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Research on Lightweight Design of Car Body Mechanism Based on Fatigue Life

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Abstract

The lightweight design of car body mechanism helps the vehicle to reduce its own energy consumption and greenhouse gas emissions, which is conducive to the realization of energy saving and environmental protection requirements, so it has high research value. At present, most of the lightweight design of car body mechanism still has much room to improve for the more complex body parts. Based on this, this paper first studies the car body mechanism, and then analyses the fatigue strength analysis and fatigue life analysis process of the car body mechanism. Finally, the optimal measurement of lightweight design of car body mechanism based on fatigue life is given, and the effect of lightweight design is analysed.

Keywords: *Lightweight Design,Car Body Mechanism, Fatigue Life ;*

1. Introduction

With the continuous development of China's social economy and the continuous improvement of people's living standards, cars have become a popular choice for the public to travel. In this context, car sales have been significantly increased. In fact, China has become the world's largest car production and marketing market. On the other hand, with the continuous improvement of national environmental protection requirements, how to make cars better meet the requirements of energy saving and emission reduction has become the continuous optimization goal of many car manufacturers. As one of the most important parts of the car itself, the design and optimization of the car body mechanism is not only related to the safety of the car members, but also related to the service life and cost of the car.

The lightweight design of car body mechanism can significantly reduce the weight of the vehicle, thus reducing energy consumption and greenhouse gas emissions, which is conducive to the realization of energy conservation and environmental protection requirements. But on the other hand, except for a small number of off-road vehicles with non-load-bearing body, most of the family cars are load-bearing body structure, that is to say, the body structure of most cars is an important bearing part of the vehicle itself, which is related to the service life of the vehicle itself and the safety of its members in case of accident.

As one of the main load-bearing parts, the car body mechanism bears more complex internal and external loads. Most of the car body mechanism damage is caused by fatigue failure. This requires static strength check and fatigue strength check for strength evaluation of car body mechanism. The lightweight design of car body mechanism based on fatigue life is helpful to the equal fatigue life model of car body mechanism, which makes the body parts reach the minimum weight under the premise of fatigue life at the same time, and makes the car body mechanism meet the environmental requirements of energy conservation and emission reduction on the premise of ensuring the cost and performance.

In addition, most of the current lightweight design of car body mechanism mainly takes the thickness of plate as design variables, and adopts the method of size optimization to carry out lightweight optimization design. For the more complex body parts, the optimization effect of these design methods still has a large space for improvement. Unreasonable lightweight design of the body mechanism will not only have adverse effects on the ride comfort, handling stability and NVH performance of the car, but also lead to structural fatigue and safety risks.

The lightweight design of car body mechanism based on fatigue life is to verify the reliability of lightweight results based on fatigue strength. Based on the consideration of car body mass and fatigue life, the relationship between mass and fatigue life of many mechanism components on car body is studied, and the system multi performance comprehensive optimization is carried out based on various factors. This research method can take into account the calculation accuracy and efficiency, and get the optimization results which can meet the requirements of comprehensive performance[1]. Therefore, the research on lightweight design of car body mechanism based on fatigue life is helpful to build the life model of car body mechanism parts, so as to reduce the weight of car body mechanism parts, reasonably distribute the fatigue life of car body parts, so as to make the utilization rate of car body mechanical components the best, so it has important research value.

2. Research on the body mechanism of car

2.1. Load bearing form of car body mechanism

According to the different load-bearing forms, car body can be divided into load-bearing, non-load-bearing and semi-bearing body mechanisms. Among them, the characteristic of the load-bearing body is that there is no frame. The body is assembled and welded into a rigid frame structure by the bottom plate, framework, inner and outer skin, and the whole-body components are all involved in the load-bearing. The non-load bearing body has an independent frame. The body is elastically fixed on the frame with springs or rubber pads[2]. The main body of the load bearing body is the frame. The body only bears the weight of the people and luggage carried. The structure of the semi load-bearing body is basically the same as that of the non-load-bearing body, and it belongs to the frame type. The difference between them is that the connection between the body and the frame is not flexible but rigid. The advantages and disadvantages of different bearing forms of car body mechanism are shown in Table 1.

Table 1. The functions and features of carbearing forms.

Bearing forms	Advantages	Disadvantages
Load-bearing	Reduce body weight,good driving stability	Difficult to modify the car body and repair it after damage
Non-load-bearing	Strong torsion resistance, independent frame	Poor comfort and high cost,heavy body weight
Semi-bearing	Basically the same as the non-load carrying body	The structure is complex and the cost is high

In order to facilitate the installation of engine and transmission system, as well as to improve the stress condition of mounting points and the comfort of passengers, some cars adopt subframe structure. The subframe is directly connected to the body through cushions. The subframe can be installed at both the front and rear ends or only at the front end, as shown in Figure 1 below.

July - August 2020
ISSN: 0193-4120 Page No. 5504 - 5512

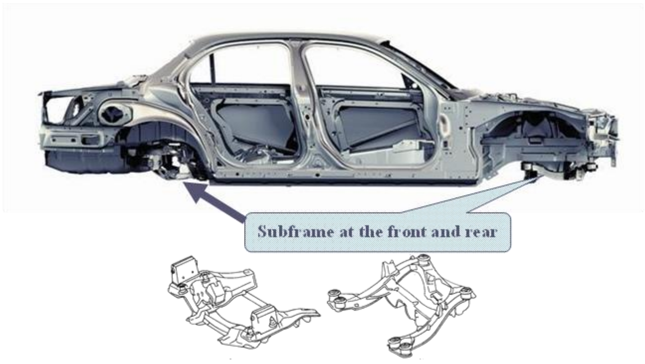

Figure 1. Subframe structure of typical passenger car.

2.2. Strength design of car body mechanism

The deformation modes of thin-walled components of car body mechanism can be expressed as bending deformation, warping deformation or wrinkle deformation. Among them, the deformation amount of wrinkle compression is the largest, which is most conducive to absorbing the impact energy. Therefore, the wrinkle compression is a design goal and direction in the energy absorption design of thin-walled components[3]. Secondly, when the cross-section of the stress bar of the car body mechanism changes suddenly, the stress concentration at the section change will be caused by the sudden change of stiffness. In the automobile body which often bears the alternating stress, the stress concentration may induce progressive cracks and lead to fatigue damage. Therefore, special attention should be paid to the design of stiffeners and joints.

In addition, the section shape of thin-walled member of car body mechanism has a great influence on the stiffness. In order to improve the stiffness of the whole body and components, the closed section should be used more. It is often necessary to open some holes on the load-bearing member of the car body to install various wires, pipes and mechanisms. Obviously, due to the stress concentration caused by these holes, the holes should be selected in the position with less stress. In addition, the stress concentration in one large hole is more serious than that in several small holes. In general, the stress concentration will appear at the connection point of longitudinal and transverse members. If the design is improper, it may cause hidden danger to the vehicle body. The common joint forms are shown in the figure below, so as to enlarge the connection area and reduce the stress concentration. The main stressed parts of the car body are shown in Figure 2 below (in red color).

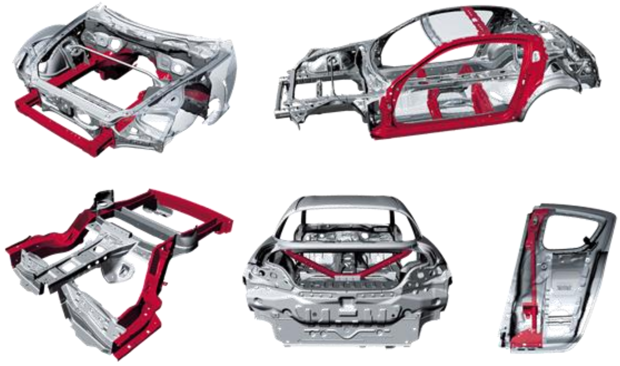

Figure 2. The main stressed parts of the body.

2.2.1. Design of body frame components

When designing the body frame components, generally, according to the experience or referring to the mature vehicle structure, after completing the preliminary design, carry out the finite element analysis or make the sample for test, and then adjust the section and size of the components according to the analysis or test results[4]. The first mode of BIW assembly should not be lower than a certain limit value. Under any working condition of the vehicle, the internal and external excitation frequencies should be effectively avoided to prevent resonance. On this premise, the natural frequency of the whole vehicle should be increased as much as possible to improve the ride comfort.

2.2.2. Design of other parts of body mechanism

The large panel with poor stiffness is easy to cause forced vibration under the excitation of vibration source. Therefore, in the shape design of the outer plate, it is necessary to consciously consider the camber of the surface and set the edge line. It is not advisable to model the parts straight. When making, the steel plate should have enough thinning rate to produce cold work hardening. Stiffeners of various shapes can be arranged on the inner panel and the unexposed outer panel.

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TEST Engineering & Management

July - August 2020
ISSN: 0193-4120 Page No. 5504 - 5512

3. Fatigue strength analysis of car body mechanism

3.1. Characteristics of fatigue failure and factors affecting fatigue life

In the process of vehicle driving, due to the influence and action of many external factors, the body structure is usually affected by alternating load, which leads to the strength problem caused by alternating load. Especially under the repeated action of alternating load, the material or structure of body mechanism is easy to be damaged[5]. For example, the material or structure may be damaged when the stress value does not exceed the strength limit of the material or even much lower than the elastic limit after repeated load changes. Fatigue is the development process of local and permanent structural changes in materials which are subjected to disturbance stress at a certain point or some points and form cracks or complete fracture after enough cyclic disturbance. Fatigue and fracture are the main reasons for the early failure of automobile body bearing structure.

3.1.1. Characteristics of fatigue failure

Under the action of variable load, the alternating stress is far less than the strength limit of the material, and the failure may occur, mainly manifested in the brittle fracture of low stress. Generally speaking, it is often shown that there is no obvious plastic deformation of sudden fracture, there is smooth area and rough area at the fracture, which is an important criterion to determine whether it is fatigue failure. Fatigue failure is a process of cumulative damage, which usually experiences different development periods and processes, such as crack formation, propagation and finally to critical size.

3.1.2. Factors affecting fatigue life

In the influence level of stress concentration, the fatigue source always appears in the place of stress concentration, which reduces the fatigue strength of the structure or component, and has a great impact on the fatigue strength. The influence of stress concentration on material strength mainly includes static strength and fatigue strength. Among them, the former is related to the properties of materials, and has a greater influence on brittle materials than on materials with better plasticity; the latter is an important factor for both plastic materials and brittle materials.

Secondly, in the dimension influence level, the size of the body structure parts has a greater impact on the fatigue strength, which is related to the stress gradient and material inhomogeneity. The stress gradients of parts are different under the same load with different sizes. Generally speaking, the high stress region of large size parts is large, and the probability of fatigue crack is high. Large size parts contain more adverse factors that may produce fatigue cracks. Therefore, when the body parts are machined, there will be some surface hardening, so as to improve the fatigue limit.

In addition, in the influence of surface processing and surface treatment, fatigue crack sources usually originate on the surface of the specimen, and the surface condition of parts has a significant impact on its fatigue strength. The stress level of the outer surface is usually the highest, and the defects are also the most. The constraint of the surface layer material is small, and the slip band is easy to start. The surface sensitivity coefficient is calculated as shown in follows formula:

$$\beta = \frac{Fatigue\ strength\ of\ specimens}{atigue\ strength\ of\ standard\ smooth\ specimens} = \beta_1\beta_2\beta_3 \qquad (1)$$

In which, β_1 is the surface processing roughness, which has a great influence on the fatigue strength. The surface processing defects are the factors of stress concentration, which are often the fatigue source, which will greatly reduce the fatigue strength. β_2 is the structure of the surface layer. The surface layer has an important influence on the fatigue strength of parts. The fatigue strength of the surface layer can be improved by surface treatment process. β_3 is the stress state of the surface layer. Cold working deformation is an effective way to

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July - August 2020
ISSN: 0193-4120 Page No. 5504 - 5512

improve the fatigue strength of parts, and its essence is to change the stress state of the surface layer of parts[6].

The higher the temperature is, the faster the creep deformation of the material is, and the shorter the damage time is. The effect of high temperature on fatigue life is to reduce its fatigue strength. Therefore, the fatigue curve corresponding to high temperature should be used to evaluate the fatigue performance of body components. In the aspect of the influence of load application form, the fatigue strength of components is related to the time of high stress level in a single cycle. With the increase of load frequency, the time of high stress level in single cycle will be reduced, and the fatigue strength will be improved.

3.2. Fatigue design method of body mechanism

Fatigue failure is one of the most important failure modes of vehicle products. In the design of vehicle body structure, in addition to the necessary static strength, fatigue analysis and fatigue design must be carried out. At present, the fatigue life design of car body mainly includes infinite life design, safe life design, damage safety design, damage tolerance design and durability design. The differences and characteristics of these methods are shown in Table 2.

Table 2. The differences and characteristics of fatigue design methods.

Design methods	Advantages	Disadvantages
Infinite life	Simple	Conservative and the components are heavy
Safe life	The working stress is allowed to exceed its fatigue limit	Safety factor must be considered to consider the dispersion of fatigue data
Damage safety	Fatigue cracks are allowed	Fracture control measures should be adopted
Damage tolerance	Embodiment and improvement of safety design method	Suitable for materials with slow crack growth and high fracture toughness
Durability	More economical and effective	Comprehensive consideration of ensuring the safety of structure

3.3. Method of determining fatigue life

The methods to determine the fatigue life include test method and test analysis method. The former completely depends on the test, which is the traditional method to obtain the required fatigue data directly through the same or similar test with the actual situation, which is reliable, but can only be carried out after the prototype trial production. Therefore, this method has the shortcomings of high cost, long cycle, and cannot be parallel with the design, and the test results are not universal. The latter determines the fatigue life of the structure according to the fatigue performance of the material and the load history of the structure, including the description of the fatigue behavior of the material and the response of the structure under cyclic load.

With the development of computer technology and finite element analysis, the current fatigue life analysis method has been widely applied. Firstly, the finite element method is based on the load and geometric structure to calculate the stress change process. Secondly, based on the obtained stress-strain response, combined with the material performance parameters, different fatigue damage models are applied to calculate the life, which makes the finite element technology become an

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July - August 2020
ISSN: 0193-4120 Page No. 5504 - 5512

indispensable analysis tool for the current car body fatigue life design.

3.4. Basic theory of fatigue analysis

Typical fatigue stress cycles mainly include symmetric, pulsating and random stress cycles, as shown in Figure 3 below. Among them, the symmetrical cycle is a completely symmetrical sinusoidal constant amplitude stress cycle, which is most common in the rotating shaft without overload and running at constant speed. The maximum stress of pulsating cycle is not equal to the minimum stress, and all of them are tensile stress. Random stress cycle means that there is no certain law of stress cycle, which is usually caused by random load acting on the structure, which is more representative in practical engineering.

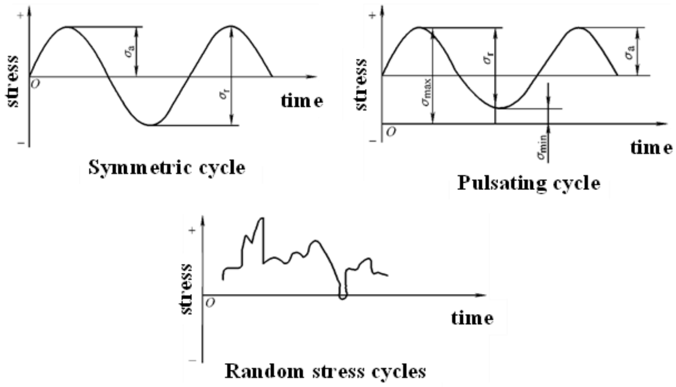

Figure 3. Typical fatigue stress cycles.

The fatigue life of car body mechanism depends on the mechanical properties of materials and the applied stress / strain level. Generally speaking, the higher the strength limit of the material, the lower the applied stress / strain level, the longer the fatigue life of the specimen. The curve representing the relationship between the applied stress / strain level and the fatigue life of the standard specimen is called the S-N curve of the material[7]. When the S-N curves of different steels with different strength are plotted with fatigue limit and ultimate tensile strength, the general S-N curves of materials can be obtained, as shown in Figure 4 below.Only when the influence of average stress on fatigue process is understood can the test data obtained from symmetrical load be used effectively for fatigue assessment.

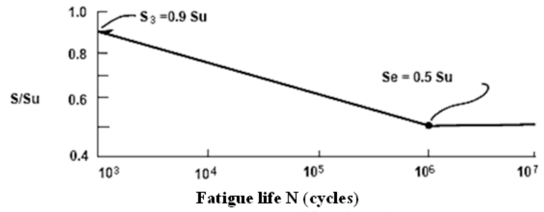

Figure 4. The general S-N curves of materials.

4. Fatigue life analysis process of car body mechanism

4.1. CAE analysis process of automobile body fatigue life

The CAE analysis process of fatigue life of car body includes several processes, such as unit filtering, channel filtering and load filtering, so as to realize the identification of durability dangerous area and sensitive unit, identification of channel load of dangerous body installation position and load of dangerous working condition, and finally achieve the purpose of calculating the stress / time history and fatigue life of dangerous unit of car body mechanism.

4.1.1. Model description and calculation

In the process, the first step is to establish the model of the reconstituted body, and describe the model into the multi-body software with the modal synthesis method, and establish the rigid flexible combination model of the whole vehicle. As shown in Figure 5, the finite element model of the car body structure is shown.

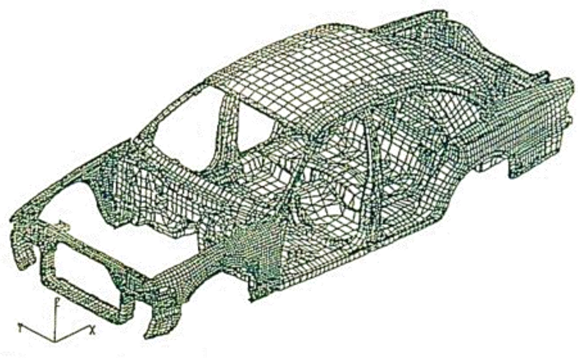

Figure 5. The finite element model of the car body structure.

4.1.2. Dangerous passage load

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July - August 2020
ISSN: 0193-4120 Page No. 5504 - 5512

The load on the chassis is transmitted to the vehicle body through the fitting part of the body. For example, a cyclic road load data is input in the durability analysis process, and the frequency curve is obtained by spectrum analysis. The load is added to the vehicle data file of rigid flexible multi-body model of the whole vehicle. Through dynamic simulation calculation, the load of each channel supported by the body is obtained, as shown in Figure 6.

Rain flow analysis was carried out on the road load data of durability analysis to obtain the load time history data of each event. The load time history data of each event are input into the vehicle model to calculate the fatigue stress of the vehicle body and identify several dangerous cycle event loads. The final fatigue life of the body structure system depends on the combination of dangerous cyclic event loads. The cyclic event loads are input into the fatigue analysis program for fatigue analysis. The stress component and one-dimensional equivalent stress time history of the dangerous element are calculated, and the frequency spectrum of the latter is analysed according to the rain flow counting method. Based on the results of spectrum analysis, the maximum and minimum stresses are obtained, and the stress parameters such as average stress and stress amplitude are calculated. The cumulative damage and fatigue cycle number, mileage and safety factor based on reference nominal stress are calculated.

Figure 6. The dangerous passage load of the car body.

4.2. Stress response calculation of body mechanism

First of all, in the level of obtaining load simulation method, the virtual test field is constructed through simulation to realize the road simulation. Including the simulation of the body, chassis and suspension system, as shown in Figure 7 below. When a car moves on rough road, the car body is equivalent to an unconstrained structure. Through the inertia release method, the static calculation or modal analysis of the unconstrained structure can be realized, which can significantly improve the calculation efficiency.

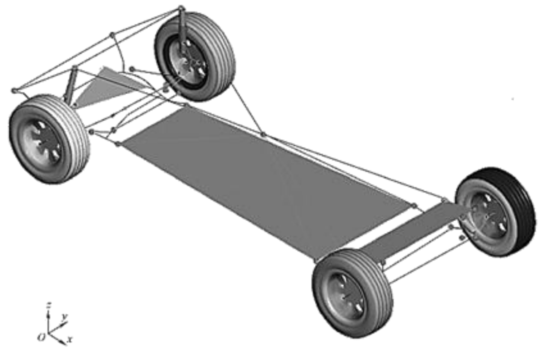

Figure 7. Load simulation of the car body, chassis and suspension system.

Secondly, when the external force acts on the unconstrained structure, the whole structure will experience a rigid body acceleration in the unconstrained direction, and the mass of each point of the structure will produce an inertial force in each free direction. When the inertial force is added to the system to counter the external force, the system is in unconstrained static equilibrium state:

$$m\ddot{u} + ku = -\tilde{m}\ddot{R} + F \quad (2)$$

Where u is the small elastic displacement field, m, k are the mass matrix and stiffness matrix related to displacement, $\tilde{m}$ is the matrix of total mass and inertia moment of rigid body, $\ddot{R}$ is the acceleration of rigid body, and F is the force vector between car body parts.

4.3. Fatigue life prediction of car body mechanism

Uniaxial fatigue stress is transformed from multiaxial stress history to uniaxial equivalent stress history:

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July - August 2020
ISSN: 0193-4120 Page No. 5504 - 5512

$$\sigma_{von} = \sqrt{\sigma_x{}^2 + \sigma_y{}^2 + \sigma_x\sigma_y - 3\tau_{xy}{}^2} \quad (3)$$

At the critical plane stress level, it is assumed that the crack is caused by the stress perpendicular to the crack plane, and the crack surface is considered to be constant, which is used to predict the damage degree on the plane inside the element:

$$\sigma_1, \sigma_2 = \frac{1}{2}(\sigma_x + \sigma_y) \pm (\frac{1}{4}(\sigma_x - \sigma_y)^2 + \tau_{xy}{}^2)^{\frac{1}{2}} \quad (4)$$

In terms of cumulative fatigue damage and life calculation, fatigue cumulative damage theory is one of the main principles of fatigue analysis. Damage refers to the subtle changes in the initial material and the formation and propagation of cracks in the later stage in the process of fatigue. The damage can be accumulated. When the damage reaches the critical value, fatigue failure will occur.

$$D_i = \sum_k \left[\frac{n^i{}_k}{(N_f)_k}\right], k = 1,2,\cdots,z \quad (5)$$

At the level of cumulative damage and fatigue life calculation, find out the plane which is dangerous to all events, and calculate the fatigue damage. On all dangerous elements, the uniaxial stress perpendicular to the dangerous plane is calculated. Cumulative damage and fatigue life calculation:

$$D_i = \sum_{k=1}^{m} \left(\frac{R_k}{r_k}\right) D_i{}^k(event\ k) \quad (6)$$

Where, R_k is the number of repetitions of event k, $D_i{}^k$ is the number of cycles of event k, and D_i is the cumulative damage of unit i.

5. Lightweight design optimization of car body mechanism based on fatigue life

5.1. Mathematical model for lightweight design of car body mechanism is established

The lightweight design optimization of car body mechanism firstly constructs the most objective function based on the variable values of various constraint conditions. Secondly, the optimization design based on fatigue life analysis of car body mechanism, such as design variable constraints and objective function. The optimal design model of car body parts with fatigue life constraints requires that the relative difference between the maximum fatigue life and the minimum fatigue life in the car body mechanism should be less than the agreed value. The optimal design model requires that the minimum fatigue life of the components of the car body mechanism meet the expected fatigue life requirements of the car. By optimizing the section thickness of the structure, the mass of the car body mechanism is reduced.

5.2. Fatigue life design method of car body mechanism

Based on the integrated lightweight method of dynamic model of car body mechanism, load spectrum of structural parts, skeleton and other life models, the lightweight technology of car body mechanism is constructed, so that the lightweight design goal of car body mechanism can be realized under the premise of ensuring cost and performance. In the aspect of life model design of car body mechanism, it is necessary to establish the optimization model of life design, which integrates the probability factors of various working conditions. At the level of multidisciplinary optimization model of car body structure lightweight, based on the main structural parameters, the optimization model is formed with the constraints of stiffness and life. In order to improve the reliability of lightweight design and the accuracy of life analysis, dynamic analysis is carried out in the aspect of integrated lightweight of car body structure.

5.3. Fatigue life design method of car body mechanism

Based on the finite element model of lightweight design of car body mechanism, statics and fatigue analysis are carried out, and then integrated optimization is integrated to move in the design

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space to find the value of design variables until the optimal solution meeting the constraint conditions is found. The variation curve of objective function after lightweight analysis is shown in Figure 8. It can be seen that the optimized body mass can achieve significant weight reduction under the premise of reaching fatigue life.

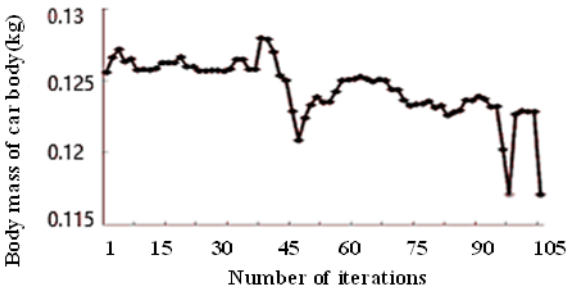

Figure 8. The variation curve of objective function after lightweight analysis.

6. Conclusion

In summary,the lightweight design of car body mechanism can significantly reduce the weight of the vehicle, thus reducing energy consumption and greenhouse gas emissions, which is conducive to the realization of energy conservation and environmental protection requirements. The lightweight design of car body mechanism based on fatigue life is to verify the reliability of lightweight results based on fatigue strength. Based on the consideration of car body mass and fatigue life, the relationship between mass and fatigue life of many mechanism components on car body is studied, and the system multi performance comprehensive optimization is carried out based on various factors.

In this paper, the strength design and framework design of car body mechanism are analyzed through the research of car body mechanism. Based on the fatigue strength analysis of car body mechanism and the research of fatigue life analysis process of car body mechanism, the fatigue design method and fatigue life prediction of car body mechanism are given. Finally, through the research of lightweight design optimization of car body mechanism based on fatigue life, the mathematical model and fatigue design of car body mechanism lightweight design are established, and the effect of weight reduction is analyzed.

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