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Lightweight Finite Element Analysis and Experimental Study of 90# Fifth Wheel

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1. Introduction

The fifth wheel is an important device in the semi-trailer tractor, which plays the role of connecting the semi-trailer with the tractor. Improper selection of the fifth wheel or the strength of the fifth wheel is not enough, which can lead to serious traffic accidents, the safety of the fifth wheel should be paid attention to [1]. It is due to the safety considerations that the fifth wheel is left with a large enough safety margin, so there is more room for optimization. Lightweight is the development trend of today's automobile industry. There are two main ways of lightweight for fifth wheel: structural lightweight and process lightweight. By optimizing the structure of each component of the fifth wheel, changing the structure under the condition of ensuring safety is the main method of automobile lightweight at present, this method is also called structural lightweight [2]. Foreign research on structural lightweight through the finite element method is early, and the finite element method is widely used because it can quickly and reliably analyse various complex engineering problems and make reasonable predictions of the results [3]. Domestic and foreign scholars not only carried out the finite element analysis of fifth wheel structure optimization, but also carried out the finite element analysis of its failure form [4]. Domestic and foreign fifth wheel is mainly divided into casting type fifth wheel and welded fifth wheel, welded fifth wheel shell is usually formed by stamping, after forming with a variety of tendons, plates welded together, most of the domestic production of fifth wheel is welded fifth wheel [5].

At present, the fifth wheel structure on the market is relatively single and the quality is large, for weight reduction considerations, this article analyzes and optimizes the design of the 90# fifth wheel. Under the premise of meeting the requirements of strength and stiffness, the lightweight goal of the fifth wheel is achieved by optimizing the structure or shape of each component, which reduces the quality of the fifth wheel to a certain extent. According to the research found in this paper, the distribution of the load of the fifth wheel during use is uneven, so by analyzing the displacement and stress distribution of each part of the fifth wheel and redesigning the thickness and shape of each component, the overall mass of the fifth wheel is finally reduced and the purpose of lightweight is achieved.

The lightweight design of the fifth wheel can effectively reduce costs and improve the economic benefits of enterprises. Because the fifth wheel has a lot of parts and components and will be subjected to a variety of forces in transportation, and the force situation is changeable, so the traditional mechanical analysis method has been unable to meet the actual needs of manufacturing enterprises. With the increasingly mature of modern computer technology in engineering application problems, finite element method has become a widely used analysis tool, through the finite element analysis method of the fifth wheel design, and the fifth wheel structure after optimization of product test production, the test results and simulation results are compared to prove that the fifth wheel after optimization to meet the actual production requirements.

2. Establishment of finite element model of the fifth wheel

In this paper, the structural lightweight of the fifth wheel is analyzed by finite element method. The essence of finite element is to discretize the continuous entity with infinite degrees of freedom into a set of finite degrees of freedom. When using finite element method for analysis, it can be summarized as follows: Continuum discretization; Select the displacement mode; Analyze the mechanical properties of the unit; Set up equilibrium equations; Finite element equation solving.

The discretization process is to divide the solved object into units with regular geometric shapes. These adjacent cells are connected to each other through a number of nodes through which external loads are transferred between the cells. In the process of continuum analysis, the displacement and stress in the element are expressed by node displacement. In order to facilitate the expression and explanation, reasonable assumptions should be made about the displacement distribution in the element. Generally, it is assumed that the element displacement is some simple function of coordinates, which is used to simulate the distribution law of the displacement within the element. This function is called displacement mode or displacement function.

$$\{\mu\} = [N]\{\delta\}^e, \quad (1)$$

where: $\{\mu\}$ is the displacement array at any point in the cell; $[N]$ is a form function array; $\{\delta\}^e$ is the element node displacement array.

According to the geometric equation, the relation between node displacement and element strain is derived:

$$\{\varepsilon\} = [B]\{\delta\}^e, \quad (2)$$

where: $\{\varepsilon\}$ is the strain array at any point in the cell; $[B]$ is a form function array.

According to the physical equation, the relation between node displacement and element stress is derived:

$$\{\sigma\} = [D][\varepsilon], \quad (3)$$

where: $\{\sigma\}$ is the array of stresses at any point in the cell; $[D]$ is an elastic matrix related to the properties of the material.

According to the principle of virtual work, the equilibrium equation of element is established:

$$[K]^e\{\delta\}^e = \{R\}^e, \quad (4)$$

where: $[K]^e$ is the element stiffness matrix; $\{R\}^e$ is the element load matrix.

Based on the principle of virtual work and the principle of minimum potential energy, the equilibrium equation of the structure can be obtained:

$$[K]\{\delta\} = [R], \quad (5)$$

where: $[K]$ is the global stiffness matrix of the structure; $[R]$ is the overall load matrix of the structure; $\{\delta\}$ is the global node displacement array of the structure.

By solving the overall balance equation, the displacement of each node is obtained, and then the stress and strain of the calculation unit is derived through the node displacement. Finally, the output result file is sorted and analyzed.

According to the existing shape and size of the fifth wheel, a 1:1 three-dimensional solid model is built. The accurate three-dimensional solid model can make the simulation results and test results better fit. It is not possible to simulate every structure of the fifth wheel accurately using the finite element method, but a certain amount of error is allowed in the actual project, as long as the error is within a reasonable range. The structure of the fifth wheel mainly consists of the shell, frame plate, support seat, hook lock and slant iron. At the same time the connection parts such as springs and pins in the structure and the parts that have less influence on the force situation of the fifth wheel are deleted in order to simplify the calculation [6, 7].

2.1. Establishment of 3D solid model of the fifth wheel

The 3D geometric model was constructed by CREO software and imported into HyperWorks software. The structural analysis of the fifth wheel was performed in HyperWorks software, and its 3D model is shown in Fig. 1.

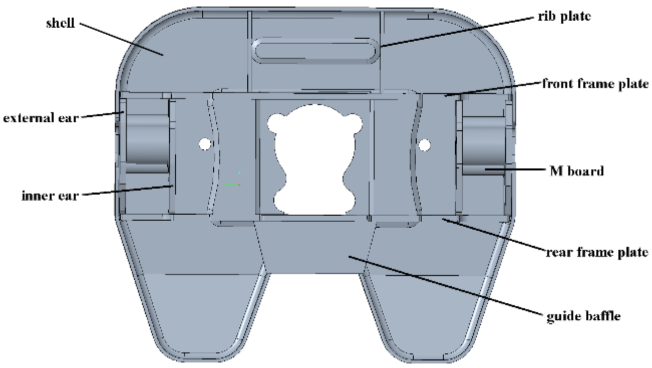

Fig. 1 3D model of the fifth wheel

2.2. Defined material properties

In HyperWorks software, data such as modulus of elasticity, density and Poisson's ratio of the material can be defined. Q345 steel was selected for the fifth wheel shell and frame, and its material properties are shown in Table 1.

Table 1

Material properties of Q345

Elasticity modulus, MPa	Poisson's ratio, μ	Density, ρ	Yield stress, MPa	Tensile strength, MPa
2E5	0.3	7.8E-06	345	510

2.3. The division of finite element mesh

The fifth wheel needs finite element modeling before finite element analysis. The most important work in finite element modeling is the delineation of the mesh, and the size, type and quantity of the mesh will affect the accuracy of the calculation [8]. When meshing the fifth wheel, the mesh size is too large or too small is not very reasonable, too large mesh can improve the calculation efficiency but will cause the calculation accuracy to decrease, too small mesh will increase the difficulty of the solution, so the mesh division should be controlled within a reasonable range [9]. At the same time, the quality of the grid should also be guaranteed.

Since the mesh at the connection should be set smaller to meet the quality requirements, the global division is carried out according to the minimum mesh. The final model after the mesh division is completed is shown in Fig. 2, with a total of 121,749 cells generated and 12,545 nodes generated.

3. Finite element static analysis of the fifth wheel of semi-trailer tractor

3.1. Determination of load conditions

In the process of tractor transportation, by the combined action of a variety of forces, the main force of the fifth wheel is the vertical downward pressure load of the semi-trailer on the fifth wheel and traction pin. The maximum load of the semi-trailer is 30 tons. In the vertical direction the fifth wheel needs to bear 30%-40% of the traction mass [10, 11], in order to consider the safety factor to take the maximum value of 12 tons, that is, 117720 N, the load will be applied to the upper surface of the shell.

In order to simulate the load on the fifth wheel during the transportation of the semi-trailer tractor, a fixed restraint is applied to the fifth wheel, which is connected to the support by pins at the inner and outer ear round holes. Only the fifth wheel is allowed to rotate in the X-axis direction, and the rest of the degrees of freedom are restricted.

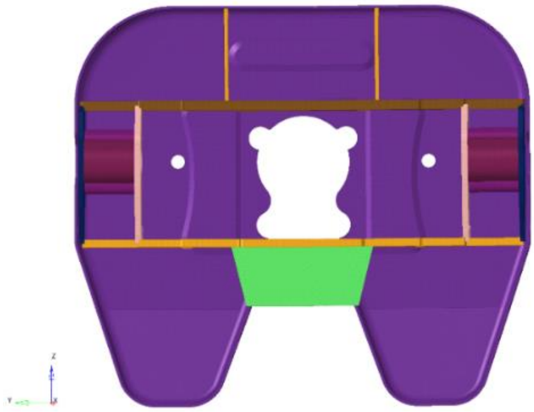

Fig. 2 Grid model of the fifth wheel

3.2. Analysis of calculation results

After setting up each analysis step, it is imported into the software to solve and analyze by the stress and displacement to which the fifth wheel is subjected, and the displacement and stress distribution of the fifth wheel is obtained, as shown in Fig. 3 and Fig. 4.

From Fig. 3, it can be concluded that the maximum deformation of the fifth wheel is mainly distributed in the upper middle region part of the shell, which is 1.314 mm. Fig. 4 shows that the stress on the fifth wheel under uniform load is mainly distributed in the middle area and the weld seam between the lower bottom frame plate welded assembly and the shell, and the maximum stress value is 227 MPa, while the yield limit of Q345 steel is 345 MPa, so it is safer under this load. The maximum stress value should occur at the welding of the shell and frame plate because the structural relationship at the welding seam is prone to stress concentration [12]. It can be seen from the displacement cloud that the deformation of the overall structure is not large and within a reasonable range. Under this load, the overall structure of the fifth wheel is satisfying the strength requirements.

4. Lightweight design of the fifth wheel structure of semi-trailer tractor

4.1. Shell as a whole area

4.1.1. Modeling of the fifth wheel optimization design

To optimize the fifth wheel, each part needs to be set up as a separate variable, so the fifth wheel is decomposed into the parts of shell, rib plate, front frame plate, rear frame plate, inside ear, outside ear, M board and guide baffle. The optimized exploded view of the fifth wheel except for the shell is shown in Fig. 5.

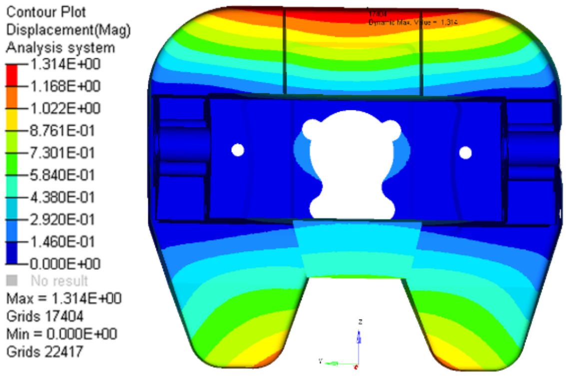

Fig. 3 Displacement nephogram under compression condition

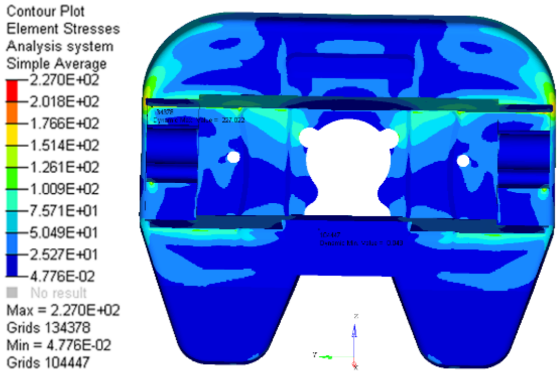

Fig. 4 Stress nephogram under compression condition

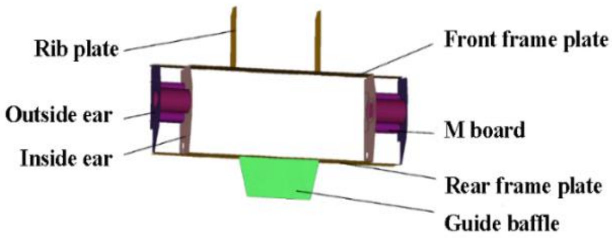

Fig. 5 Exploded view of the fifth wheel

In the analysis, the plate thickness of the shell structure is used as the design variable, and the objective function is the minimum mass of the whole structure. The constraints are the stress of the outside ear is no more than 60 MPa, the stress of the shell and rib plate is no more than 280 MPa, the stress of the M board is no more than 220 MPa, the stress of the front frame plate is no more than 250 MPa, the stress of the rear frame plate is no more than 180 MPa, the stress of the inner ear After submitting the analysis task, the optimization results are shown in Table 2

The graph between the minimization of the volume of the objective function and the number of iteration steps is obtained by the Graph tool in Hyperworks software as shown in Fig. 6.

4.1.2. Static structural strength analysis after optimization

The optimized the fifth wheel should also meet the stiffness and strength requirements, so the optimized plate thickness data are brought back into the model for analysis and calculation. The displacement and stress distribution after the optimized rounding are shown in Fig. 7 and Fig. 8.

Table 2

Data comparison of the fifth wheel before and after optimization

Name	Code Name	Initial value, mm	Lower size limit, mm	Upper size limit, mm	Iteration value, mm	Final value, mm
Shell	kt	8	5	12	7.238	7.3
Rib plate	lb	8	5	12	5.907	6
Front frame plate	qkjb	14	10	20	10	10
Rear frame plate	hkjb	14	10	20	20	20
Inside ear	mb	8	6	12	11.01	11
Outside ear	wer	14	10	20	10.19	10
M board	ner	14	10	20	14.12	14
Guide baffle	dxdb	12	6	18	6	6

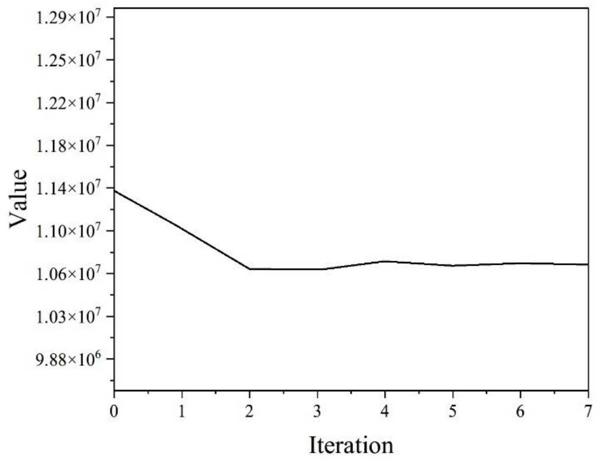

Fig. 6 Volume change curve during iteration

From Fig. 7, the maximum deformation displacement of the fifth wheel is 2.084 mm. It can be seen from Fig. 8 that the stress on the fifth wheel under uniform load is mainly distributed in the middle area and the weld seam between the lower bottom frame plate welding assembly and the shell, and the maximum stress value is 307.7 MPa, which is a safer structure. The deformation of the overall structure is not very large, and is within a reasonable range. So, it is said that the overall structure of the fifth wheel meets the strength requirements under this kind of load.

4.1.3. Finite element analysis of the fifth wheel after optimization

The main content of this analysis is to analyse the strength aspects of the fifth wheel structure. The strength characteristics of the fifth wheel under static load are analysed to give the stress and displacement distribution. Finally, based on the results of the strength analysis, an optimized design scheme is proposed for the shell structure, with the minimum mass of the shell structure as the objective function and the design variable as the plate thickness of the shell structure. The mass is reduced by 5.79% after optimization.

4.2. Dividing the shell into zones according to the force

4.2.1. Optimisation of the fifth wheel design model

The stresses on the housing are unevenly distributed during the loading process, with the housing being subjected to higher stresses at the connection with the frame plate and lower stresses at other locations. In order to meet the strength and stiffness requirements of the fifth wheel shell, it is necessary to ensure that the requirements are met at the maximum stress. If the shell is divided into zones according to the stress level and designed separately, the shell thickness can be significantly reduced while satisfying the stress requirements, so the shell is divided into zones and each connection is analysed separately, the breakdown is shown in Fig. 9.

In the analysis of this paper, the plate thickness of the shell structure is used as the design variable, and the objective function is the minimum mass of the whole structure. The constraints are the stress of shell 1 is not greater than 80 MPa, the stress of shell 2 is not greater than 60 MPa, the stress of shell 3 and outside ear is not greater than 60 MPa, the stress of shell 4, rib plate and M plate is not greater than 220 MPa, the stress of front frame plate is not greater than 120 MPa, the stress of rear frame After submitting the analysis task, the optimisation results are shown in Table 3.

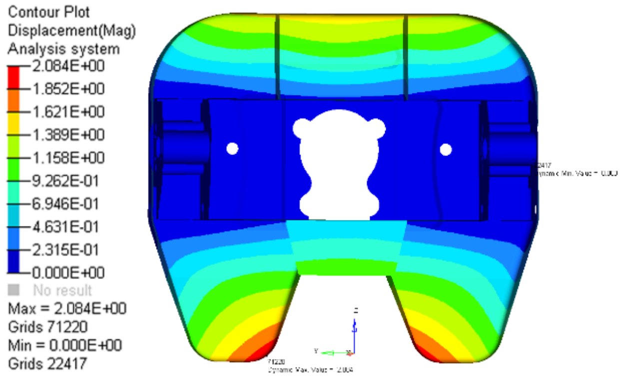

Fig. 7 Displacement nephogram after optimization

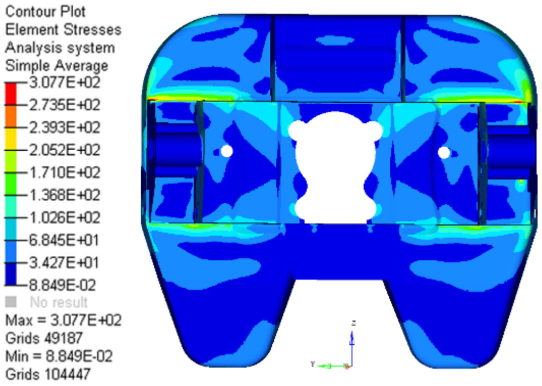

Fig. 8 Stress nephogram after optimization

Table 3

Data comparison of the fifth wheel before and after optimization

Name	Code Name	Initial value, mm	Lower size limit, mm	Upper size limit, mm	Iteration value, mm	Final value, mm
Shell 1	kt1	8	6	12	6.264	6.3
Shell 2	kt2	8	5	12	5	5
Shell 3	kt3	8	6	12	7.817	7.8
Shell 4	kt4	8	5	12	5.509	5.6
rib plate	lb	8	5	12	7.318	7.4
front frame plate	qkjb	14	10	20	16.09	16
rear frame plate	hkjb	14	10	20	20	20
Inside ear	mb	8	6	12	6	6
Outside ear	wer	14	10	20	10	10
M board	ner	14	10	20	12.59	12.6
guide baffle	dxdb	12	6	18	6	6

The Graph tool in HyperWorks software was used to obtain the relationship between the volume minimization of the objective function and the number of iteration steps, as shown in Fig. 10.

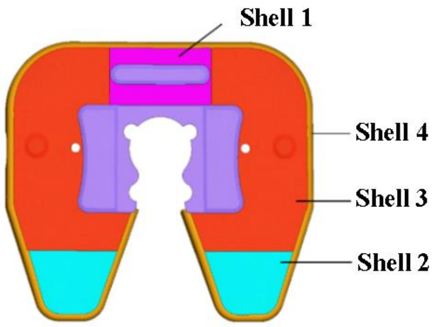

Fig. 9 Breakdown of the fifth wheel

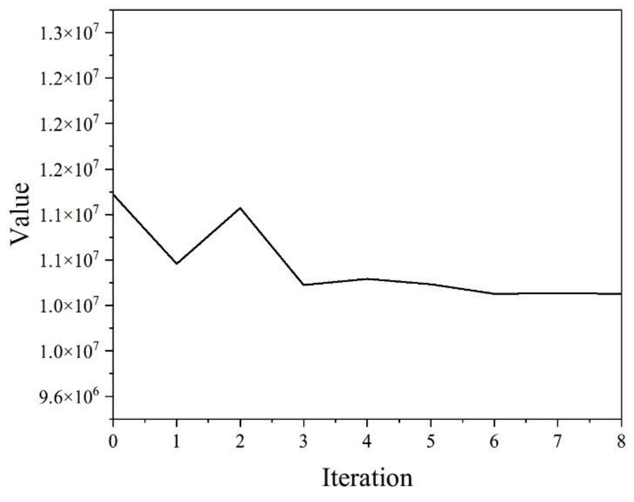

Fig. 10 Volume change curve during iteration

Through the above analysis, after 8 iterations of optimisation, the overall mass of the fifth wheel was reduced from 132.44 kg to 122.19 kg, which is 92.26% of the original, with a clear effect of light weighting.

4.2.2. Static structural strength analysis after optimization

The optimised the fifth wheel should also meet the stiffness and strength requirements, so the optimised plate thickness data is brought back into the model for analysis and calculation. The displacement and stress clouds after the optimized rounding are shown in Fig. 11 and Fig. 12.

As can be seen from Fig. 10 and Fig.11, the maximum stress of the optimized rounded the fifth wheel under compression is 246.7 MPa, which is less than the yield strength of Q345, and the maximum displacement is 1.302 mm, which is in accordance with the relevant regulations.

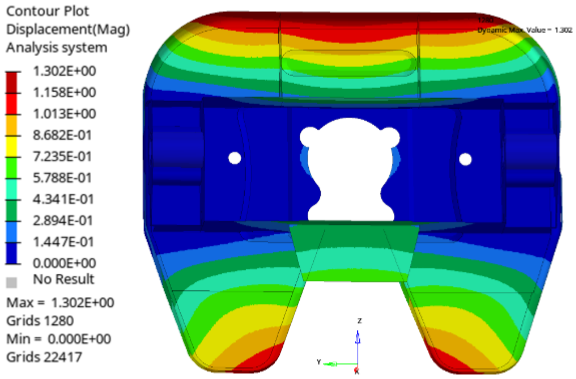

Fig. 11 Displacement nephogram after optimization

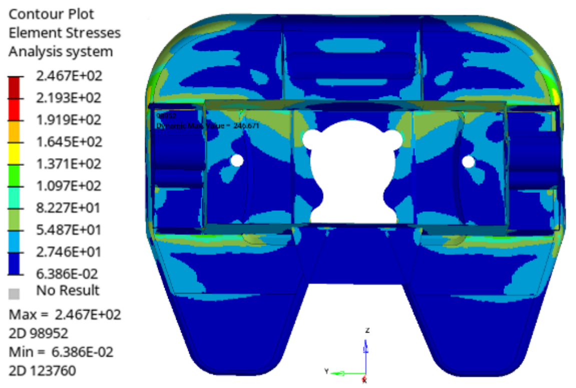

Fig. 12 Stress nephogram after optimization

4.2.3. Finite element analysis of the fifth wheel after optimization

The strength of the fifth wheel structure is analysed, and the distribution of stress and displacement is given. Finally, based on the results of the static analysis, an optimised design solution is proposed for the shell structure.

After optimization, the mass is reduced by 7.74%. The effect of lightweight according to this solution is more obvious, but the actual machining process is difficult and costly.

4.3 The fifth wheel shape structure optimization

Some parts of the fifth wheel do not bear too much load, can remove part of the mass or adjust the shape of some parts to reduce the overall quality of the fifth wheel under the condition of not reducing the safety and stability. Fig 13 shows the three-dimensional model of the fifth wheel after shape structure optimization.

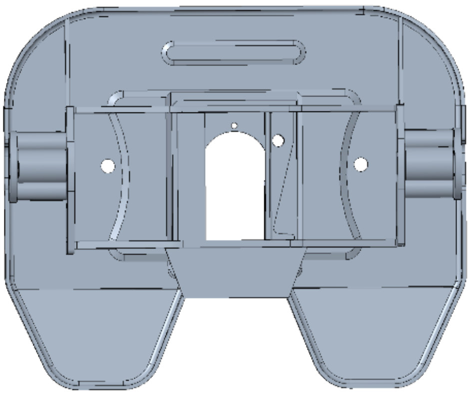

Fig. 13 3D diagram after model optimization

The overall length was reduced from 814.8 mm to 760 mm, the length of the front and rear frame plates was shortened, the thickness of the front frame plate was reduced by 2 mm, the thickness of the rear frame plate remained the same but some of the material was removed, the shape of the outer lug connection plate was changed and the overall mass of the fifth wheel was reduced from 132.44 kg to 115.09 kg. In order to verify the usability of the frame, it was necessary to apply both longitudinal and transverse loads to the fifth wheel, to carry out a static analysis of the shaped the fifth wheel and to verify its correctness.

4.3.1. Determination of load conditions

The tractor is not only subjected to the pressure in the vertical direction of the semi-trailer during travel, but also to the pulling force of the traction pin. According to the calculation method in the national standard for the strength test of the fifth wheel, $F_{v,t}$ and $F_{h,t}$ are applied simultaneously. $F_{v,t}$ is the pressure applied to the upper surface of the fifth wheel and $F_{h,t}$ is the traction force applied to the traction pin. the numerical value of U is 25t and the numerical value of D is 165 kN.

$$F_{v,t} = 1.2 \times g \times U = 294.3 \text{ kN}, \tag{6}$$

$$F_{h,t} = 0.6 \times D = 99 \text{ kN}. \tag{7}$$

A force of 99 kN is therefore applied at the front frame plate to simulate the pulling force of the traction pin on the fifth wheel, and a load force of 294.3 kN is applied to the upper surface of the fifth wheel shell. The constraint situation remained the same as the previously applied restraint.

4.3.2. Static structural strength analysis

After setting up the individual analysis steps and importing them into the software, the displacement cloud (Fig. 14) and the stress cloud (Fig. 15) of the fifth wheel are obtained.

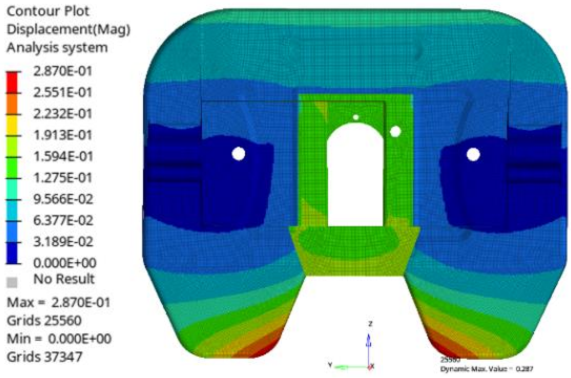

Fig. 14 Displacement nephogram of the fifth wheel

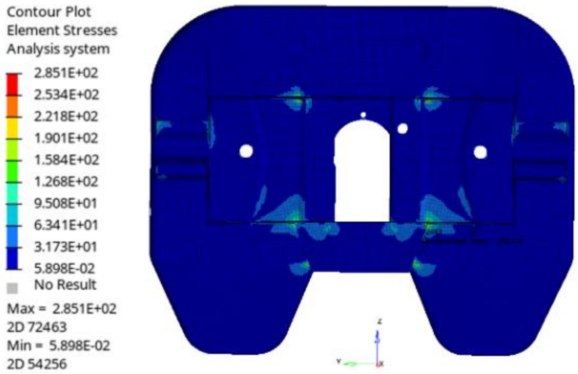

Fig. 15 Stress nephogram of the fifth wheel

As can be seen from the graph, the displacement distribution of the fifth wheel is not uniform and the displacement is small, its maximum deformation displacement is distributed in the lower part of the fifth wheel shell, which is 0.287 mm, within the safe range. The stresses on the fifth wheel under uniform load are mainly in the middle area and at the weld seam between the welded assembly of the lower bottom frame plate and the housing, with a maximum stress value of 285.1 MPa, so the structure is safe.

5. Test

Based on the results of the above finite element analysis, the best solution was selected for the test. The solution with the changed structure of the fifth wheel had the most significant effect on lightweight, so the solution with the optimized shape and structure was used for the test. The fifth wheel shell was manufactured by cold stamping according to the 3D geometry model with optimized shape, and the rest of the components were manufactured by cutting and welding.

The main processes in the production of the fifth wheel are undercutting, pressing, punching, cleaning, machining and welding. Cutting of steel plates by means of CNC plasma cutting machines in order to obtain higher precision and increase production efficiency. Transferring the steel plates to a 2000 tonne press to complete the shell and base plate in one pass; Workpiece drop and punching with punching machines; Complete workpiece degreasing with washing machine housing; The rest of the components are manufactured by CNC machines, drilling and milling machines to increase the precision of the machining; Finally the components such as the housing and frame plate are welded using the welding robot to obtain the complete the fifth wheel as shown in Fig. 16.

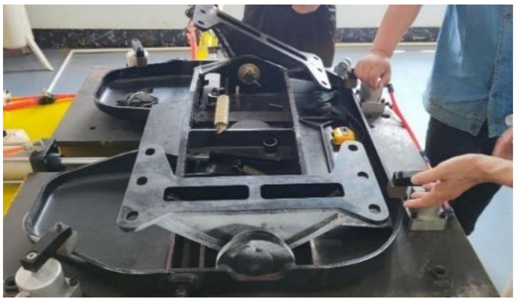

Fig. 16 Solid model of the fifth wheel

The assembled the fifth wheel was fatigue tested on a dynamic test stand according to national standards. The fifth wheel did not produce permanent deformation after 20,0972 cyclic loads [13], thus verifying that the shape changed the fifth wheel meets the requirements, as shown in Fig. 17. After the test, the fifth wheel complied with the relevant specifications.

Fig. 17 Fatigue test of the fifth wheel

The new fifth wheel with the changed shape was assembled in a real vehicle and installed as shown in Fig. 18. The reliability of the stability and strength of the fifth wheel is considered from a practical point of view and the rationality of the simulation is verified.

Fig. 18 Installation drawing of the fifth wheel

6. Conclusions

Based on the data relating to the fifth wheel and the results of the finite element analysis, the main conclusions are as follows:

1. The shell part of the fifth wheel is considered as a whole, the mass of the shell structure is minimised as the objective function and the plate thickness of the shell structure is used as the design variable for the finite element analysis. The optimised mass is reduced from 132.44 kg to 124.77 kg, a reduction of 5.79%.

2. The shell is divided into zones according to the stress level, and the objective function is to minimise the mass of the shell structure. The design variables are the split shell zone and the plate thickness of the frame plate and other connecting parts. The optimized mass was reduced from 132.44 kg to 122.19 kg, a 7.74% reduction in mass after optimisation.

3. The structural shape of the fifth wheel is adjusted to obtain a new fifth wheel model, and the mass of the fifth wheel is reduced to meet the requirements of strength and stiffness of the fifth wheel, and the safety of the new fifth wheel is verified by means of tests.

4. The stress and displacement distribution of the fifth wheel under load condition are obtained by finite element analysis of the fifth wheel lightweight, Different lightweight design methods are used to design the fifth wheel, and the structure of the fifth wheel is adjusted by the combination of size optimization and shape optimization. The mass is reduced by 17.35 kg, which greatly reduces the quality of the fifth wheel. Moreover, the fifth wheel samples produced by lightweight fifth wheel are verified to be feasible after fatigue test and real vehicle verification, which has great guiding significance for the actual production of enterprises.

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LIGHTWEIGHT FINITE ELEMENT ANALYSIS AND EXPERIMENTAL STUDY OF 90# FIFTH WHEEL

S u m m a r y

The fifth wheel is a connecting device between the semi-trailer and the tractor, which plays the role of connecting and steering. According to the finite element analysis technology, the fifth wheel model is established by CREO software, and import the established model into HyperWorks software, the static analysis and lightweight design of the structure are carried out by finite element simulation. Finally, the optimal solution of fifth wheel structure is obtained, the static performance of the optimized fifth wheel is verified, which proves that the optimized structure is reasonable and meets the requirements of strength and stiffness. After the optimization of fifth wheel for actual production test, the optimized fifth wheel to meet the requirements of national standards.

Keywords: the fifth wheel, lightweight, finite element analysis, test.

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