

Structural Design of the Electric Vehicle Components Using Runge-Kutta Optimization Algorithm

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ABSTRACT

This research focuses on the optimization of a battery pack housing profile of an electric vehicle using advanced structural optimization techniques, specifically topology and shape optimization. The newly developed Runge-Kutta optimization algorithm(RKOA) was applied to minimize the component's weight without violating allowable stress constraints for the shape optimization phase. The artificial neural network (ANN) surrogate modeling method was employed to model the objective and constraint functions accurately. The findings indicate that RKOA delivers improved optimization results compared to the Harris Hawks algorithm, demonstrating its effectiveness in achieving an electric vehicle design's lightweight and structurally sound battery pack housing profile.

Runge-Kutta Optimizasyon Algoritması Kullanılarak Elektrikli Araç Bileşenlerinin Yapısal Tasarımı

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ÖZ

Bu araştırma, gelişmiş yapısal optimizasyon teknikleri, özellikle topoloji ve şekil optimizasyonu kullanılarak bir elektrikli otomobil batarya paketi muhafaza profili optimizasyonuna odaklanmaktadır. Şekil optimizasyonu aşamasında, izin verilen gerilme kısıtlamalarını ihlal etmeden bileşenin ağırlığını en aza indirmek için yeni geliştirilen Runge-Kutta optimizasyon algoritması (RKOA) uygulanmıştır. Hedef ve kısıt fonksiyonlarını doğru bir şekilde modellemek için yapay sinir ağı (ANN) vekil modelleme yöntemi kullanılmıştır. Bulgular, RKOA'nın Harris Hawks algoritmasına kıyasla daha iyi optimizasyon sonuçları verdiğini ve hafif ve yapısal olarak sağlam bir elektrikli araç batarya paketi muhafaza kutusu tasarımı elde etmede etkinliğini gösterdiğini ortaya koymaktadır.

1. INTRODUCTION

The automobile has been widely used in daily life for over a century. The demand for low-cost and lightweight vehicle components is increasing in the automotive industry to meet cost-effective solutions. Automotive components are often subjected to unpredictable loads that can cause localized deformations. Therefore, defining proper design criteria is crucial to ensure the desired performance characteristics. Among these components, the electric vehicle's battery pack housing profile plays a vital role in vehicle safety.

Recently, software tools based on structural optimization techniques have gained considerable attention for enabling rapid and efficient design of automotive components [1-9]. For instance, [2] aimed to reduce weight in electric vehicle body structures by employing carbon twill weave fabric composites. In [7], an automotive cross-car beam's topology, size, and shape optimization were investigated to enhance its structural performance. Using advanced finite element analysis and optimization techniques, they explored design variations that minimize weight while maintaining stiffness and crashworthiness. The study confirmed that optimized cross-car beam designs can significantly reduce mass without sacrificing safety or functionality. Various design scenarios were analyzed numerically to evaluate structural performance under lightweight conditions. The results demonstrated that the composite body structure can provide significant mass savings without compromising safety and stiffness. As the service life of a vehicle is closely linked to its weight, weight reduction efforts are paramount in automotive design. Topology optimization is a widely adopted structural optimization approach used to generate optimal geometries and material distributions for components. This method offers an efficient material layout that assists designers in initiating the product development process with a strong foundation.

Swarm intelligence-based optimization techniques have been successfully implemented to solve real-world problems across many disciplines, including the automotive and healthcare sectors. These methods offer effective solutions for almost all design problems and outperform conventional techniques by not requiring derivative information [10-20].

With the increasing interest in automobiles, the selection of appropriate optimization methods has become crucial to achieving optimal designs and contributing to efficient product development. In this study, the Runge-Kutta optimization algorithm (RKO) was employed to design the optimal battery pack housing profile of an electric vehicle. Introduced in [10], the Runge-Kutta optimization algorithm (RKO) has been successfully applied to problems such as gear design, three-bar truss structures, and marine propeller optimization. Moreover, [16] demonstrated its superiority in solving complex engineering design optimization problems, including brake disc design, welded beam problems, DC motor design, and motor speed reducers, outperforming other algorithms in these cases.

Given its proven success in engineering design applications, the Runge-Kutta optimization algorithm (RKO) was selected for use in this study. An electric vehicle's battery pack housing profile was optimized using the Runge-Kutta optimization algorithm and the Harris Hawks algorithm. Comparative results demonstrate that the Runge-Kutta optimization algorithm(RKO) performs better. These findings indicate that the Runge-Kutta optimization algorithm(RKO) can be effectively employed to solve challenging design optimization problems.

2. MATERIAL AND METHOD

This paper uses the Runge-Kutta optimization algorithm(RKO) to optimize battery pack housing profiles of electric vehicles. The Runge-Kutta optimization algorithm (RKO) [16] is a metaheuristic technique inspired by the classical Runge-Kutta method used in numerical analysis. It applies a step-by-step prediction and correction strategy to improve the precision of solution updates throughout the optimization process. The Runge-Kutta optimization algorithm (RKO) effectively balances global exploration and local exploitation by modeling solution trajectories in a multi-dimensional space. It is especially suited for tackling challenging nonlinear optimization problems where conventional algorithms often fall short. Additionally, RKO's adaptive nature helps preserve diversity within the population and reduces the risk of getting trapped in local optima.

3. STRUCTURAL OPTIMIZATION OF THE ELECTRIC VEHICLE BATTERY PACK HOUSING PROFILE

The battery pack housing profile of an electric vehicle has a vital role in vehicle design, as shown in Figure 1. This research optimized the structural design using the Runge-Kutta optimization algorithm (RKO). ST37 steel was selected as the construction material due to its suitable mechanical properties. The optimization aimed for performance while maintaining structural integrity.



Figure 1. Battery pack housing profile of electric vehicle three-dimensional representation

This design problem can be formulated as follows:

$$\text{Min } F(x) = \text{Weight}(x) \quad (1)$$

Constraints:

$$\text{Stress}(x) \leq \text{Maximum Stress} \quad (2)$$

$$x_i^l \leq x_i \leq x_i^u, \quad i = 1, \text{TSD}, \quad (3)$$

The goal of the problem is to reduce the structural mass by adjusting the design variables within the specified lower (x_l) and upper (x_u) bounds. A stress constraint is included to ensure the design remains safe under operational loading conditions. The maximum stress is limited to 200 MPa, which corresponds to the yield strength of the chosen material. This constraint is represented by the peak stress experienced by the component under the defined boundary conditions.

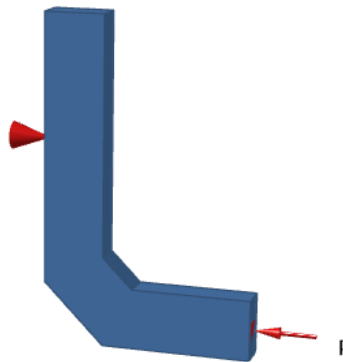


Figure 2. Boundary conditions of the battery pack housing profile of an electric vehicle

The initial geometry and boundary conditions applied to the battery pack housing profile of the electric vehicle are presented in Figures 1 and 2, respectively. The finite element model developed for the analysis comprises 13.026 nodes and 11.415 elements. In the conducted topology optimization, the objective function was set as compliance minimization, while volume reduction served as the constraint. This configuration established the foundation for the battery pack housing profile of the electric vehicle's topology optimization process.

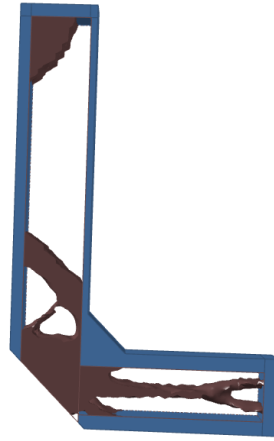


Figure 3. Optimized material layout from topology optimization

Using the topology optimization results in Figure 3, a new battery pack housing profile for electric vehicle design was developed. The white areas in Figure 3 represent regions where material can be eliminated. Guided by these results, a redesigned 3D model was created, as shown in Figure 4, reflecting the optimized geometry suggested by the finite element analysis. Stress distribution for the redesigned battery pack housing profile of the electric vehicle is shown in Figure 5.

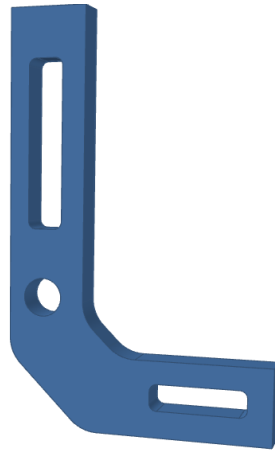


Figure 4. Redesigned the battery pack housing profile of an electric vehicle

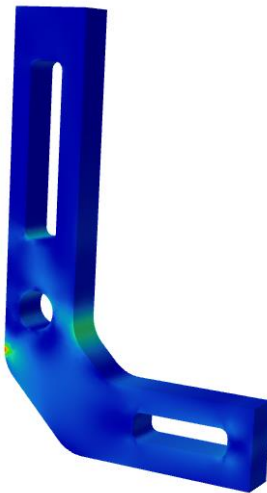


Figure 5. Stress distribution for the redesigned battery pack housing profile of an electric vehicle

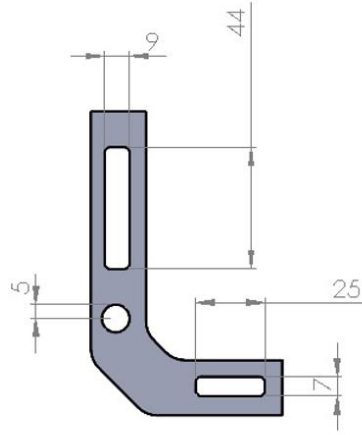


Figure 6. Design variables

In the battery pack housing profile of electric vehicle's shape optimization, three key design parameters were selected, as illustrated in Figure 6, with their values restricted between specific upper and lower bounds: $5 < X_1 < 20$, $6 < X_2 < 22$, $8 < X_3 < 26$, $30 < X_4 < 50$, and $5 < X_5 < 15$. The optimization problem, governed by Equations (1–3), was addressed using the Runge-Kutta optimization algorithm (RKO) applied in this study. The artificial neural network (ANN) surrogate modeling technique was employed to obtain the objective and constraint functions accurately.

The objective was to achieve the minimum possible weight for an electric vehicle's battery pack housing profile while maintaining stress levels within safe limits. Both the goal and the constraint functions were explicitly formulated to reflect these conditions.



Figure 7. The optimum battery pack housing profile of electric vehicle design obtained using the Runge-Kutta optimization algorithm

The final optimized design obtained through the shape optimization process is depicted in Figure 7. In Figure 8, the stress distribution for the optimum battery pack housing profile of an electric vehicle is shown.

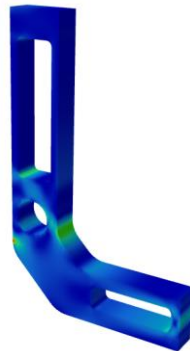


Figure 8. Stress distribution for optimum battery pack housing profile of an electric vehicle

Table 1 summarizes the outcomes of the battery pack housing profile of electric vehicle optimization using the RKO algorithm. Following the optimization, the weight of the battery pack housing profile of the electric vehicle decreased from 1252.6 grams to 1068.3 grams. This change represents a weight reduction of approximately 14.7% compared to the initial design.

Table 1. Optimization outcomes for the electric vehicle battery box side profile

Method	Weight (grams)	Stress (MPa)
Initial design	1252.6	118
Redesigned model of the side profile	1194.1	136
Harris Hawks algorithm	1134.1	178
Runge-Kutta optimization algorithm	1068.3	190

Table 2 displays the comparison results obtained from 30 separate optimization runs. Each run was conducted with a population size of 30 and iterated over 100 generations. The Runge-Kutta optimization algorithm (RKO) outperformed the Harris Hawks algorithm (HHA) across all key metrics, including minimum, maximum, mean, and standard deviation. These findings highlight the effectiveness and consistency of RKO in addressing the shape optimization of the battery pack housing profile of an electric vehicle.

Table 2. Optimization statistics for the battery pack housing profile of an electric vehicle

Method	Minimum weight (grams)	Mean weight (gram)	Maximum weight (gram)
Initial design	1252.6	1252.6	1252.6
Redesigned model of the side profile	1194.1	1194.1	1194.1
Harris Hawks algorithm	1134.1	1150.4	1180.6
Runge-Kutta optimization algorithm	1068.3	1085.7	1098.6

4. RESULTS AND DISCUSSION

This research explores the application of the Runge-Kutta optimization algorithm (RKO) for the structural optimization of the battery pack housing profile of electric vehicle components. The study aims to support the development of lightweight yet structurally sound designs, addressing the increasing demands of optimization in the automotive sector. By applying the Runge-Kutta optimization algorithm (RKO), the weight of the battery pack housing profile of the electric vehicle was reduced by 14.7% from 1252.6 g to 1068.3 g without exceeding allowable stress thresholds. A comparative evaluation in Tables 1 and 2 confirms that the Runge-Kutta optimization algorithm (RKO) outperforms the Harris Hawks algorithm in terms of efficiency, reliability, and consistency. The results demonstrate that the Runge-Kutta optimization algorithm (RKO) is a promising tool for tackling various engineering optimization tasks.

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