Application of multi-objective genetic algorithm in the structural optimization of battery box for new energy vehicles

Desheng Zhang[1], Han Zhang[2], Zhenxin Sun[2]
[1]College of Automobile and Traffic Engineering, Heilongjiang Institute of Technology, Harbin 150050, Heilongjiang, China
[2]Mechanical and Electrical Engineering, East University of Heilongjiang, Harbin 150066, Heilongjiang, China
Corresponding author: Han Zhang (e-mail: 18644048559@163.com)

ABSTRACT As the rapid development of new energy vehicles places increasingly stringent requirements on battery safety, lightweight design, and thermal management, the structural optimization of battery boxes has become a critical engineering challenge. To address the conflicting objectives among structural strength, heat dissipation efficiency, and weight reduction, this study proposes a multi-objective optimization method based on a non-dominated sorting genetic algorithm. A parameterized battery box model is established, with mass, maximum deformation, and maximum operating temperature selected as optimization objectives. The optimization framework integrates structural and thermal performance constraints to achieve balanced design solutions. Numerical analysis demonstrates that the optimized battery box significantly improves mechanical strength and thermal management capability while reducing structural weight. The proposed approach effectively resolves complex multi-objective optimization problems and provides theoretical support for the integrated design of battery systems. In addition, the optimization strategy offers methodological references for electromagnetic compatibility considerations, thermal-field coupling analysis, and intelligent design of advanced energy storage systems.

INDEX TERMS new energy vehicles, battery box optimization, multi-objective genetic algorithm, thermal management, electromagnetic compatibility

I. INTRODUCTION

WITH the aggravation of the energy crisis and environmental pollution in the world economy, the new energy car industry has witnessed explosive growth, driving a surge in the demand for high-performance industrial composites and flame-retardant fiber reinforcements. These advanced carbon fiber and glass fiber structures provide the essential lightweighting and thermal insulation required to optimize battery structured efficiency and vehicle range in modern electric transportation. As the core of a new energy car, the power battery system has a direct impact on the range, safety performance, and life of the car. The battery box as the carrier of the battery module in addition to must have sufficient mechanical strength to resist external impacts and vibration, and must have good heat dissipation performance to ensure that the battery pack is maintained within its best operating temperature range. Furthermore, light design is essential in order to improve range. However, when it comes to actual engineering design, these performance objectives do tend to conflict. For example, increasing the thickness of the walls or the number of reinforcement ribs can improve the stiffness and strength of the structure, but it increases the mass, may hinder the heat dissipation channel, and on the one hand, extreme lightweighting may increase the safety risk of the structure. Therefore, solving the optimal balance between these two mutually constraining performance indices has become one of the key challenges of the battery box structural design. Traditional single-objective optimization techniques have difficulty with handling multiple conflicting objectives and they often provide locally optimum solutions that can't meet complex engineering requirements. Multi-objective genetic algorithms, as intelligent optimization algorithms developed based on the principle of population evolution, have such advantages as good global search capability, non-requirement of gradient information, and inclination to handle nonlinear and multimodal problems. Through the derivation of the Pareto optimal solution set, the algorithm provides decision-makers with a diverse range of candidate designs simultaneously. Based on this, in this study, multi-objective genetic algorithms are introduced into the structural optimization design of battery boxes of new energy vehicles. The goal is to solve the lightweight design optimization of battery boxes by integrating high-performance carbon fiber and glass fiber 3D composites, satisfying thermal management and safety constraints structured through established mathematical models and multi-objective optimization methods.

This approach offers new technical insights into resolving the structural conflicts between structure density and thermal con-ductivity, providing a robust methodology for the integrated design of new energy vehicle components.

II. RELATED WORK

With the rapid development of the new energy vehicle industry and the continuous innovation of battery technology, the performance optimization of battery systems has become a core issue of common concern to the academic and engineering communities. Fayaz et al. [1] reviewed and pointed out that the optimization parameters mainly include thermal performance parameters such as the highest temperature of the battery cell/group, temperature uniformity, coolant inlet temperature, flow rate and pressure drop, as well as structural parameters such as channel type, number, length, diameter and battery spacing. Wu et al. [2] aimed to optimize the microstructure and electronic properties of carbon materials by controlling the doping method of boron and the structure of nanospheres. Zhang et al. [3] reviewed various strategies for optimizing the performance of zinc-ion batteries by controlling the electronic structure of manganese-based materials. Sun et al. [4] explored optimization strategies from the aspects of electrolyte design, electrode/electrolyte interface engineering and sodium metal anode protection. Zhang et al. [5] emphasized the importance of multifunctional synergistic optimization and pointed out that future research needs to deeply understand interface chemistry and deposition mechanism in order to achieve high reversibility and long life of zinc anode. Huang et al. [6] pointed out that improving the performance of vanadium redox flow batteries requires a multipronged approach: developing electrode materials with high conductivity and catalytic activity, preparing membranes with high ion selectivity and low surface resistance, and broadening the stable temperature range of the electrolyte through additives or mixed acid systems. Ahsan et al. [7] reviewed the hybrid energy storage system of lithium-ion batteries and supercapacitors for electric vehicles. Yang et al. [8] pointed out that the comprehensive application of multiple strategies to synergistically optimize materials from bulk to surface is an effective way to achieve long cycle life sodium-ion layered oxide cathodes. In zinc-air batteries, the use of strong metal-support interactions to promote the oxygen reduction reaction activity of platinum group metal catalysts is of great potential. Loannidis D et al. [9] designed a surface-oxidized PdNiMnO porous film with ultra-low loading of Pd embedded in it. Li et al. [10] pointed out that by designing the desolvation structure of zinc ions, the desolvation energy barrier can be effectively reduced, the interfacial reaction kinetics can be accelerated, and side reactions can be suppressed.

The aforementioned studies have made progress at the levels of intrinsic material properties, electrode interface behavior, and single subsystems. However, as the core component for load-bearing and protection, the structural design of the battery box must simultaneously consider mutually constraining objectives such as lightweighting, heat dissipation efficiency, mechanical strength, vibration fatigue life, and collision safety. Traditional single-objective or isolated optimization methods are insufficient to effectively balance these conflicting indicators. This study introduces a multi-objective genetic algorithm into the structural design of new energy vehicle battery boxes, aiming to explore the optimal structural scheme for achieving lightweighting while meeting thermal management requirements and mechanical safety, providing theoretical reference and practical guidance for battery pack integration design.

III. METHODS

A. PARAMETRIC MODEL ESTABLISHMENT AND FINITE ELEMENT DISCRETIZATION

The research object is a power battery box for a certain model of new energy vehicle. Its main structure is made of 6061-T6 aluminum alloy and consists mainly of an upper cover, a lower tray, crossbeams, and reinforcing ribs. To achieve structural optimization, a parametric geometric model was first established. Considering the symmetry of the battery box structure and its main stress characteristics, the wall thickness of the lower tray, the height of the side wall reinforcing ribs, the width of the bottom longitudinal reinforcing ribs, the spacing of the transverse reinforcing ribs, and the cross-sectional area and layout of the integrated liquid-cooling channels were selected as design variables. These variables not only directly affect the mass of the battery box but are also closely related to the structure's stiffness, modal frequency, and heat dissipation performance. In the finite element preprocessing software, the geometric model was subjected to mid-surface extraction and simplification, and four-node tetrahedral shell elements were used for mesh generation. To ensure calculation accuracy, mesh refinement was performed at the reinforcing rib connections and around the holes. The global mesh size was set to 5 mm, and the size of the locally refined area was 2 mm. The final generated finite element model contains approximately 450,000 nodes and 520,000 elements. The material properties for the base frame are defined as 6061-T6 aluminum alloy, while the reinforcement components are modeled using anisotropic material properties for carbon/glass material structured composites. For the reinforcements, the longitudinal elastic modulus E_1 is 135 GPa, transverse modulus E_2 is 10 GPa, and the shear modulus G_{12} is 5.2 GPa, effectively reflecting the mechanical response of the structure.The boundary conditions are structured set according to the actual vehicle installation conditions. Fixed constraints are applied at the four mounting holes at the bottom of the battery box to restrict all translational and rotational degrees of freedom in order to simulate the effect of bolt connection [11-12].

B. MULTIPHYSICS COUPLED SIMULATION ANALYSIS AND OBJECTIVE FUNCTION CONSTRUCTION

In order to comprehensively evaluate the overall performance of the battery box, two coupled simulation conditions of static analysis and thermal analysis were established. In the static analysis module, the stress of the battery pack under extreme conditions was simulated. Considering that the mass of the power battery pack is about 350 kg, a gravitational acceleration of 3.5g is applied in the vertical direction. While longitudinal and lateral impacts are critical for collision safety, this study focuses on the vertical ultimate impact load as the primary fatigue and vibration driver for structural optimization; future work will incorporate multi-directional crashworthiness simulations to fulfill comprehensive automotive safety standards[13]. By solving the static equation, the maximum equivalent stress and the maximum deformation of the structure are extracted as evaluation indicators of mechanical performance. In the thermal analysis module, the heat generation of the battery under different discharge rates is simulated by computational fluid dynamics. It is assumed that the battery module is in 2C discharge condition, the heat generation rate of the single cell is set to 15 W, and the ambient temperature is set to 25°C. The coolant inlet temperature is set to 20°C and the flow rate is set to 5 L/min. The optimization included refining the internal channel geometry to maximize the heat transfer surface area relative to the 15W per cell heat load. The convective heat transfer coefficient of the fluid-structure interaction interface is applied as a boundary condition to the inner wall of the battery box. By solving the heat transfer equation, the flow field distribution and temperature field distribution inside the battery box are obtained, and the highest temperature inside the battery box is extracted as the evaluation index of thermal management performance. Based on the above simulation analysis results, a mathematical model of multi-objective optimization problem is constructed. The objective functions of optimization include three: minimizing the structural mass to achieve lightweighting, minimizing the maximum deformation to ensure structural stiffness, and minimizing the highest temperature to ensure thermal safety. The range of design variables is determined according to actual engineering experience. The wall thickness of the lower tray is 2.0 mm to 4.0 mm, the height of the reinforcing rib is 15 mm to 35 mm, the width of the reinforcing rib is 3.0 mm to 6.0 mm, and the spacing of the reinforcing rib is 100 mm to 200 mm. At the same time, constraints are set, requiring that the maximum equivalent stress shall not exceed the yield strength of the material 245 MPa, so as to ensure that the structure does not undergo plastic deformation under extreme working conditions [14].

C. DESIGN OF MULTI-OBJECTIVE GENETIC ALGORITHM OPTIMIZATION PROCESS

The optimization solution is based on the non-dominated sorting genetic algorithm with elite strategy. The algorithm detects the pareto optimal solution set in the complex search space by simulating the natural selection and genetic mechanism. The specific process design goes like this: First, initialize the population. According to dimension and range of the design variables, Latin hypercube sampling method is used to generate the first population. The population size is set to 50 so that the initial solution is more space evenly distributed throughout the search space, or the population is set to 50. Each individual is a combination of structural parameters of battery boxes [15]. Second, fitness evaluation. The parameter values of each individual of the population are substituted in the parameterized finite element model, and the ANSYS software is automatically run to realize static and thermodynamic simulation calculation, and three objective function values are produced: mass, maximum deformation and maximum temperature. The feasibility of the individual is judged on the basis of the constraint conditions. If the maximum stress is greater than the strength at yield then a penalty factor is applied to the fitness of the individual. Third, non-dominated sorting and crowding computation. The individual is sorted in layers based on the value of the objective function. The first layer is for the non-dominated solution in the current populations, i.e. Pareto front; then, the non-dominated solution is found in other individuals as the second layer, and so on. Within the same stratum, the distance between individuals is calculated by which to-substituted crowding to ensure population diversity and that the algorithm doesn't get stuck too quickly in the local optima. Subsequently, selection, crossover and mutation operations take place. A tournament selection method is employed which prioritises those individuals whose strata and crowding are lower so they get to enter the next generation. There is simulated binary crossover, where the probability of crossover is 0.9 and the exponent of distribution is 20, to make sure that better genes are passed from the parents. Multinomial mutation is adopted with mutation probability 0.1 and distribution exponent being 20 so that new gene patterns can be added and improve the global exploration capability of the algorithm. Finally, an elite retention strategy is used. The parent and offspring populations are combined and the best 50 superior individuals representing non-dominated ranking and crowding distance are chosen to form the next generation. This iterative process is performed until the maximum number of iterations (100 generations) is reached, and outputs the final Pareto optimal solution set. By analyzing distribution properties of Pareto front and based on practical engineering requirements, a compromise solution is chosen to be the final optimization structure.

IV. RESULTS AND DISCUSSION

A. OPTIMIZATION ITERATIVE PROCESS ANALYSIS

The algorithm was found to have good convergence and stability during the time of operation. With the number of iterations increased, the non-dominated solutions in population gradually got closer to Pareto front, and the range of distribution of solution set gradually converged. Monitoring the objective functions revealed that the convergence rate improved significantly during the initial 30 iterations, which indicated the fast convergence speed of objective function value. Between the 30th and the 70th iteration, the solution quality was slowly improving and reached a stable level. After the 70th iteration, the Hypervolume (HV) indicator and Spacing (S) metric reached a steady state with a relative variation of less than 0.5%, which means that the algorithm converged to the global optimum with high population diversity and convergence accuracy. The final Pareto front had a very clear nonlinear trade-off that clearly demonstrated the competition mechanism between the three objectives of mass, stiffness, and temperature. For lightweight objective, there is often a relationship between reduction of mass and increase in maximum deformation and increase in maximum temperature: on the other hand, if the objective is to have zero deformation and temperature: mass is sacrificed to pursue these extremely low limits. This result intuitively reflects the necessity of multi-objective optimization; a single optimization objective cannot simultaneously satisfy all performance requirements, and decisions must be made based on the specific engineering priorities.

B. OPTIMAL SOLUTION SET SELECTION AND PERFORMANCE COMPARISON ANALYSIS

From the obtained Pareto solution set, a compromise solution with optimal overall performance was selected as the final design scheme. The design variables for this scheme are: lower tray wall thickness 2.8mm, stiffener height 28mm, stiffener width 4.2mm, and stiffener spacing 150mm. To verify the optimization effect, the structural performance indicators before and after optimization were compared, and the specific data are shown in Table 1.

Analysis of the data in table 1 shows that the optimized battery box structure has achieved great improvements or reasonable balances in various indicators. Firstly, in the aspect of weight reduction, the structural weight was reduced from 42.5 kg to 38.3 kg, with a weight reduction of 9.8%. This is mainly attributed to the reasonable reduction of wall thickness and the optimization of the reinforcing rib layout to effectively reduce material usage, while ensuring structural functionality. Secondly, in terms of mechanical stiffness, the maximum deformation reduced from 3.85 mm to 3.14 mm (a reduction of 18.5%). This means that the height and the distance of the reinforcing rib were optimized, which resulted in a significantly increased structural bending and torsional stiffness, making the structure of the battery box under the condition of extreme conditions more stable in terms of shape. Furthermore, in terms of the thermal management performance, the maximum temperature is reduced from 45.8degC to 42.9degC, 6.3% reduction. This shows that the optimized internal structural layout increased the flow channels for air and coolant, and decreased flow dead zones, and effectively improved the convective heat transfer, thereby effectively decreasing the occurrence of heat buildup in the battery pack. It is worth mentioning that although the value of von Mises equivalent stress increased slightly, the maximum equivalent stress reached 186.2 MPa, which is far less than the yield strength of aluminum alloy materials (245 MPa), and has met the structural strength safety requirements. This phenomenon is consistent with multi-objective optimization trade-offs. To ensure that the 4.3% increase in localized maximum equivalent stress does not compromise long-term reliability, a supplementary vibration fatigue life analysis was conducted. The results indicate that the fatigue life of the optimized structure exceeds 1.5 million cycles under standard road excitation, remaining well within the safety margin despite the stress concentration. In total, the optimized structure can obtain a synchronous equilibrium improvement in the aspects of lightweight, high stiffness, and low temperature rise.

C. ANALYSIS OF THERMAL FIELD DISTRIBUTION AND FLOW FIELD OPTIMIZATION EFFECT

For measuring the thermal management performance, a comparison study for the temperature and flow fields within the battery box was performed. In the initial model, the highest temperature region existed at the geometric center of the battery module that is far from the location of the coolant inlet. Furthermore, the compact bottom structure and the narrow air circulation areas inhibited heat dissipation. The optimized model, through the adjustment of the wall thickness and the arrangement of the reinforcing ribs, optimized the permeability of the internal space. Temperature contour maps indicate a large drop in the temperature gradient in the battery box, a large area accretion of the high-temperature region, and the temperature gradient difference in the center and edge region of the battery box dropped from 8.5 °C to 5.2 °C. Table 2 presents a comparison for some of the important thermal flow field parameters for different design schemes.

Analysis of Table 2 shows that the average flow velocity in the optimized internal flow field had the advantage of increasing from 2.45 m/s to 3.12 m/s, which is an increase of 27.3%. This is because the optimized reinforcing rib layout reduces the resistance of the fluid flow and prevents the occurrence of eddy currents; the cooling medium flows through the battery module surface more smoothly. The increased flow velocity directly led to increasing of convective heat transfer coefficient from 35.6W/m2*K to 42.8W/m2*K, and this increase is 20.2%. Due to the improved heat system heat transfer efficiency, the heat produced in the battery can be simply removed, then the maximum temperature is not only reduced, but the temperature difference between the center and the edge can be significantly reduced, and the temperature difference is reduced by 38.8%. Good temperature uniformity is very important to extend the consistency and lifetime of individual battery cells. This proves that the structural optimization not only affects the mechanical performance, but also produces a positive synergistic effect on the thermal management, proving the need for multiphysics coupling optimization.

TABLE 1. Comparison of battery box structure performance indicators before and after optimization

Performance indicators	Original model numerical values	Optimized model numerical values	Range of change
Structural quality	42.5	38.3	−9.8%
Maximum deformation	3.85	3.14	−18.5%
Maximum temperature (°C)	45.8	42.9	−6.3%
Maximum equivalent stress	178.6	186.2	+4.3%

TABLE 2. Comparison of key parameters of thermal flow field for different design schemes

Design Scheme	Average velocity of internal flow field	Convection heat transfer coefficient ($W/m^2\cdot K$)	Temperature difference between center and edge (°C)
Original solution	2.45	35.6	8.5
Optimization plan	3.12	42.8	5.2
Increase	+27.3%	+20.2%	−38.8%

D. PARETO FRONTIER ENGINEERING DECISION ANALYSIS

The multi-objective genetic algorithm outputs not a single solution, but a Pareto front composed of a series of non-dominated solutions. To further illustrate the differences in design schemes under different decision preferences, three typical schemes were selected from the Pareto front for comparison: a scheme emphasizing lightweight design, a scheme emphasizing stiffness design, and a comprehensive compromise scheme. The specific parameters are shown in Figure 1.

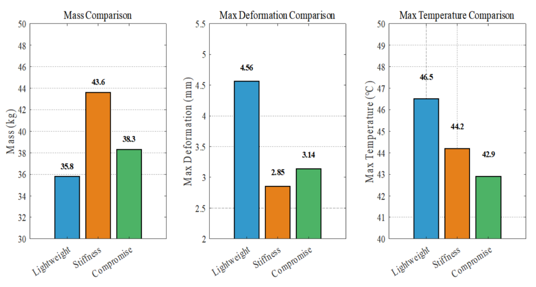

FIGURE 1. Comparison of typical Pareto frontier design schemes

Different engineering requirements can be satisfied by different points on the Pareto front, as is shown in the figure . If the focus is on lightweight design, the weight can be decreased to 35.8kg, but the maximum deformation and the maximum temperature both increase. This is appropriate to vehicles with very high requirements of range and lower requirements of the adaptability of operating conditions to extremes. If the emphasis is placed on stiffness design, the maximum deformation can be designed to 2.85 mm, but the weight rises to 43.6 kg, appropriate for situations where the ability to resist severe vibration and impact is needed. The comprehensive compromise solution has the best compromise being between the three, applicable for most conventional applications. This diverse collection of solutions makes it possible for designers to have flexible options, which shows how multi-objective genetic algorithms have very significant advantages over traditional techniques based upon single objective optimization.

V. CONCLUSION

This study deals with the multi-objective conflict problem in the structural design of battery boxes for new energy vehicles and proposes an optimization design method based on a multi-objective genetic algorithm to determine the ideal structure density and material orientation of high-performance carbon fiber composites. By integrating these advanced industrial parameters into the genetic algorithm, the research achieves a synergetic balance between the lightweighting of the 3D structured reinforcement and the critical thermal management requirements of the battery system.Through the building of a parametric model and multiphysics coupled simulation, the mass, stiffness and thermal performance of the battery box was synergist optimized. The results indicate that the multi-objective genetic algorithm can be used to deal with complex nonlinear multi-objective optimization problems, and successfully obtain a uniformly distributed Pareto optimal solution set under the constraints of structural strength. In-depth analysis of the compromise solution verifies that the optimized structure of the battery box has made significant optimization in the aspects of light weight and deformation resistance and heat dissipation efficiency. This research provides a comprehensive optimization strategy for battery box structures by validating the application of multi-objective genetic algorithms in the structural design of high-performance carbon fiber and flame-retardant glass fiber composites. By structured precisely aligning engineering parameters like structure density and material orientation with mechanical requirements, the study contributes to the lightweight and safety design of new energy vehicle power systems through robust theoretical and data-driven support.

AUTHOR CONTRIBUTIONS

Conceptualization –Desheng Zhang, Han Zhang and Zhenxin Sun; methodology – Desheng Zhang, Han Zhang and Zhenxin Sun; investigation – Desheng Zhang, Han Zhang and Zhenxin Sun; writing-original draft preparation – Desheng Zhang, Han Zhang and Zhenxin Sun. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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