Stress State Measurement and Result Analysis of Car Wheels

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Abstract. The stress state of the car wheel is one of the guiding design indicators for the wheel structure. This paper uses the combination of finite element method and bench test to study the stress state of the wheel when driving straight. Through the finite element simulation of bending fatigue and radial fatigue, the position of dangerous points during the use of the wheel is obtained. The location of the dangerous point is used as the strain measuring point, and the test bench is built. The strain gauge is used to measure the strain of these points in the straight running condition, and the test results are analyzed. The results show that when the vehicle is traveling straight, the tire will have a greater impact on the load of the wheel. The squeezing deformation between the tire and the wheel, as well as the positive and negative rotation, will have an effect on the stress state of the wheel. The maximum strain of the wheel appears on the inside of the wheel rim, the rim is in contact with the tire and along the circumference of the wheel. The strain near the center of the wheel is small. Different loads have no effect on the variation of wheel strain, but have an effect on the maximum and minimum peaks.

Key words: car wheel, stress state, dangerous points, strain measure

1. Introduction

Car wheel is one of the most important safety components in the vehicle. If the vehicle has fatigue and fracture damage during driving, it directly affects the safety of life and property of the driver and passenger. Therefore, the reliability design of the wheel is the most important content of the car design[1]. In recent years, with the stricter regulations on energy conservation and emission reduction of vehicles, higher requirements have been placed on the weight reduction of wheels. Many new wheel structures have emerged, and more new materials have been applied, such as composite wheels, new processes, etc[2]. The current wheel reliability design method is mainly carried out from two aspects: structural optimization design based on simulation calculation and product optimization design based on experiment [3][4][5]. In the early stages of wheel design, since the rim of the wheel is in direct contact with the tire, its structural form is determined by the standardized tire size, and the space for design optimization is small. The finite element structure optimization method is generally used to optimize the design of the spoke structure. The finite element can be used to calculate the stress state of the wheel under a specific load [6], but the final fatigue strength of the wheel is not only related to the basic structure, but also to the processing of the wheel. The process is related to the state of use of the wheel, etc., and the final state of force of the wheel is the result of the combination of these factors [7]. These factors are not fully considered in the simulation calculation process [8][9][10][11]. The other method is the bench reliability test. The bench test is used to evaluate the fatigue life under typical working conditions of the wheel. The test sample is the final product state, which can truly reflect the wheel load state. However, it is difficult to measure the load state of all positions of the wheel during the test, and
it is generally based on engineering experience to measure the unidirectional load of some special positions[12][13]. These locations are not necessarily the location of the wheel load hazard. In response to the above problems, this paper establishes a method combining simulation and experiment to analyze the force state of the wheel. This article will first analyze the load state of the wheel during use. Then, the wheel rig test method is selected according to the load state, and the wheel finite element model is established to predict the position of the dangerous point of the wheel during the reliability test. In the third step, the strain flower is used to measure the stress state of the wheel at the dangerous point and under the straight running condition of the wheel, and comparative analysis is carried out. Through the above analysis, the load state of the wheel under driving conditions is obtained, which provides a reference for the optimization design of the fatigue reliability of the wheel.

2. Load distribution when using car wheels

The rim of a typical car wheel is used in conjunction with a tire, and the center of the wheel is connected to the hub. The load of the tire transmits the load to the hub through the rim, the spokes, and the wheel center during the running of the vehicle, and then transfers the load to the vehicle suspension and the vehicle body through the hub. At the same time, the body load is transmitted to the wheels through the hub. For this reason, the wheel will withstand the translation load in three directions and the three-direction rotational load during use, as shown in the figure 1. In this paper, the positive direction definition of the wheel load is consistent with the SAE standard, the forward direction is the forward direction of the vehicle, Fx is the driving force or braking force of the wheel, Fy is the lateral force direction of the wheel, and Fz is the vertical load aspect of the wheel. The moment around the x direction is the rolling moment Mx of the wheel, the moment around the y direction is the braking or driving torque My, and the moment around the z direction is the yaw moment Mz[1]. In a large number of engineering practices, wheel engineers have found that car wheels mainly include straight-line running conditions and cornering conditions during use. The contribution of various loads to the fatigue damage of the wheel under different driving conditions is also different. The following is a brief overview of the wheel load status under these two conditions.

![Figure 1. Wheel load direction definition](image-url)

2.1. Straight driving condition

During the use of the vehicle, most of the driving conditions are straight-line driving. The vertical force analysis is shown in Figure 2 when the wheel is in a straight line. The driving torque transmitted by the hub and the friction torque generated by the tire are balanced with each other, and the wheel is mainly subjected to a vertical load. The wheel bears the vertical load $F_g$ transmitted by the body to the hub, and the vertical load $F_t$ that the tire transmits to the wheel, which can be expressed as:

$$F_v = F_t k$$  \hspace{1cm} (1)

$F_t$ For the static vertical load of the wheel, $k$ the dynamic load factor of the wheel.
2.2. Turn driving conditions

Another more working condition in the use of the wheel is the turning driving condition. The force of the wheel under this condition is shown in Figure 3. At this time, the wheel not only needs to bear the vertical load, but also needs to bear the lateral load. Assume that the integrated action point between the tire and the wheel is point C. At this point the wheel is subjected to a vertical load \( F_y \) and a lateral load \( F_y \). The equivalent bending moment generated at the center of the wheel is:

\[
M_x = F_y d + F_f R
\]

(2)

Where: \( F_y \) is the dynamic vertical load transmitted to the wheel for the tire, \( F_f \) is the lateral load transmitted to the wheel by the tire, \( d \) is the wheel offset, and \( R \) is the wheel rolling radius.

3. Finite element calculation method for car wheel reliability

Through the analysis of the wheel fatigue test principle and process in the previous section, it can be seen that the load state of different parts of the wheel is investigated by different test. For example, the radial fatigue test of the wheel mainly investigates the ability of the wheel rim to withstand the load, while the bending fatigue test mainly investigates the ability of the wheel spoke to withstand the bending load. And the above fatigue test is only used as the final reliability assessment of the wheel, and cannot directly guide the design. Only knowing the stress distribution under these test conditions can provide a basis for further optimization design. Therefore, this paper proposes a bench test to measure the stress distribution of the wheel under different working conditions, based on which the wheel fatigue life is predicted. However, the engineer does not know the position of the wheel stress concentration point. To solve this problem, this paper proposes a finite element method to predict the stress distribution during wheel fatigue test. Thereby, the position of the stress measurement point of the wheel fatigue bench test can be determined. The following is a brief description of the finite element simulation method for radial fatigue and bending fatigue.

3.1. Radial fatigue finite element simulation

3.1.1. Finite element model establishment. According to the principle of radial fatigue test, during the bench test, the drum transmits the load to the wheel through the tire. In order to reduce the complexity
of the simulation, the interaction force between the tire and the wheel is generally simplified to the contact force of the tire acting on the wheel rim position. However, it is difficult to accurately express the load distribution of the tire on the rim. According to the literature [1], the radial load can be approximated as a cosine distribution at the position where the tire is pressed into contact with the wheel rim. Assume that the loading pressure in the wheel plane is a cosine function distribution in the $2\theta$ angle range. The axial direction of the bead seat on both sides of the wheel rim is evenly distributed, as shown in Figure 4. Assume that the load at the contact position of the wheel with the tire bead is symmetric, that is, the load on each side is

$$F' = \frac{F_x}{2}$$  \hspace{1cm} (3)

Where: $F_x$ is the radial load corresponding to the bending fatigue bench test.

On the other hand, depending on the load distribution definition between the tire and the wheel, the load on each side of the tire bead position can be expressed as:

$$F' = B \int_{0}^{\theta_0} A r_b d\theta$$ \hspace{1cm} (4)

Where, B is the bead width, $2\theta_0$ is the angle range of the tire and the wheel load, and $r_b$ is the radius of the tire bead.

$A$ is the pressure distribution amplitude of the tire bead position at any position, which can be defined as:

$$A = A_0 \cos\left(\frac{\pi \theta}{2\theta_0}\right)$$ \hspace{1cm} (5)

According to the above formula, the maximum amplitude of the pressure distribution of the tire bead position can be obtained:

$$A_0 = \frac{\pi F_x}{8 \theta_0 B r_b}$$ \hspace{1cm} (6)

Figure 4. Simplified wheel load during radial fatigue test

According to Stearns J et al., the general assumption is $\theta_0 = \frac{2\pi}{9}$. According to the size of the wheel studied in this paper, the maximum amplitude $A_0$ of the pressure is 1.4MPa.

Figure 5. Radial fatigue finite element model
After determining the load, the wheel finite element mesh is then divided. Due to the complex structure of the wheel, geometric cleaning is required before meshing. Clean up the small fillets and chamfers in the geometry, and finally use the hypermesh software for tetrahedral meshing. The size of the grid is 5mm, and the minimum size is controlled above 2mm, and the resulting grid is shown in the figure 5. The material of the wheel studied in this paper is ZL101A-1 aluminium alloy wheel. According to the structural characteristics of the wheel studied in this paper, the maximum radial hole of the wheel under radial load is the weakest and the stress concentration is easy. Therefore, the position of the wheel rim bead bearing the maximum pressure is as shown in the figure A point. It is more complicated to load continuous cosine pressure on the wheel finite element model. It can be discretized into finite segments during simulation. In this paper, it is set to 20 segments, and each segment is loaded with uniform pressure. The pressure amplitude is the average amplitude in this segment. At the same time, in order to simulate the effect of the inflation pressure of the tire on the surface of the wheel, a uniform pressure distribution load is applied at a position where the surface of the rim contacts the gas in the tire. In this paper, the applied inflation pressure is defined as 0.45 MPa according to the requirements of [12] the wheel under study. In order to be consistent with the radial fatigue reliability test state, the degree of freedom of all bolt holes at the position of the spokes is constrained during the test.

3.1.2. Analysis of finite element calculation results. According to the method described in the previous section, the finite element model is established and submitted to the static solver of the solution software. Finally, the stress distribution state of the wheel under this load can be obtained, as shown in Figure 10 below.

![Figure 6. Radial fatigue stress simulation analysis results](image)

It can be seen that there is a large stress concentration point at the rim position of the wheel, and the deformation amount at the spoke position is small. The stress of the wheel is mainly concentrated on the position where the wheel rim is in contact with the tire, and the stress on the inner side of the corresponding wheel rim is larger than the outer side of the corresponding position.

3.2. Finite element simulation of bending fatigue

3.2.1. Finite element model establishment. With reference to the wheel bending fatigue bench test standard and the test equipment principle, a 0.9m long loading shaft is assembled in the wheel finite element model. Import the model into Hypermesh software for finite element preprocessing. The assembly model is meshed using a tetrahedral element. The wheel model has a cell size of 5 mm and a minimum size of 2 mm. According to the method requirements of test standard [12], a fixed constraint is imposed on the inner edge to constrain all degrees of freedom. The bolt connection between the flange face of the load shaft and the wheel mounting surface is simulated with the rbe2 unit. A loading force perpendicular to the loading axis is applied at the end of the loading shaft. The direction of the force is the centerline pointing to the position of the largest through hole of the spoke, as shown in Figure 7.
3.2.2. Analysis of finite element calculation results. Set up the analysis step and finally submit the static analysis model to the software solver. The wheel stress distribution corresponding to the analysis results is shown in the figure 8(a). It can be seen that in the radial fatigue test, the main deformation position of the wheel is located on the spoke. In the bending fatigue simulation, the wheel spokes and the wheel center position are greatly deformed. The deformation of the rim position is small. The wheel center position is partially enlarged, as shown in figure 8(b). It can be seen that stress concentration occurs at the connection position between the spoke and the wheel center. At the same time, there is stress concentration at the wheel bolt mounting position.

4. Measurement and analysis of position stress of dangerous points on car wheels

4.1. Strain measurement

4.1.1. Measuring point arrangement position. Through the above finite element analysis, as the picture 9 shows, it can be concluded that in the bending fatigue test, the maximum stress point may occur at the chamfering position 4 of the spoke and the position of the wheel center position 5. In the radial fatigue simulation, the stress concentration is likely to occur at points 1, 2, and 3 of the spoke position, and at
the position where the tire is in contact with the tire bead seat, and the stress on the inner side of the rim is large. However, since the strain gauges cannot be pasted at this position, the inside of the wheel facing the bead seat serves as the stress measurement point 6.

Figure 9. Strain measurement point location

According to the determined stress point concentration in the above figure 9, the measurement strain gauge is pasted. As shown in figure 10, in order to study the change of the plane stress at the measuring point position, the plane stress is measured by using 0-45-90 strain flower in this paper. At the same time, when the strain gauge flower is pasted, the distribution of the strain gauges at 0, 45, and 90 degrees is defined as the horizontal direction, the middle direction, and the vertical direction. The direction of the strain in the horizontal direction is the direction of the contour parallel to the corresponding position. For example, the horizontal direction of the strain gauges 1, 2, and 3 is parallel to the longitudinal direction of the spoke, and the vertical direction is perpendicular to the length of the spoke. The horizontal directions of the 4th and 5th strain flowers are chamfered directions parallel to the corresponding positions. The horizontal direction of the strain gauge No. 6 is parallel to the wheel extension, and the corresponding vertical direction is parallel to the axis direction of the wheel. Due to the small temperature variation of the wheels during the test, in order to simplify the test process, a quarter bridge was used in the test.

Figure 10. Test wheel strain paste position

4.1.2. Test bench construction. The stress measurement in the radial fatigue of the wheel is shown in Figure 11. The wheel strain sensor is directly connected to the data collector during the test, and the data acquisition parameters are controlled by the computer. The wheel is loaded with radial loads by means of a drum. In the process of wheel radial fatigue test, there is no special regulation on the wheel rotation speed in the standard. In order to reduce the influence of the wheel dynamic response on the test results, only the wheel load change during the quasi-static rolling process is considered in the test, and the wheel rotation speed is considered as small as possible.
4.2. Analysis of measurement results

Due to space limitations, only the strain variation laws of several typical locations are shown. The following is a comparison of the horizontal and vertical strains of measuring points 1 with the change of the wheel angle, as shown in figure 12. This measuring points are located at the spoke. In the figure 12, the C curve indicates that the wheel rotates clockwise, and the A curve indicates that the wheel rotates counterclockwise. It can be seen that during the rolling of the wheel, two change cycles appear at one measuring point, and the two positions are exactly 180 degrees apart. This is because the position of the maximum peak-to-peak corresponds to the position where the measuring point is closest to the ground. In another position, the measuring point is located farthest from the ground when the wheel is rotated 180 degrees from the first position. At this time, the pressure of the tire and the bead position of wheel is increased due to the wheel extrusion deformation, so that the deformation at the position of the spoke of the wheel is increased. It can be seen that the peak occurring in the change of the horizontal and vertical stress amplitudes at the first point position is the largest. The law of load change in the forward and reverse directions is basically the similar. However, the peak parameters vary, mainly due to the nonlinearity of the tire. At the same time, it can be seen that at the measuring point 1, the peak in the horizontal direction is larger than the vertical direction. From the horizontal and vertical phases, it can be seen that the phase of the horizontal phase changes exactly opposite to the phase of the vertical direction.

The strain at the position of the measuring point 5 is also the rolling periodic variation of the wheel, as shown in figure 13. The change in amplitude is relatively small relative to the position of the measuring point 1. This is because the measuring point 5 is located at the center of the wheel and bears less load under straight driving conditions. As shown in figure 14, it can be seen from the strain law at the position of the measuring point 6 that the strain change process is basically the same as that of the measuring point 1, but the maximum peak value changes rapidly. It indicates that the load on the position of the measuring point 6 changes rapidly when the tire is in contact with the ground during the rolling process of the wheel. There is a certain difference in the load change in the vertical direction of the measuring point 6 when the wheel rotates in the forward and reverse directions. The horizontal strain value is 10 times larger than the vertical direction.

Comparing the above three measuring points, it can be seen that the rim of the wheel bears the maximum load during the radial load test, and the load in the horizontal direction has an absolute advantage with respect to the vertical direction. At the same time, there is also a large load change in the horizontal direction of the spokes and rim. The load change at the center of the wheel is small.
5. Conclusion

Based on the specific conditions of the wheel, this paper analyzes two typical operating conditions of wheel reliability. Based on this, the finite element simulation and test method is established to analyze the stress variation law during the radial fatigue test of the wheel. The following conclusions can be drawn:

- During the use of the wheel, the tire will have a large influence on the load of the wheel. The deformation of the tire and the ground, as well as the positive and negative rotation, will have an impact on the stress state of the wheel.
- When the wheel is running straight, the maximum stress of the wheel appears at the position where the tire is in contact with the ground. The stress near the center of the wheel is small.

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