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Research Article

Lightweight Design of Special Axle Hub Based on ANSYS Consider Different Working Conditions for Low Carbon

Cuixia Zhang ,[1] Qiang Li ,[1] Xiuxiang Zhang,[1] Xinyu Wang,[1] Jianqing Chen,[2] and Xuehong Shen[3]

[1]*School of Mechanical and Electronic Engineering, Suzhou University, Suzhou 234000, China*
[2]*Qiuzhen School, Huzhou University, Huzhou 313000, China*
[3]*Xiangyang Road and Bridge Construction Group Co., Ltd., Xiangyang 441057, China*

Correspondence should be addressed to Qiang Li; liqiang1205@163.com

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The lightweight design is considered to be of great significance for carbon reduction. Therefore, a lightweight design of a special axle hub is proposed based on ANSYS considering different working conditions. The structure of a special axle hub is identified. The ANSYS Workbench is used to mesh the hub and import the mechanical and physical parameters. Considering full load, emergency turning and braking, and the treatment of constraints and loads, the stress concentration position is obtained, and the lightweight design is carried out. The free vibration analysis and fatigue life prediction of the hub after lightweight design are verified. After the lightweight design, the optimized hub mass is reduced by 7.52%, and its structural stability and strength meet the demands of various working conditions. The application of a lightweight hub reduces CO_2 emissions by 49875 kg during the life cycle of the vehicle. This study provides theoretical and methodological support for lightweight design of mechanical parts for low carbon.

1. Introduction

Since COVID-19, human society has been more clearly aware of the fact that the fate of man and nature is interdependent [1]. Carbon peaking and carbon neutralization are important measures to build a harmonious coexistence between man and nature [2]. The sustainable development of the manufacturing industry has become a challenge and difficult [3].

The lightweight design of automobile parts is of great significance for energy saving and emission reduction [4, 5]. In terms of lightweight design, the aluminum wheel hub was lightweight designed based on reliability as researched by Tong et al. [6]. A lattice-filled lattice cell suitable for the application of rotating periodic symmetric structure is designed for lightweight design by Zhang et al. [7]. The lightweight design of a lightweight manipulator hybrid structure is proposed based on carbon fiber-reinforced plastic and aluminum alloy by Yin et al. [8]. A lightweight optimal design model for bolted flange joints without gaskets is studied considering its sealing performance by Ma et al. [9]. A six-sigma robust design optimization to explore the lightweight design and crashworthiness of electric vehicles with uncertainty is proposed by Li et al. [10]. In terms of proposing difference, as a typical part of the automobile, the hub has a complex structure and great stress variation. Therefore, the lightweight design of the hub is being discussed by experts and scholars. A lightweight designed monobloc fingered hub is studied by Topouris and Tirovic [11], aiming at reducing disc mass but maintaining rotor thermal capacity. Combine the reverse modeling technique with the topological optimization method to derive lightweight wheel hubs based on the principles of mechanics by Xu et al. [12]. Considering stress and fatigue life, a lightweight design of the axle hub based on ANSYS is studied by Zhang et al. [13]. Digital twin of the rotor shaft of a lightweight electric motor during aerobatic loads is studied by Goraj [14]. The lightweight design of automotive front rails by the nonlinear structural optimization method is researched by Liang et al. [15]. The design and optimization of interference-fit and adhesively bonded joints in lightweight structures for shaft-hub is addressed by Croccolo et al [16]. From a life cycle assessment perspective, the optimization design of lightweight components of automobiles with flax fiber-reinforced polymer composite is studied by Deng et al. [17]. An integrated optimization control method for remanufacturing assembly systems was put forward by Liu et al. [18]. In terms of lightweight design's positive effects, it is found that when the weight of the car is reduced by 10%, fuel utilization will be increased by 8%, and exhaust emissions will be reduced by 4%. It is considered to play an important role in improving equipment performance and reducing costs for enterprises [19, 20]. Optimal operations of a closed-loop supply chain were done by Liu et al. [21]. A novel cooperative game-based method to coordinate a sustainable supply chain was put forward by Liu et al. [22]. A data-driven manufacturability evaluation method of waste parts was done by Liu et al. [23].

Low-carbon design is an aspect of green design; it has become one of the hot topics for scholars at home and abroad. Low carbon has become a new rule in the automotive industry today [24]. In terms of low-carbon consumption, how to implement a low-carbon design in the process of automobile design so that automobile products become internationally certified low-carbon products, keeping up with the trend of the consumption market and occupying the green consumption market, has become the long-term development strategy of automobile manufacturers. Emission reduction and a low-carbon economy are in the same line. Only by fully recognizing the importance of emission reduction can we improve the current environmental pollution and develop low carbon by a long way. Automotive lightweight design is an important means to implement low-carbon strategy development. Transmission technology is one of the key energy efficiency technologies by Liu and Zeng [25]. Considering the environment, product performance, economy, and other factors, the AHP method is used to make a decision on the process of automobile bumper beam [26]. A low-carbon design platform for typical auto parts based on the Creo platform has been developed to support the low-carbon design and manufacturing of auto products and achieve a quantitative evaluation of carbon emissions of typical auto parts in the early stages of design. The life cycle carbon emission performance of automotive products was optimized through material selection, structural optimization, and process optimization by Jiang [27].

Through the above research, it is not difficult to find that most of the existing research is focused on the finite element analysis and fatigue life prediction of aluminum alloy or other similar alloy wheel hubs for ordinary cars by Prasad et al. and Xiong et al. [28, 29]. However, the relevant research on ductile iron wheel hub of a special vehicle axle is relatively less, and the stress of different working conditions is limited. The relationship between hub lightweight and low carbon has not been reported. Therefore, this paper studies the lightweight design of a special axle hub based on ANSYS and considers different working conditions. The influence of lightweight hub design on vehicle low-carbon performance is also studied. This study provides theoretical and methodological support for the lightweight design of mechanical parts for low carbon.

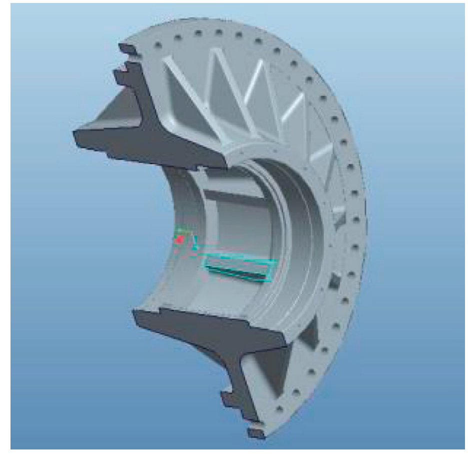

Figure 1: Sectional view of the wheel hub 3D model.

Table 1: QT500-10 material mechanical parameters.

Name	Density (kg/m^3)	Poisson's ratio	Young's modulus (Pa)	Yield strength (Pa)
QT500-10	7.1×10^3	0.29	1.7×10^{11}	6.25×10^8

2. Methods

2.1. 3D Model and Parameters of the Wheel Hub. This study uses the hub of a special axle as the research object. Pro/E is used to establish the hub model (Figure 1). The whole wheel hub is mainly composed of the bearing chamber, inner and outer rib plates, upper and lower rib plates, tire, bolt holes, and wheel side support. After the wheel hub model is created, it is converted into a more compatible Para solid ($^*.x\_t$) format. It chooses to use the solid form. After saving, it opens with the static structure of ANSYS Workbench to enter the model interface for the next operation.

The material of this hub is qt500-10 ductile iron; its advantages are high mechanical strength, good tensile strength, and convenient processing. Therefore, it is suitable for heavy-duty special vehicle hub. The specific material mechanical parameters are shown in Table 1.

2.2. ANSYS Workbench. The mesh application module of ANSYS Workbench is used to mesh the imported wheel hub finite element model. Because the wheel hub structure shape is more complex, the free mesh division is used to divide the wheel hub. The selected grid type is ten node tetrahedral grids. Then, according to the yield failure of the hub in the actual working condition, the mesh is refined and added to the place where the stress is concentrated. It usually occurs at the wheel side support. Therefore, the mesh is refined at the wheel edge support of the hub, the size is set to 5 mm (Figure 2), and the number of entity units and nodes (a

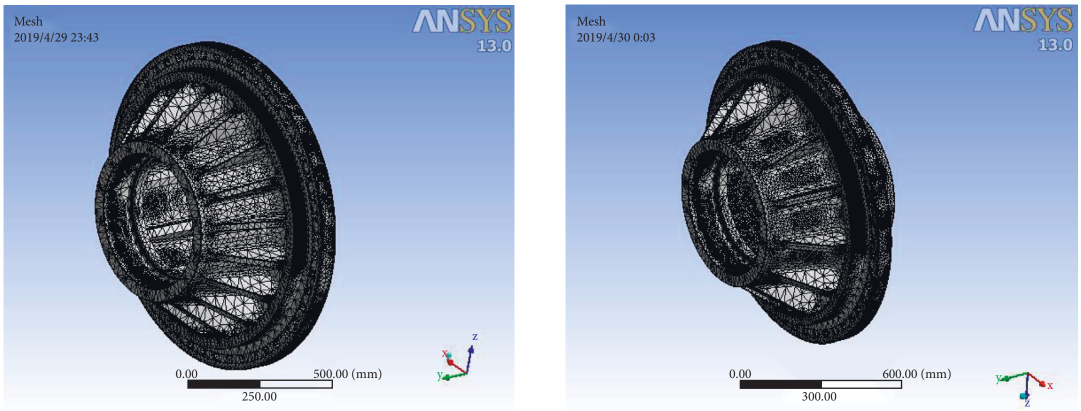

Figure 2: Meshing of hub structure.

Table 2: Grid data.

	Before optimization	After optimization
Number of nodes	747635	631840
Number of entity units	444093	369399

connecting point at which several lines come together) before and after division are shown in Table 2.

2.3. Addition of Load and Constraint under Hub Working Condition. The constraint condition of the hub is mainly provided by the tire rim. Therefore, in the finite element analysis, we can meet the demand by fixing the constraint on the flange surface (Figure 3). The constraint type added in ANSYS Workbench is fixed support, that is, the six degrees of freedom on the selected surface of the wheel hub model are constrained. We add a cylindrical support to the inner bearing chamber of the hub. This constraint is axial and radial and does not restrict the rotation. After the constraints are added, the finite element analysis of the hub under different working conditions is carried out, and the comparison of various parameters before and after lightweight is carried out.

In order to have a more comprehensive understanding of the hub before and after a lightweight, the finite element analysis is carried out under three special conditions: full load, emergency braking, and emergency turning. Three special working conditions mentioned above are typical, and the wheel hub is the most complex. It has the value of analysis and comparison.

2.3.1. Condition 1: The Vehicle Is Fully Loaded at Rest or Driving at Low Speed. In this study, the wheel hub of the special axle which is analyzed by the finite element method is assembled with a larger vehicle type, and it is transported in the desert terrain. Therefore, its driving speed is low, only 10 km per hour, and the wheel hub load is the same as the static condition. It is known that the single axle bearing capacity of the wheel hub studied in this study is 200 tons, then the single wheel hub bearing capacity is 100 tons, and the load is as follows:

$$F_1 = \frac{mg}{2}, \quad (1)$$

where m is the bearing capacity of the hub and g is the acceleration of gravity.

By comparing the results of finite element analysis, the maximum displacement before optimization is 0.025759 mm, the maximum stress is 106.24 MPa, and the safety factor is 5.88 under the vertical static load of 98000 N. After optimization, the maximum displacement is 0.039459 mm, the stress at the maximum stress position is 107.86 MPa, and the safety factor is 5.79. The specific positions are shown in Figure 4.

2.3.2. Condition 2: The Vehicle Is under Emergency Braking. When the vehicle is in the braking state, it is mainly considered that when the maximum braking is used for deceleration, the braking force on the ground has a greater radial impact on the hub of the axle. At this time, the radial load on a single hub is shown in the following formula:

$$F_2 = k \times \frac{mg}{2}, \quad (2)$$

where k is the impact coefficient, generally 1.2.

Through the comparative observation of the finite element analysis results, under the load of 1176000 N, the maximum displacement before optimization is 0.03091 mm, the maximum stress is 127.49 MPa, and the safety factor is 4.91.

After optimization, the maximum displacement is 0.047351 mm, the maximum stress position is 129.44 MPa, and the safety factor is 4.83. The specific location is shown in Figure 5.

2.3.3. Condition 3: The Vehicle Is in the State of Emergency Turning. The working condition of emergency turning is mainly considered when the car is turning at the maximum turning speed. The whole car hub will be affected by inertial force. Other load treatments are the same as adding static load in Condition 1. However, this needs to add a load generated by the axial inertial force. Along the Y direction, the result of the whole resultant force is shown in Figure 6:

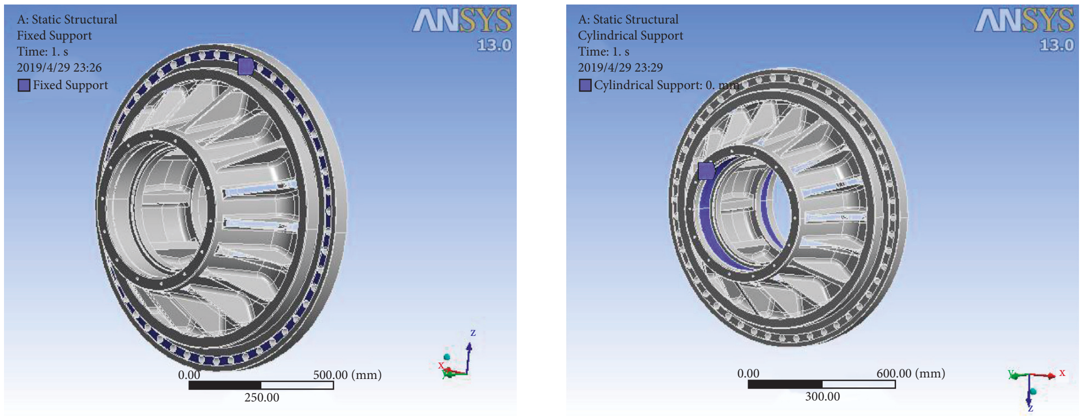

Figure 3: Fixed supports and cylindrical support of hub.

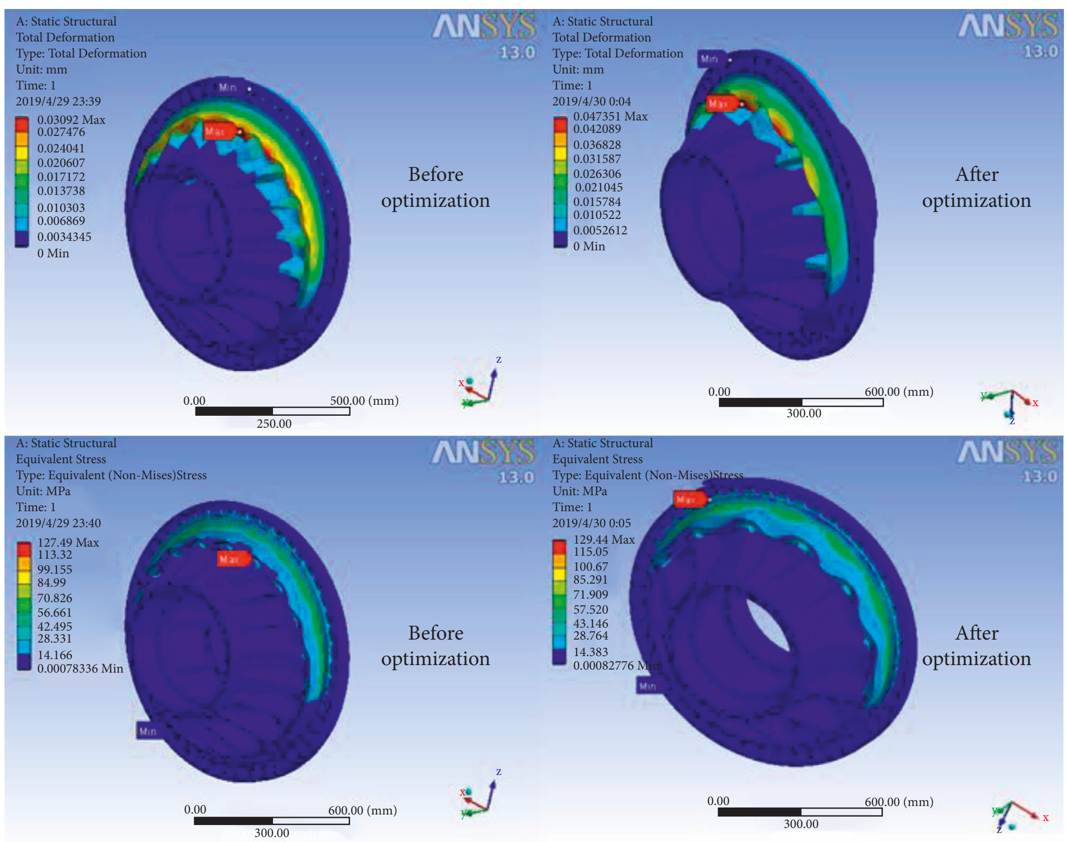

Figure 4: Displacement and stress nephogram of fully loaded.

$$N = \mu \times F_1, \quad F_3 = F_1 + N, \tag{3}$$

where μ is the adhesion coefficient, and 0.4 is taken according to the enterprise experience and investigation under this condition.

Through the comparison of the finite element analysis results, it can be seen that, under this load, the maximum displacement before the optimization is 0.01961 mm, the maximum stress is 75.913 MPa, and the safety factor is 8.23. After optimization, the maximum displacement is 0.03133 mm, the maximum stress is 124.79 MPa, and the safety factor is 5.01. The specific location is shown in Figure 7.

2.4. Results of Finite Element Analysis. Through the identification of the relevant structure of the wheel hub, the analysis report generated by the later finite element method, and the calculation of the relevant mechanical parameters, the final optimization results are obtained: the wheel edge support of the wheel hub is widened by 7 mm, and the thickness is reduced by 2 mm. The number of stiffeners has been reduced from 18 to 12. The hub mass before optimization is 0.94638

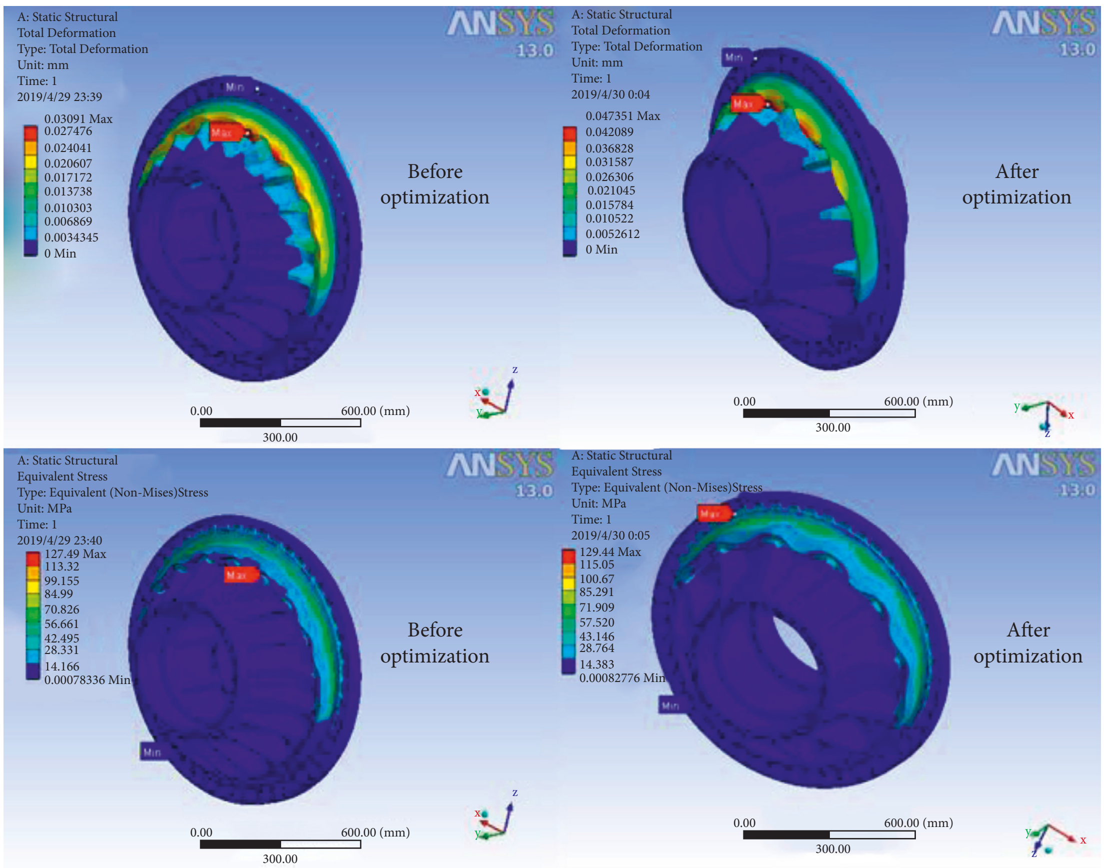

FIGURE 5: Displacement and stress nephogram under emergency braking.

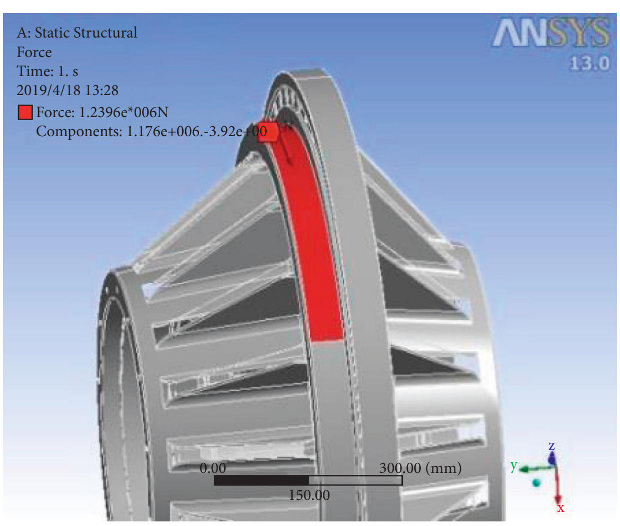

FIGURE 6: Stress condition of working condition.

tons and that after lightweight design modification is 0.87513 tons. The overall mass is reduced by 0.07125 tons, accounting for 7.52% of the total mass. The volume is reduced from $1.3329e+8\,\mathrm{mm}^3$ to $1.2326e+8\,\mathrm{mm}^3$. The results of finite element analysis and calculation show that the overall quality of the hub decreases, but the stability of its structure and its own strength does not change greatly, but the reduction of its own weight can effectively reduce.

The relevant data provided by the company show that the unit price of wheel hub material is about 20 CNY/kg, so it can be calculated that the cost of a single wheel hub can be saved by nearly 1425 CNY. And through the finite element analysis results and calculations, it is found that the overall quality of the hub decreases, but the stability of its structure and its own strength have not changed greatly, but the reduction of its own weight can effectively reduce the quality of the whole transport vehicle, which has a positive effect on reducing energy consumption and carbon emissions.

3. Modal Analysis and Fatigue Analysis Verification

3.1. Modal Analysis. Six order modal analysis is carried out for the wheel hub before and after optimization to ensure the comparative effect. The following results are obtained through the modal analysis of ANSYS Workbench.

The frequency test data in Table 3 show that the natural frequency of the hub model before and after optimization has not changed greatly. The observation results show that the natural frequency of the hub is at a higher value. However, when the wheel is running normally, the wheel hub is in a stable environment with a low driving speed of 10 km per hour and a vibration frequency of less than 100 Hz; that is, the hub structure after lightweight design can still have good stability.

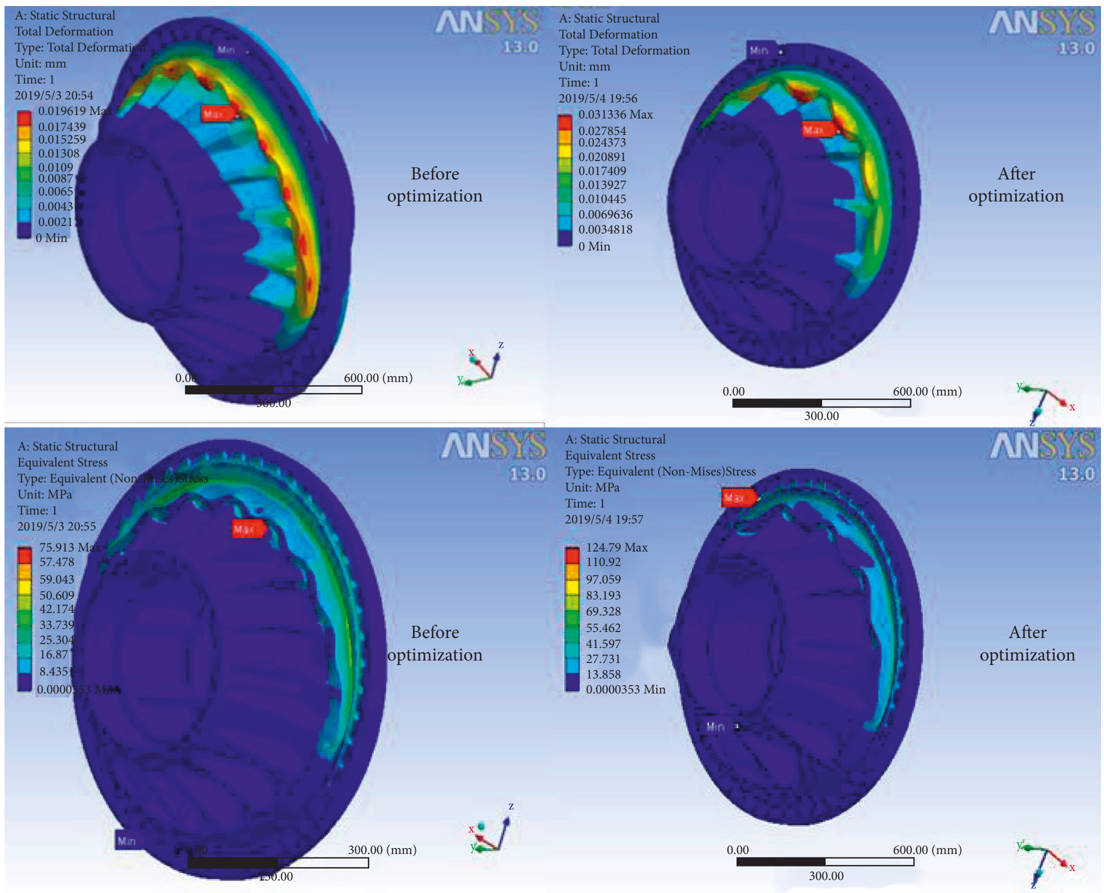

Figure 7: Displacement and stress nephogram in the state of emergency turning.

Table 3: Sixth-order vibration frequency of a wheel hub model.

Order	Before optimization (Hz)	After optimization (Hz)	Rate of change (%)
1	3123.2	3132.8	0.3
2	3123.7	3133.2	0.3
3	3220.9	3152.5	2.1
4	3227.4	3234.4	0.2
5	3229.5	3235	0.17
6	3335.1	3472.8	4.1

3.2. Fatigue Analysis Verification. It can be seen from the life analysis nephogram of ANSYS Workbench that, after a certain number of load cycles' tests, the dangerous position of the studied hub mainly appears in the flange position and the wheel edge support of the hub, which has the tendency of fracture; itis consistent with the actual fatigue failure. However, it can be seen from the data that the minimum failure life is $1.817\,E+9$, which is far greater than the 106 required by the international standard, and the safety factor is 1.4073, which is also greater than 1 required (Figure 8). Moreover, the fatigue sensitivity curve (Figure 9) is used to verify that the sensitivity curve of the optimized hub is similar to the S-N curve under the set cycle times and load constraints. It proves the correctness of the design.

Therefore, the lightweight wheel hub designed in this study can meet the usage requirements.

The low-carbon effect caused by lightweight automobile hub is very obvious. The most direct is the emission of carbon dioxide from automobile exhaust. The relationship between automobile carbon dioxide emission and automobile mass reduction can be expressed by

$$Q = \eta \times m \times L, \tag{4}$$

where Q is carbon dioxide emissions, kg, η is the emission coefficient $(\text{km})^{-1}$, and L is the vehicle mileage, km.

According to formula (4) and the research results of hub lightweight above, the low-carbon efficiency of the whole life cycle of this model of an automobile can be calculated. As a matter of experience, η is 5×10^{-5} $(\text{km})^{-1}$ [23]. The heavy truck has a total of 20 axle hubs. The weight of each axle hub is reduced by 71.25 kg, and the total weight of the vehicle is reduced by 1425 kg. Mandatory scrap life is 7×10^{5} km;

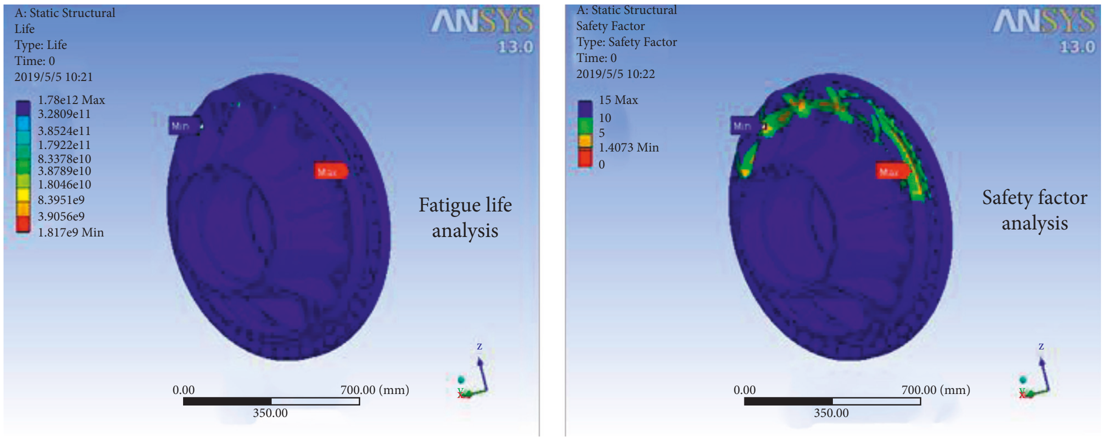

Figure 8: Fatigue life and safety factor.

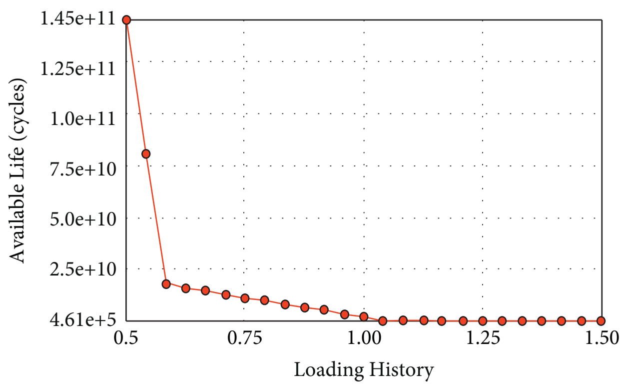

Figure 9: Fatigue sensitivity curve.

calculate the full life cycle, namely, L is 7×10^5 km. By substituting the value into formula (3), it can be obtained that $Q = 49875$ kg, and the effect is obvious. If all heavy trucks produced by the enterprise are applied to the lightweight hub, the low-carbon efficiency is even more considerable.

4. Conclusion

Under the regulation of carbon peaking and carbon neutralization, energy conservation and emission reduction have become an urgent demand for the sustainable development of enterprises. The lightweight design of parts is considered to be an effective means. This study takes a special axle hub as the object to carry out the lightweight design. The main conclusions are as follows: (i) the restraint and load of the hub under full load, emergency turning, and braking conditions are studied, (ii) the free vibration analysis and fatigue life prediction of the hub before and after lightweight design are compared and verified, (iii) the optimized hub mass is reduced by 7.52%, and the cost of each hub can be saved by 1425CNY, which meets the use requirements, and (iv) the application of lightweight hub reduces CO_2 emissions by 49875 kg during the life cycle of the vehicle.

In the future, the lightweight design of different parts under uncertain environment will be further studied, in particular, the effects of low carbon. This study provides theoretical and methodological support for the lightweight design of mechanical parts for low carbon.

Data Availability

All data included in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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