Lightweight Design and Test of Electric Experimental Car

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Abstract. A lightweight electric experimental vehicle is designed. According to the lightweight design requirements, the power battery, the battery manager and the driving Motor controller are designed and selected, the chassis frame, anti-rolling frame, steering system and driving system are designed and validated with CAD and CAE software respectively. On this basis, we have carried out the production, assembly and commissioning of the real vehicle. The test results show that the electric experimental vehicle has high practical value and can meet the requirements of experimental teaching. It is worthy of further study, performance optimization and application.

1. Introduction

With the increasing automobile production capacity, energy consumption is increasing, and environmental problems are becoming more and more serious. Automobile lightweight is one of the technical means to improve energy utilization. Automobile lightweight design has attracted more and more attention of domestic scholars. In 2016, Xu Zhongming, Xia Xiaojun, Lai Shiyang and other scholars of Chongqing University established the finite element model of the car body for modal analysis and topology optimization, improved the first-order modal frequency and stiffness of the car body, and realized the lightweight design of the truck in order to improve the first-order modal frequency of a small truck [1]. Yu Yuzhen and others analyzed the frame beam layout based on the DesignXplorer module and obtained a reasonable optimization scheme [2]. An automobile component structure including tire looseness alarm is designed by Wu Huibo et al [3].

In the teaching process, it is very necessary for us to design a lightweight electric experimental car combined with new energy and lightweight direction. We can not only design an experimental car with low cost, simple structure and easy to use, but also improve the practical teaching level and cultivate students' vehicle design ability.

Aiming at lightweight, safety, reliability and high driving performance, this paper analyzes the lightweight technology path from the chassis, roll cage and power part of electric vehicle. The power part is designed, and the electric drive, battery and controller are selected according to the given standard parameters. We established the chassis model, meshed the chassis model, simulated the working conditions of the vehicle, solved the stress, optimized the results, and preliminarily determined the size and shape of the chassis. Based on the chassis foundation, we designed the roll cage, divided the grid, simulated the working conditions of the vehicle, solved the stress, analyzed the solution results, and optimized the analysis again.

On the basis of the roll cage, we have carried out the selection and lightweight design of some parts such as transmission system and driving system. After the design of all components is completed, we used software for pre assembly, conducted finite element analysis on the input assembly of parts,
checked the interference between assembly components, modified the problematic components, and constantly verify and optimize. Finally, we assembled the experimental vehicle as a whole and carried out real vehicle experiments to verify the design results.

2. Basic Technical Requirements for Design and Manufacture of Experimental Trolley

The structure of the lightweight electric test car is similar to that of the formula racing car. Its basic structure and size are shown in figure 1. In combination with the formula racing regulations and national standards, the vehicle design principles are formulated and the overall design requirements are put forward:

![Figure 1. Structure diagram of lightweight electric test trolley.](image)

The requirements are as follows: 1. The trolley shall meet the normal driving of a driver with a height of 180 cm and a weight of 100 kg, and shall be able to ensure that there will be no rollover and collision during driving; It can be driven normally on mountains, dirt roads, stones, slippery roads, etc. 2. The output (nominal) voltage of the whole vehicle driving battery shall not exceed DC 60V, and the working voltage of the control system shall be DC 12V; The power system must be sufficiently safe and completely insulated from the chassis and any conductive parts. 3. The power source of the whole vehicle can only be the power battery, which shall meet the requirements that the external output voltage is lower than 60V.

3. Vehicle Design

3.1. Design and Selection of “Three Electricity”

The core technology of electric vehicle is “three electricity”, including electric drive, battery and controller. The functions of the “three electricity” modules designed in this paper are based on the control logic of the electric vehicle, and the components are designed by using the exclusive accessories for the high voltage and low voltage of the electric vehicle to the greatest extent. It will step down the high voltage of electric vehicles properly and use dc-60v voltage to ensure the safety of drivers; At the same time, in the vehicle control system, the high-voltage power on and power off process is controlled in strict accordance with the control logic of the electric vehicle; It can also collect the temperature, single voltage, total voltage, current and other data information of power battery and display it in detail in the instrument. Lithium iron phosphate high-performance and high-power single battery with stable performance and wide application is selected as the power battery. At the same time, the internal power battery BMS system collects the information of single battery voltage, battery pack temperature, total voltage and current of power battery, and calculates the SOC value. The BMS system sends the information of single battery voltage, battery pack temperature, total power battery voltage, current and SOC value
through the bus, which is convenient for the driver to intuitively grasp the power battery status. The overall dimensions of the power battery are shown in figure 2, and the specific parameters are shown in table 1.

![Power battery dimensions](image1)

**Figure 2.** Power battery dimensions.

| Name                          | Value                  |
|-------------------------------|------------------------|
| Nominal voltage               | 69.35V                 |
| Nominal power                 | 2.4Kwh                 |
| Rated capacity of single cell | 20Ah                   |
| Nominal voltage of single cell| 3.65V                  |
| Rated current                 | 60A                    |
| weight                        | 35Kg                   |
| Overall dimension (with connector) (long× wide × High) | 570mm×390mm×180mm |

![Dimension diagram of vehicle controller](image2)

**Figure 3.** Dimension diagram of vehicle controller.

The whole vehicle controller collects the information of accelerator pedal, vehicle speed, brake pedal, power battery voltage, temperature, SOC, gear, etc., outputs a torque and vehicle driving direction information to the motor controller through calculation, and the drive motor controller receives this information to control the vehicle operation; in the process of vehicle charging, detect the connection state of vehicle charging gun, battery power information, etc., and control vehicle charging; meanwhile, in the process of vehicle power on and off and charging, the vehicle power on and off process is controlled according to the new energy vehicle control logic. The specific dimensions are shown in figure 3, and the specific parameters are shown in table 2.
Table 2. Specific parameters of vehicle controller.

| Name                        | Value                        |
|-----------------------------|------------------------------|
| Main power supply           | DC 12V                       |
| Use environment             | -20°C-50°C                   |
| Relative humidity           | ≤95, No condensation         |
| Power waste                 | ≤200W                        |
| Degree of protection        | IP65                         |
| Weight                      | 2Kg                          |
| Overall dimension (with connector) (long × wide × High) | 320mm × 250mm × 100mm |

DC-DC and high voltage distribution functions are integrated into the drive motor controller to form the power control unit PEU (power control unit). 12V voltage is used when the whole vehicle is running, and the low-voltage battery needs to be charged by the power battery when the vehicle is running. The model of DC-DC module is NES-75-12, and the specific parameters are shown in table 3. Its external connection plugs are high-voltage and low-voltage connectors of new energy vehicles, and its flow capacity, safety protection ability and reliability are greatly guaranteed. It integrates motor controller MCU, current sensor, shunt, charging relay, etc. to centrally distribute the high-voltage power supply. At the same time, it receives the information of the whole vehicle controller to control the torque and direction of the driving motor.

Table 3. Basic parameters of drive motor controller.

| Name                        | Value                        |
|-----------------------------|------------------------------|
| Rated voltage               | 60V                          |
| Rated current               | -60A                         |
| Rated power                 | 3Kw                          |
| Conversion efficiency       | 98%                          |
| Cooling mode                | Natural cooling              |
| Working temperature         | -20 ~ 55°C                   |
| Degree of protection        | IP67                         |
| Weight                      | 10Kg                         |
| Overall dimension (with connector) (long × wide × High) | 570mm × 315mm × 150mm |

3.2. Lightweight Design of Vehicle Chassis Frame

The chassis frame is designed. The chassis of lightweight vehicle is welded with aluminum alloy square tube Al6063. The material is shown in table 4. The chassis frame is modeled with UG software, and the established model is imported into CAE module. The design dimension and structure of chassis frame are shown in figure 4.

Figure 4. Design dimension and structure of chassis frame.
Table 4. Basic parameters of chassis frame materials.

| Name                          | Material or value |
|-------------------------------|-------------------|
| Material Science              | Al6063            |
| Poisson's ratio               | 0.33              |
| Modulus of elasticity /GPa    | 202               |
| Density /(g·cm − 3)           | 2.7               |
| Yield strength /MPa           | 500               |

We set the material properties in the CAE module. The chassis frame is welded, and the surface adhesion is used to simulate the solder joint. The automatic meshing mode is adopted to mesh the frame, which can refine the nodes and adjust the number of cells. After the mesh generation, the finite element model of the frame is established. The frame is divided into 955703 nodes and 478355 elements, and the mesh quality is good.

Through the modal analysis of the chassis frame, we test whether the natural frequency of the frame coincides with the external excitation frequency of the frame, resulting in resonance; The seventh order modal natural frequency of the frame is obtained by CAE analysis. The modal analysis results of the frame are shown in Table 5.

The sixth order modal frequency of the frame is 140HZ, the minimum displacement is 0.198mm, and the maximum displacement is 0.588mm. Through analysis, the frame will not affect the service life of the structure due to serious resonance.

Table 5. Modal analysis results of chassis frame.

| Order | Natural frequency |
|-------|-------------------|
| 2     | 30                |
| 3     | 40                |
| 4     | 80                |
| 5     | 120               |
| 7     | 180               |

Figure 5. Sixth order modal analysis of chassis frame.

3.3. Lightweight Design of Vehicle Roll Cage
The experimental car designed in this paper adopts space truss frame, and the designed frame is
analyzed by linear static analysis and real eigenvalue analysis respectively.

The basic loads borne by the electric vehicle frame include: body shell mass, cabin mass (including passengers), motor mass, power battery mass and frame weight. According to the static equivalence principle, the load on the vehicle can be regarded as evenly distributed, the motor mass is added to the corresponding parts in the form of concentrated load, and the dead weight of the frame is realized by applying vertical downward gravity acceleration to the frame. The basic load of the frame is shown in figure 6:

![Figure 6. Load distribution of frame.]

1. Steering gear 2. Driver 3. Power battery 4. Drive motor

Considering the actual working conditions of electric vehicle, two typical working conditions are selected for frame analysis, namely bending condition and torsion condition.

In the finite element analysis, we should not only fully reflect the actual situation of the model, but also ensure that the frame does not have rigid displacement. Under bending condition, the vehicle runs faster, the safety factor is 1.7 [4], and the allowable stress of the frame is 138 MPa. The constraint conditions of the frame under full load bending condition are shown in table 6.

| Constraint point        | Degree of freedom limit |
|-------------------------|-------------------------|
| Left-front wheel        | X,Y                     |
| Right-front wheel       | X,Y,Z                   |
| Left-rear wheel         | Y                       |
| Right-rear wheel        | Y,Z                     |

The deformation distribution and stress distribution of the frame under bending condition are obtained through finite element solution, as shown in figure 7. It can be seen from the figure that the maximum displacement of the frame occurs at the cross beam in the middle of the frame, and the maximum displacement is 1.413mm. The middle of the frame is the main load-bearing part, and the load is relatively large. The maximum stress of the frame is 52.89Mpa, which is less than the allowable stress of the frame 138Mpa. The stress values of other parts of the frame are generally small, which shows that the strength of the frame is sufficient.
This paper mainly simulates the situation that the left front wheel of the vehicle is suspended. Due to the low speed under torsional condition, the safety factor is 1.2, and the allowable stress of frame structure is 196MPa. The restraint conditions of the frame under full load torsion condition are shown in Table 7. After analysis, the deformation distribution and stress distribution of the frame under torsional condition are obtained, as shown in Figure 8. It can be seen from the figure that the maximum displacement of the frame under torsional condition is 2.79mm, which is located at the left front wheel in the middle of the frame. Because the simulated working condition is that the left front wheel is suspended, the deformation is reasonable, and the frame stiffness is sufficient compared with the allowable deflection of the frame of 7.35 mm [5]. The overall maximum stress of the frame is 75.8018MPa, which is still less than the allowable stress of the frame 196MPa, and there is room for lightweight optimization.

### Table 7. Restraint conditions of frame under full load torsion condition.

| Constraint point       | Degree of freedom limit |
|------------------------|-------------------------|
| Left-front wheel       | Free                    |
| Right-front wheel      | X,Y                     |
| Left-rear wheel        | Y                       |
| Right-rear wheel       | Y                       |

**Figure 8.** Deformation and stress distribution under torsional condition.

### 3.4. Modal Analysis of Frame

The significance of modal analysis of the frame is to see whether the natural frequency of the frame coincides with the external excitation frequency of the frame, resulting in resonance. Resonance
phenomenon will greatly reduce the service life of the structure. The sixth order modal natural frequency of the frame is obtained through UG-CAE software analysis, and the modal vibration mode of the frame is shown in figure 9. Pure electric vehicles will receive several kinds of excitation during actual driving [6]: 1) Vehicles will receive excitation from the road during driving, which is about within 0 ~ 20 Hz; 2) The excitation brought by the suspension is generally 1 ~ 3 Hz; 3) The excitation caused by wheel imbalance is generally 1 ~ 30 Hz. The dynamic influence of the low-order vibration mode on the components is greater than that of the high-order performance [7]. The natural frequency of the frame shown in the figure is 176Hz, which is significantly greater than the excitation frequency caused by the imbalance of the road, suspension and wheels. The analysis shows that the frame can effectively avoid resonance.

Figure 9. Modal shape of frame.

3.5. Design of Driving System
The basic requirements for driving system design are as follows:
1. The suspension can fully withstand the impact and does not interfere with the steering system during operation. It is connected with the frame by screw link, and the link bolt grade is grade 8.8. Wheel bolts and nuts adopt self-locking nuts, and the screw rod is exposed for 3 turns of threads.
2. The wheel is exposed, that is from the top view, the upper part of the front and rear wheels is not obscured by any object, and the overall contour of the front and rear wheels is not obscured by any object [8].
3. The size of the rim is 10 inches, and the front and rear rims are the same.
4. The clearance between brake caliper and rim shall be at least 10mm.
5. The reducer and chassis (rear axle) are connected by bolts. The reducer adopts single-stage deceleration with a reduction ratio of 4:3.

The system adopts double wishbone suspension structure. The assembly static finite element analysis of double wishbones is carried out. The analysis results are shown in figure 10. Simulate the extreme working condition of the vehicle driving on a flat road and restrict the pin shaft of the mounting hole. When a load of 2000N is applied, the maximum unit stress is 88.11 Mpa. The suspension is welded with 6063 aluminum alloy steel pipe. According to the material manual, the yield strength of aluminum 6063 is greater than 170Mpa, and the safety factor is considered. The overall maximum stress of the frame is 88.1059Mpa, the allowable stress of the suspension is 180MPa, and there is room for lightweight optimization.
3.6. Selection of Other Systems

1. We chose a FIVE-POINT NYLON over-the-shoulder harness with a belt and shoulder strap width of 76 mm.

2. The seat is a racing car seat made of carbon fiber. In the normal sitting position, the seat can completely wrap the driver, and the seat is designed to be in the normal vertical sitting position [9].

3. The braking system is designed as two independent hydraulic circuits, and each circuit can only control two wheels, so that in case of leakage or failure at any point in the whole system, the effective braking force will still be maintained on the other two wheels.

4. The vehicle design does not have a speed change gear, but is directly integrated on the control panel with a knob.

5. The firewall is made of 1.0mm thick aluminum alloy plate.

6. The power system components (cables, wires, etc.) are wrapped in the roll cage to prevent damage to the vehicle in case of collision or rollover.

7. The vehicle is equipped with three emergency stop switches. Press one of them to separate the battery and power system from the circuit. Each emergency stop switch uses a rotary emergency switch to press the switch to disconnect the safety circuit.

4. Vehicle Assembly and Commissioning

Based on the theoretical results of the design, the real vehicle is manufactured and assembled, including pipe processing, "three electricity" assembly, steering system installation, braking system assembly and so on. The specific steps are as follows:

1. We use the software UG to assemble all the parts and check for interference, as shown in figure 11.

2. Based on the model drawing, we process the raw material and cut the AI6063 pipe.

3. Then we will cut the pipe, for Welding and assembly.

4. Manufacture and installation of other mechanical parts.

5. Our installation of the “Three electricity” system.
6. After the frame is painted, the fitting is installed. Kill.
7. Assemble the vehicle as shown in figure 12.
8. Training test
   After the assembly of the test trolley, it is necessary to adjust the toe in angle, tire pressure, anti roll bar, load distribution, etc. We use GPS, motion camera and other software to analyze the acceleration, deceleration and trajectory of the car. Some parameters of the vehicle are shown in table 8.

| Parameter                           | Numerical value                      |
|-------------------------------------|--------------------------------------|
| Frame length / width / height       | 2600mm/1180mm/1800mm                 |
| Wheel base                          | 1800mm                               |
| Track width [front / rear]          | 1200mm/1180mm                        |
| Axle load distribution              | 44:46                                |
| Minimum ground clearance            | 80mm                                 |
| Frame Weight                        | 32Kg                                 |
| Turning radius                      | 3m                                   |
| Brake lever ratio                   | 4.2:1                                |
| Gear ratio of reducer               | 12:1                                 |
| Frame torsional stiffness           | 1750Nm/deg                           |
| Rim                                 | 10 inch aluminum alloy               |
| Tyre                                | 195/55R/10C                          |
| Rated voltage of battery box        | 60V                                  |
| Battery box discharge current       | 80A                                  |
| Motor rated power                   | 3Kw                                  |
| Nominal power                       | 1.924kWh                             |
| Waterproof grade of battery box     | ZIP67                                 |
| Steering wheel mass                 | 260g                                 |
| Shock absorber stroke               | 51±2mm                               |
| Outer diameter of anti roll bar     | 20mm                                 |

5. Conclusion
This paper takes the design of lightweight electric vehicle as the theme, and carries out the design on the premise of ensuring safety. The research conclusions are as follows:
1. From the aspects of material lightweight and structure lightweight, the overall design of the experimental car is carried out by means of three-dimensional modeling, finite element analysis and topology optimization.
2. It focuses on the lightweight design of vehicle chassis frame, anti roll frame and suspension, the modal analysis of vehicle frame, and the design and selection of "three electricity" system.
3. The experimental car is assembled and debugged. The experiment shows that the car meets the requirements of lightweight design.
4. The developed lightweight electric experimental car has high practical value and plays a great teaching role. It is worthy of further research, performance optimization and popularization and application.

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