequency is only 21.049Hz, which is far lower than the 40Hz required by the national standard. Further comparison of 6061 aluminum alloy, QAl9-2 copper alloy and TC4 titanium alloy reveals that the first-order frequency of 6061 aluminum alloy is 40.675Hz, which can meet the national standards and strength requirements, and performs outstandingly in terms of lightweight and cost control. The research results provide optimization value for the engineering application of battery trays for new energy vehicles.

Keywords: Lightweight, Battery tray, Modal analysis, FEA, Numerical simulation.

1. Introduction

The power battery pack is the "heart" of new energy vehicles. Its performance directly affects the vehicle's driving range, usage safety, and cost control, etc. It is a key part of the vehicle's overall safety protection system and a crucial element in enhancing the market competitiveness of new energy vehicles.

The structure model of the power battery of a certain pure electric vehicle is shown in Figure 1. The power battery pack itself is relatively heavy. While enhancing the driving range, it will inevitably increase the overall vehicle weight, thereby increasing the vehicle's energy consumption and reducing its power performance. Therefore, achieving lightweight design while ensuring the performance of power battery packs has become an important direction for technological breakthroughs in new energy vehicles at present [1].

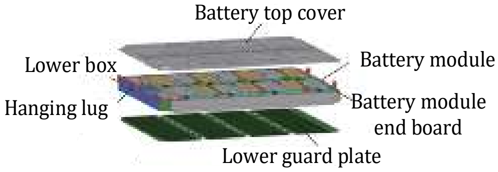

Figure 1: Structure diagram of power battery

The battery tray and lifting lugs structure, as the load-bearing frame, are important components for bearing the weight of the battery and mitigating the impact during driving. The lifting lugs are distributed on both sides of the lower box body, made of forged steel parts or lightweight alloys, and are connected to the chassis through bolts. They undertake the functions of lifting and fixing. The structural design must meet the NVH performance requirements to reduce the transmission of dynamic loads. To ensure the structural strength and safety of power battery packs, processing and manufacturing qualified battery brackets is an important guarantee for ensuring the performance of electric vehicle brackets [2, 3].

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The optimization design method of the electric pallet support mainly optimizes the strength of the structure from the perspectives of shape optimization, size optimization, material optimization and process optimization [4-6].

The main design methods for shape optimization include the design element method [7], the natural variable method [8], and the boundary element method [9, 10]. The design element method divides the product into several subdomains, with each subdomain corresponding to a design element, and controls the design element by controlling the nodes of the shape of the design element. This method can reduce design variables, but it is prone to mesh distortion. The natural variable method applies virtual loads to the control points of the product and takes the displacement of the control points as the design variable. It is assumed that there is a linear correlation between the virtual load and the displacement of the control nodes. Then, a new grid is formed with the coordinates of the control nodes as nodes, and the new virtual load is determined by sensitivity analysis. This process is repeated until the virtual load is zero. This method can reduce grid distortion. But the amount of calculation is greater. The boundary element method divides grids on the boundaries of the product and approximates the boundary conditions required for design with functions. Compared with the finite element method, the boundary element method has fewer elements and simpler calculations, but the calculation results are not as effective as those of the finite element method. The design method for size optimization is usually topological optimization design, followed by the optimization design of detailed parts. The drawback is that it can only conduct limited optimization design for the already designed and formed structure. When facing multivariate optimization objectives, the optimization process is relatively complex. However, in recent years, with the rise of machine learning, the calculation process of structural optimization design has been simplified [11, 12].

With the emergence of new materials and new processes, high-strength steel (with a yield limit greater than 700MPa) and new processing techniques provide better options for the design optimization of battery tray structures. By selecting different materials to process and design battery trays, and integrating multiple small components into one part through processes such as hydraulic forming and laser splicing, the structural performance of battery trays can be greatly enhanced [13-15].

2. Battery Tray FEA Modeling

With the emergence of new processes and new materials, only by comprehensively considering factors such as the material selection and economic cost of battery trays can the production and processing of products be better achieved [16, 17]. In order to compare the properties of several common materials used in battery tray processing, a finite element analysis of the battery tray structure was carried out. Based on the battery bracket of a certain product, the three-dimensional structure model of the battery tray established is shown in Figure 2. The overall contour dimensions of the battery tray are designed to be 750mm in length, 600mm in width, and 290mm in height.

Figure 2: Structure diagram of the battery tray and lifting lugs

2.1 Grid Discretization

After simplifying the structure of the battery tray, the three-dimensional model is meshed. The size of the grid division unit is 1.5mm, and the grid type is a tetrahedral grid structure, as shown in Figure 3. The quality assessment of grid division is shown in Figure 4.

Figure 3: Discretization of the battery tray grid

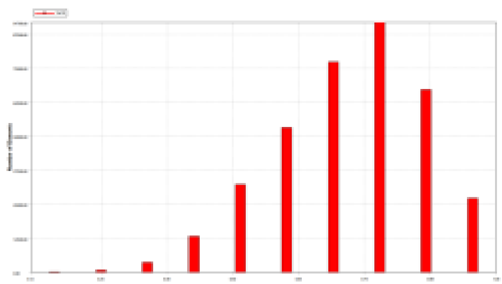


Figure 4: Quality assessment of battery tray grid

According to the results of the grid quality assessment, it is known that the grid quality index is relatively close to 1, and the proportion of grids with an index proportion exceeding 0.7 exceeds 79.46%, which can basically be used for finite element analysis.

2.2 Definition of Material Properties

The material properties of battery trays for pure electric vehicles need to comprehensively consider multiple factors such as strength, lightweight, corrosion resistance and processing technology. The main frame is made of Q235 steel, which has high strength and good plasticity and can provide stable support for the battery pack. The base plate, front and rear side plates, front and rear reinforcing parts and other components are made of ZG270-500 material, which has good load-bearing capacity and impact resistance, and is suitable for withstanding the weight of the battery and complex loads during driving. Some key support components, such as the front and rear π -shaped brackets, are made of 510L steel, which enhances the structural stability. Moreover, the material has good processing performance and is convenient for forming through processes such as bending. The properties of various materials are shown in Table 1.

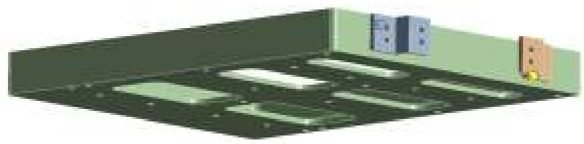
Table 1. Material Properties

Material	Density (kg/m^3)	Elastic modulus (N/mm2)	Poisson's ratio	Yield strength (MPa)
Q235	7850	2.1e5	0.3	235
ZG270-500	7800	2.0e5	0.3	270
B510L	7530	2.1e5	0.3	355

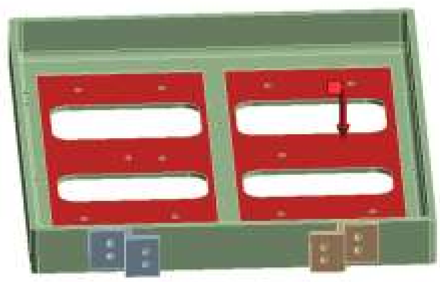
2.3 Constraints and Load Application

In the UG NX software, the bolt connections in the battery tray are modeled and constrained through Mate Constraint. In the ANSYS software, the finite element model of the battery tray assembly is subject to degree-of-freedom constraints. Ignoring the influence of the vehicle body on the deformation of the pallet, constraints are added to the connection plane between the pallet and the vehicle body to limit its vertical degree of freedom. In addition, at the center point of the unit at the bolt connection hole between the pallet and the vehicle body, full constraints will be applied to limit its degrees of freedom in six directions. a constraint relationship is established based on the positional relationship between the battery tray and the vehicle body in the real vehicle, as shown in Figure 5 (a).

Apply the gravitational acceleration at the center of mass of the battery tray and establish a rigid connection between the bolt hole and the center of mass of the battery box. Apply the corresponding gravitational acceleration at the position of the center of mass of the battery box to calculate the magnitude and direction of the force it experiences, as shown in Figure 5 (b).



(a) Constraints of the lug structure



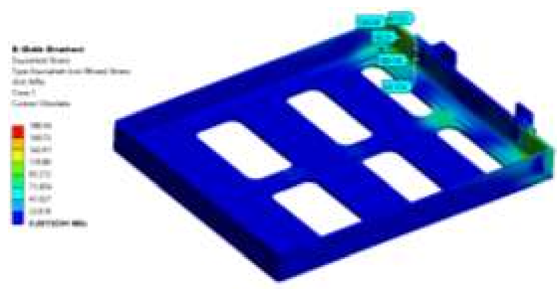
(b) The application of gravitational acceleration on the battery tray

Figure 5: Establishment of battery tray constraints and load definitions

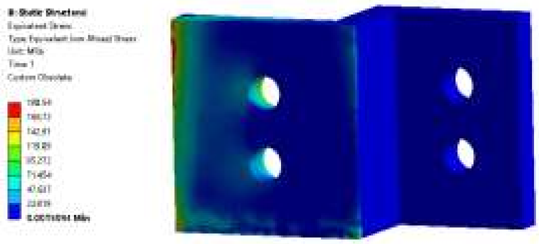
3. Static and Dynamic Characteristics Analysis of Battery Trays

3.1 Statics Analysis

Based on the driving conditions of electric vehicles under typical working conditions given in the literature, the force load of the pallet was analyzed [18, 19]. When the electric vehicle is at rest, the battery pack housing is affected by the mass of the battery module and the intermediate control component, which restricts the full degrees of freedom of the bolt holes of the two lifting lug bases and applies the gravitational force on the battery module and the control module at the bottom. The static analysis stress variation cloud diagram is shown in Figure 6.



(a) Stress cloud diagram of the battery tray bracket



(b) Stress cloud map of the front π -shaped support

Figure 6: Stress distribution map of the battery tray and bracket

As shown in Figure 6 (a), it can be known from the stress cloud diagram that the maximum stress of the battery tray support is 190.54MPa. The yield strength of Q235 steel in the main frame is 235MPa, and the safety factor is 1.23. This indicates that under the current working conditions, the overall structure has not exceeded the load-bearing capacity of the material, and the stress level in most areas is relatively low, basically meeting the strength requirements. According to the results shown in Figure 6 (b), it can be found that the stress cloud map of the front π -shaped support shows its equivalent stress distribution. The maximum stress is 66.72MPa, which is much lower than the yield strength of B510L steel, which is 355MPa. This indicates that under the current working conditions, the overall front π -shaped support has not reached the material yield limit, and the structure can basically meet the requirements in terms of strength.

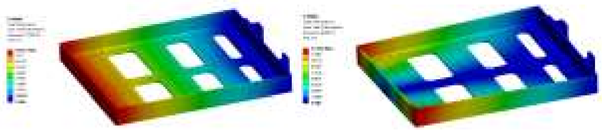
3.2 Modal Analysis

Modal analysis is a technique that analyzes the structure of battery trays through mathematical calculations and simulation methods. It can determine parameters such as the resonant frequency, vibration mode and deformation position of the support to evaluate the stability and reliability of its structure. To evaluate the vibration mode mechanical properties of the battery tray structure, after constralling the battery tray support and bolt holes, the natural frequencies of each order of the battery tray were analyzed and obtained as shown in Table 2 below.

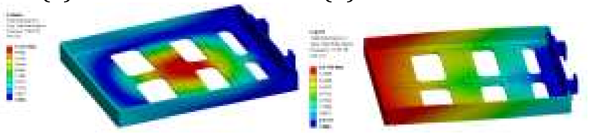
Table 2. Resonance Frequencies of the battery tray structure under various working conditions

Order	1	2	3	4	5	6
Frequency（Hz）	21.049	40.69	136.42	217.61	261.61	293.68

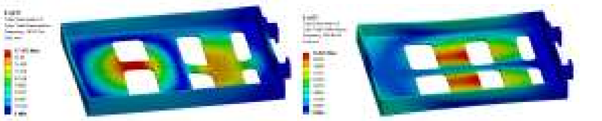
The modal shapes of each order of natural frequencies are shown in Figure 7 below.



(a) The first order (b) The second order



(c) The third order (d) The forth order



(e) The fifth order (f) The sixth order

Figure 7: the vibration mode diagrams of 1-6 order of the battery tray

The vibration mode deformation characteristics corresponding to the battery tray show significant differences with the increase of frequency. However, the first-order natural frequency shows a value of 21.049Hz, which obviously does not meet the anti-vibration requirements of the electric vehicle bracket. According to national standards [20] and relevant production experience, the natural frequency of the battery bracket for electric vehicles should be higher than 40Hz to ensure that the battery is protected from resonance damage. Therefore, it is necessary to improve the structure and materials to avoid resonance problems.

4. Battery Tray Material Improvement and Performance Comparison

4.1 Material Selection

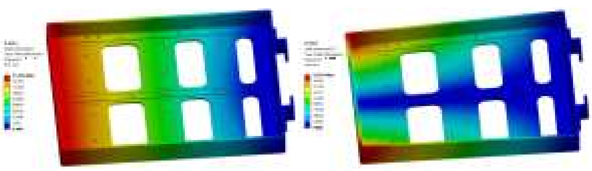
Material properties are one of the important indicators affecting the performance of battery trays. Three common materials were used to reanalyze the modal vibration patterns of the battery tray to observe whether its structural performance could meet the anti-vibration requirements. Q235 steel has the highest density, good yield strength and tensile strength, but a relatively high specific gravity. Aluminum alloy 6061 has a relatively low density, medium mechanical properties, and excellent processability and corrosion resistance. The density of QAl9-2 copper alloy is close to that of steel, with a moderate modulus and excellent electrical conductivity. TC4 titanium alloy combines high strength with low density. There are differences in density, strength, modulus and fatigue performance among various materials. By comparing the mechanical properties of battery trays made of aluminum alloy (6061), copper alloy (Qal9-2) and titanium alloy (TC4), the suitable material can be identified from the perspective of structural vibration resistance. The mechanical properties of each structure are shown in Table 3 below.

Table 3. Properties of the main Material of the pallet support

Material	Density (kg/m^3)	Elastic modulus (N/mm2)	Poisson's ratio	Yield strength (MPa)
Q235	7850	2.1e5	0.3	235
6061	2750	7.1e4	0.33	280
Qal9-2	7600	1.1e5	0.34	280
TC4	4510	9.6e4	0.36	830

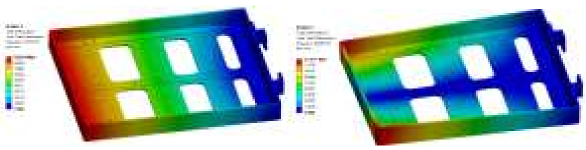
4.2 Result Analysis

Keeping the conditions of each constraint load unchanged, the modal analysis of the battery tray structure was re-conducted, and the first five vibration modes of various materials were obtained. Only the first two vibration modes are shown here. The vibration mode of the aluminum alloy (6061) battery tray is shown in Figure 8. The vibration mode of the copper alloy (Qal9-2) battery tray is shown in Figure 9. The vibration mode of the titanium alloy (TC4) battery tray is shown in Figure 10. Meanwhile, the first two natural frequencies obtained are shown in Table 4.



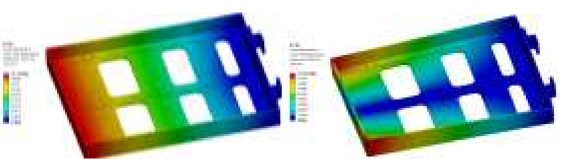
(a) The first order (b) The second order

Figure 8: Vibration mode of the aluminum alloy (6061) battery tray



(a) The first order (b) The second order

Figure 9: Vibration mode of the copper alloy (Qal9-2) battery tray



(a) The first order (b) The second order

Figure 10: Vibration mode of titanium alloy (TC4) battery tray

Table 4. The first two resonant frequencies of battery trays made of three materials

Order	1	2
Aluminum alloy (6061)	40.675Hz	102.5Hz
Copper alloy (Qal9-2)	15.818Hz	30.386Hz
Titanium alloy (TC4)	19.161Hz	36.691Hz

Through the observation of vibration modes of each order, it is found that the strain forms of battery trays of the same frequency made of various materials show similar variation laws. Since the yield limits of the three alloy materials are not weaker than those of the aluminum alloy materials, the stress-strain conditions all meet the strength requirements.

In terms of natural frequency, the modal frequency of Q235 steel pallets is moderate. However, due to its high density, the material density is relatively large, making it difficult to meet the lightweight requirements. 6061 aluminum alloy has a good modal frequency distribution. The response deformation is slightly large but reasonably distributed, demonstrating good stiffness control and mass balance. The density of QAl9-2 copper alloy is also relatively high, but its first-order natural frequency is too low. Although it has strong anti-deformation ability and modal stability, its performance in structural vibration resistance is not good. Although TC4 titanium alloy has high strength and relatively low mass density, its modal frequency is not significantly better than that of aluminum alloy. Meanwhile, the deformation amplitude control is average, the material cost is high, and its applicability is limited.

In conclusion, based on the original steel, 6061 aluminum alloy, QAl9-2 copper alloy and TC4 titanium alloy were selected as materials, and modal analysis and comparison were carried out under the same working conditions. The results showed that the performances of various materials were different. The selection of 6061 aluminum alloy material can achieve better anti-vibration performance. The first-order natural frequency of the battery tray is significantly increased and meets the national standard of 40Hz, but it may face a deficiency in terms of usage strength. TC4 titanium alloy and Q235 do not perform well in terms of structural vibration resistance, especially when the first-order natural frequency is significantly lower than the national standard. However, they have relatively high strength requirements. But the production and processing costs of TC4 titanium alloy are relatively high, making it unsuitable for the processing and production of ordinary battery trays. The yield strength of QAl9-2 copper alloy is similar to that of aluminum alloy, but its production cost, material weight and structural vibration resistance are also slightly inferior, and it is not suitable for the design of battery tray brackets. Therefore, at present, aluminum alloy 6061 material remains an important material for the design and production processing of electric vehicle battery trays. However, attention should be paid to the installation form and structural stiffness design of the battery trays.

5. Conclusions

According to the technical indicators in the national standard "Safety Requirements for Traction Power Batteries of Electric Vehicles", Q235 material was used as the main material of the battery bracket, and the mechanical properties of the battery tray were checked for strength and analyzed for mode. Q235 exhibits good mechanical properties in terms of strength. However, the modal analysis results show that its first-order natural frequency is 21.049Hz, and resonance damage is very likely to occur during use.

Based on the design principles of material improvement and lightweight, the anti-vibration effects of aluminum alloy (6061), copper alloy (QAl9-2), and titanium alloy (TC4) materials as the main support for battery trays were compared on the original basis. The results show that aluminum alloy (6061) achieves excellent lightweight effects due to its advantage in density. Meanwhile, its first-order natural frequency is relatively high, which can meet the numerical requirements stipulated in the national standards. This also verifies the reason why most battery trays are made of aluminum alloy at present. Other materials cannot meet the national standards in terms of structural vibration resistance.

To further enhance the mechanical properties of the battery tray, it is necessary to further improve and design the structure and process of the battery tray. By combining the advantages of various materials and production costs, a reasonable structure of the battery tray should be designed. Although copper alloy (QAl9-2) and titanium alloy (TC4) materials have excellent mechanical strength properties during use, their influence on the stiffness of battery trays is limited. Improving the structural form of battery trays is an important way to enhance the mechanical properties of battery trays.

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