Research on Vibration Characteristics and Structural Optimization of Battery Bracket in Electric Vehicles

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Abstract - *The structural design of the electric vehicle battery bracket significantly affects the noise, vibration, and harshness (NVH) characteristics of the electric vehicle. This paper takes the battery bracket as its object of study, examining its vibration characteristics through frequency response analysis and modal analysis. The aim is to verify the validity of the support structure design. This paper takes the battery bracket as its object of study, employing frequency response analysis and modal analysis to investigate its vibration characteristics and validate the rationality of the structural design of the battery bracket. Firstly, a 3D model of the battery bracket was constructed, and a run strength analysis and constrained modal analysis were conducted using the NASTRAN solver. The results demonstrate under the forward and downward working conditions, the maximum stress exceeds the yield strength of the material. Additionally, the first-order mode is below the idle excitation of the engine. Following the design principle of the bracket structure, the original structure is optimized by increasing the thickness of the bracket steel plate and the number of connection points. The simulation results demonstrate that the stiffness of the optimized bracket enhances the design requirements. Consequently, this research provides a theoretical basis for the design and optimization of the bracket structure.*

Key Words: electric vehicle battery bracket, strength analysis, modal analysis, vibration characteristics.

1. INTRODUCTION

Noise, vibration, and harshness (NVH) performance are important indicators of vehicle quality. The vibration and noise problems during use are not only a source of pollution of the sound environment outside the vehicle but also cause discomfort and even injury to occupants or cargo within the vehicle [1-2]. A vehicle's NVH target system comprises four levels: vehicle level, system level, subsystem level, and component level. To achieve the NVH target of the entire vehicle, it is necessary to design and adjust the components within each system so that they can ensure that the performance of the entire vehicle aligns with the design requirements during the synthesis process from the top-down approach [3-4].

2. LITERATURE REVIEW

The battery bracket of an electric vehicle is a component of the body system, the function is to mount the battery on the body. The battery bracket is situated close to the powertrain. Consequently, any vibrations transmitted from the powertrain will also affect the battery bracket, which will then be transmitted to the vehicle body. This results in an increase in noise and vibration levels within the body [5]. It is imperative to analyze and optimize the vibration characteristics of the battery bracket during the development and design of the vehicle body, which plays a positive role in shortening the design cycle and reducing the development cost. In the literature [6], the finite element technique was employed to conduct both strength and modal analyses for the water tank bracket of a light truck, along with subsequent road verification and modal testing. In the literature [7], a solution to the cracking problem of a light truck sub-tank bracket was sought through a vibration strength analysis of its finite element model. The literature [8] presents a power battery bracket scheme devised by the established design principles. Through finite element technology, the structure of the power battery bracket is subjected to modal analysis, impact strength analysis, frontal collision simulation analysis, and mounting bolt force analysis. This enables achieving a stable, fixed-power battery within the smallest possible space.

Literature [9] performed a frequency response analysis of the pipeline to obtain the effect of acceleration excitation on the stress distribution of the pipeline system. Literature [10] solved the fracture problem of air condition lines by adding brackets, which can avoid the excitation sympathetic vibration. To address the fracture issue associated with the urea tank bracket of trucks, a strength analysis was conducted using ANSYS Workbench software. The analysis result revealed that the maximum stress location was identical to the actual fracture location. The stress of the urea tank bracket was significantly diminished through the implementation of reinforcement and protection measures.

This paper presented a 3D model of the battery bracket based on a real vehicle and carried out a strength analysis and a constrained modal analysis using the NASTRAN solver. Following the structural design principles of the bracket, the original structure is optimized. Subsequently, the optimized structure is also verified through simulation analysis, demonstrating that the battery bracket could meet the design requirements. Therefore, this research offered a theoretical foundation for designing and optimizing the supporting structure.

3. VIBRATION CHARACTERISTIC OF BATTERY BRACKET

3.1 Fundamental Theory of Frequency Response Analysis

Frequency response analysis described the relationship between the external excitation, once transformed using the Fourier transform, and the target response. By employing this technique, it is possible to ascertain the vibration performance of a system across a range of frequencies. The dynamical equations of a linear time-invariant system with n degrees freedom can be expressed as follows[12-14]:

$$\mathrm{M}\ddot{u} + C\dot{u} + Ku = F(t)\#(1)$$

Where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, u is the displacement vector, $\dot{u}$ is the velocity vector, $\ddot{u}$ is the accelerated vector, and F(t) is the load function.

The displacement vector can be written as:

$$u{=}u_1 + iu_2$$

$$u_1 = A\sin(\omega t + \varphi)$$

$$u_2 = A\cos(\omega t + \varphi)$$

Upon substituting the solution into equation (1), the following result is obtained:

$$(-\omega^2 M + i\omega C + K)\big(Asin(\omega t + \varphi) + iAcos(\omega t + \varphi)\big) = F(t)\#(2)$$

Where A is amplitude, ω is inherent frequency, φ is the phase, and t is time. The displacement of the system frequency response can be obtained by solving the equation.

3.2 Fundamental Theory of Modal Analysis

Modal analysis is mainly employed to calculate the vibration frequency and vibration pattern of the system structure. According to the modal analysis, the system's inherent frequency and modal formation can be determined. The system motion differential equation is as follows[15-16]:

$$[M]\{\ddot{x}\} + [C]\{\dot{X}\} + [K]\{X\} = \{0\}\#(3)$$

Where [M] is the mass matrix, [C] is the damping matrix, [K] is the stiffness matrix, and X is the response vector.

When [C]=0, let X=Asin(ωt+φ) into equation (3):

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

Where ω is eigenvalue, $\{X\}$ is eigenvector. Eigen equation of equation (4) is as follows:

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

The intrinsic frequency of the system and its modal formations can be determined by solving equation (5).

4. DESIGN PRINCIPLES AND MODAL CONTROL OBJECTIVES

To design an electric vehicle battery holder that can meet the requisite performance standards, two fundamental principles are adhered to:

1. Avoiding the excitation frequency of the main excitation source

The battery is connected to the vehicle body through a bracket, thereby forming a 'spring-mass' system. This system is primarily susceptible to external excitation frequencies generated by the engine and road surface. When these frequencies coincide with the system frequency, the system will generate sympathetic vibration and transmit vibration to the body through the battery bracket, which in turn affects the NVH performance of the body. Therefore, it is essential to avoid these excitation frequencies during the design process.

In this paper, a certain hybrid electric vehicle is a research object, and the powertrain comprises an engine and an electric motor. The engine idling excitation is regarded as an external excitation because of pronouncing more vibration. The engine excitation frequency is calculated as follows[17]:

$$f = \frac{2kn}{60T} \ \#(6)$$

Where k is the number of cylinders, n is the rotation speed, and T is the number of strokes. We consider the engine is 4 cylinders and 4 strokes; the rotation speed is 1000 rpm at idling, and we calculate the engine idling excitation frequency f=33Hz by equation (6).

2. Ensuring the sufficient strength of the battery bracket

To prevent deformation or breakage when subjected to shock loads under various working conditions, the battery holder should have a certain level of strength. The strength of the battery bracket is expressed by the safety factor, which is calculated using the following formula:

$$K = \sigma_b/\sigma_x \#(7)$$

Where σ_b is yielding strength, σ_x is the max stress at working condition. K is larger than 1 in general.

4. DESIGN PRINCIPLES AND MODAL CONTROL OBJECTIVES

4.1 Modelling and Pre-processing

According to a real hybrid electric vehicle, modeling software is used to establish a 3D solid model, as shown in Figure 1. Then use the finite element simulation software ANSA to pre-process the 3D solid model. To simplify the solution, choose the right side of the front of the vehicle where the battery bracket is located to mesh, as shown in Figure 1. The geometric features of the model are simplified, and the neutral surface is extracted. The model of the battery bracket is meshed by a 4mm shell, with a total mesh count of approximately 210,000. The connection between each sheet metal part is simulated using RBE3 and RBE2, and the battery is simulated by establishing CONM2. Table 1 describes the information about batteries. The battery's mass is 200kg, and the position of the mass center is X=116.97mm, Y=441.89mm, and Z=545.58mm.

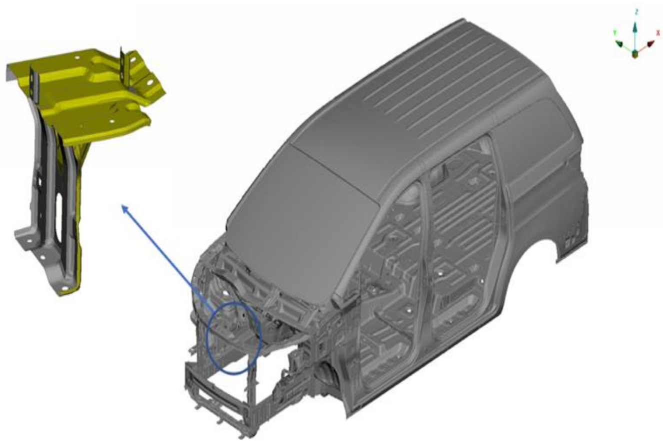


Fig-1: 3D solid model of the vehicle body

Table -1: Battery information

	Mass	Position of the mass center		
Battery	m=13.086kg	X=116.97	Y=441.89	Z=545.58

The material properties of the vehicle body and battery bracket are shown in Table 2. Among them, the material selected for the power battery bracket is DC01, with a thickness of 0.8 mm.

Table -2: Material information

Material	Elasticity Modulus N/mm^2	Poisson Ratio	Density kg/mm^3
DC01	204500	0.36	7.85E-9
DC03	188000	0.34	7.85E-9
DC04	191200	0.35	7.85E-9
DC05	190100	0.3	7.85E-9
DC06	187900	0.33	7.85E-9
B340/590DP	200500	0.3	7.85E-9
B280VK	205000	0.28	7.85E-9
SS400	210000	0.3	7.85E-9
Q345	210000	0.3	7.85E-9

4.2 Results of the frequency response analysis

The battery bracket is situated in a harsh working environment, and it is also subjected to load impacts from many working conditions, such as vertical shocks, forward and reverse braking, and left and right turns. Therefore, the fatigue of the bracket should be carefully evaluated in the design. In strength simulation analysis of the bracket, boundary conditions are added to the finite element model: constraints on the six freedoms of the model truncated surface and the six freedoms of the center of the front and right suspension mounting points; Considering the working conditions of the battery bracket and the load results of the road test, the loads are respectively loaded in the acceleration fields of 5G in the front, 5G in the back, 5G in the left, 5G in the right, and 10G in the vertical direction, as shown in Table 3.

Table -3: Loads in different working conditions

Working Conditions	X	Y	Z
Frontward	5G	0G	-1G
Backward	-5G	0G	-1G
Leftward	0G	5G	-1G
Rightward	0G	-5G	-1G
Downward	0G	0G	-10G

The material of the battery bracket is selected as DC01. The battery sets the mass unit to solve the maximum stress under different working conditions using the NASTRAN solver, and the analysis results are shown in Table 4.

Table -4: Results of the strength in different working conditions

Working Conditions	Max stress MPa	Yielding Strength MPa	Target value	Safety Factor
Frontward	182.5	171	≥1	0.9
Backward	162.4	171	≥1	1.1
Leftward	121.5	171	≥1	1.4
Rightward	129.6	171	≥1	1.3
Downward	181.5	171	≥1	0.9

The results of the above calculation demonstrate that the maximum stress of the battery bracket under working conditions 1 and 5 is 182.5 MPa and 181.5 MPa, which exceeds the yield strength of the material (171 MPa). It indicates a potential risk of strength design. Further optimization of the design is therefore necessary.

4.3 Results of the modal analysis

To avoid sympathetic vibration of the battery bracket under engine idle excitation, which affects the NVH performance of the body, it is necessary to ensure that its first-order modes under the constrained modes are above the engine idle excitation of 33 Hz, which we calculated before. Boundary conditions that constrain six freedoms on the truncated surface of the model are established on the finite element model. The first-order modal frequencies of the battery bracket are 26.6 Hz, 40 Hz, and 64 Hz by using the NASTRAN solver, as shown in Figure 2. The modal configurations are bending around the X-axis, Y-axis, and Z-axis. In this instance, the risk of generating sympathetic vibration exists because the frequency of 26.6 Hz is below the target value for engine idle excitation, so the bracket structure is required to optimize.

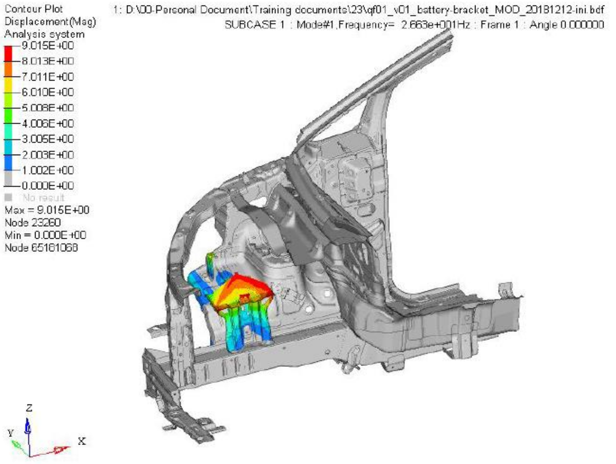


Fig -2: The first-order vibration mode of buttery bracket bending around the X-axis

The results of the strength and modal analysis of the battery bracket taken above indicate the presence of structural deficiencies. The strength and modality of the battery bracket are contingent upon stiffness and mass. To enhance the performance of the bracket, it is essential to circumvent excessive length, augment the number of connection points between the bracket and the body, refine the distribution of these points, or increase the thickness of the steel plate of the battery. In this paper, the structure of the battery bracket is optimized through the following two aspects:

1. increasing the thickness of the steel plate of the battery

Increasing the material thickness can enhance stiffness without modifying the bracket material. In this paper, the thickness of the bracket material is increased from the original 0.8mm to 1.2mm.

2. increasing the number of connecting points between the battery bracket and the vehicle body

The upper bracket is originally connected to the vehicle body at two points. As illustrated in the diagram, increasing one connection point on the right side can enhance the stiffness of the bracket without affecting the installation of other parts. As shown in figure 3.

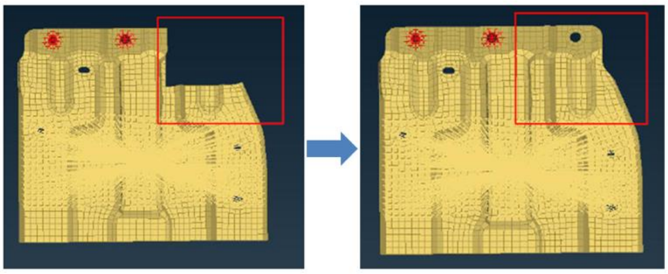
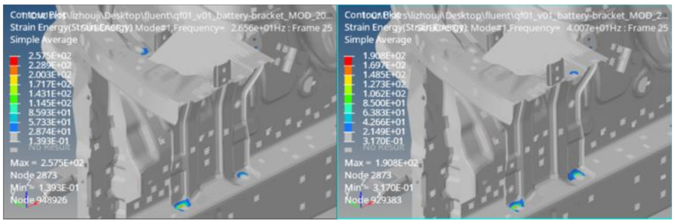


Fig -3: The optimized connection mode between the battery bracket and the vehicle body

The optimized battery bracket has been subjected to strength analysis and modal analysis. The simulation results are presented in Table 5. It can be seen that the safety factor exceeds 1 under five working conditions. The first-order modal frequencies under the constrained modes are 40Hz, 53Hz, and 64Hz, which avoids the engine idle excitation frequency. Additionally, the maximum strain energy of the bracket has been significantly reduced, indicating that the stiffness of the bracket has been enhanced. As shown in figure 4. In conclusion, the optimized scheme fulfills the requisite strength and modal state design, demonstrating the optimization scheme's feasibility.

Table -5: Simulation results of the optimized battery bracket in strength analysis under different working conditions

Working conditions	Max stress in the original scheme MPa	Max stress in the optimized scheme MPa	Yielding stress MPa	Target value	Safety factor
Frontward	182.5	155.2	171	≥1	1.10
Backward	162.4	136.7	171	≥1	1.25
Leftward	121.5	112.3	171	≥1	1.52
Rightward	129.6	117.8	171	≥1	1.45
Downward	181.5	153.3	171	≥1	1.12



(a) (b)

Fig -4: Strain energy of first-order modes bending around the X-axis: (a) in the original scheme, (b) in the optimized scheme.

5. CONCLUSIONS

This paper presents a study of the vibration characteristics of the battery bracket based on the electric vehicle. Initially, a 3D model is constructed, and then the NASTRAN solver is used to perform strength analysis and modal analysis on the processed model. The simulation results demonstrated that the original battery bracket cannot meet the requisite strength target value under frontward and downward conditions. Additionally, the first-order vibration frequency under constrained modes is less than the engine idle speed frequency, indicating the presence of design defects. According to the design principle of the bracket structure, the stiffness of the bracket is improved by increasing the thickness of the steel plate and increasing the number of connection points between the bracket and the body. This allows the optimized bracket's strength and modal analysis results to reach the design target. This paper presented the vibration characteristics of the battery bracket and verified the design principle of the reasonableness of the bracket structure. Furthermore, it offers a theoretical foundation for the design of bracket structures, which can shorten the design cycle and reduce the development cost of the enterprise.

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BIOGRAPHIES

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