Research on Discrete Data Analysis of Vehicle Retread Tire Performance Based on Radial Stiffness Method

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Abstract. The retreaded tires of transportation vehicles often cause delamination and tearing of the tread and carcass due to the temperature rise of the tires. For the failure analysis and rational use of the retreaded tires, a steady-state thermal analysis model of the retreaded radial tires in the rolling state is established and carried out the temperature measurement test. On this basis, the numerical simulation, simulation calculation and experimental analysis of the thermal-structure coupling field are carried out, which truly reflects the thermal stress status of the retreaded tire.

Keywords: Engineering Retread Tire, Vibration Mode, Radial Stiffness Method, Natural Frequency, Natural Vibration Mode

1. Introduction
With the continuous extension of highway mileage, the continuous operation time of transportation vehicles also continues to increase. Due to the complex road conditions, there are often tumbling, rolling off sand and rocks, etc., and transportation vehicles generally have a higher center of gravity, which exacerbates the wear of tire treads of wood transportation vehicles [1-2]. The tire pattern of a vehicle is worn to a certain extent and can no longer be used safely [3-4]. Therefore, in order to improve the service life of the tire and reduce the cost of wood transportation, retreaded tires are often used. A retreaded tire refers to a process in which a tire whose surface has been worn to a certain degree, after surface treatment, is refitted with a new layer of tread [5-6]. However, the currently used retreaded tires often show failure phenomena such as early wear, aging and tearing. Therefore, it is of great significance to strengthen the research in this area. The tire is a revolving body with a complex viscoelastic structure, which bears periodic alternating loads. The heat generation and temperature rise characteristics of the tire will have a great impact on the service life of the tire [7-8]. When tires are running on the road, the heat source that causes the temperature to rise mainly comes from two aspects: one is the heat energy that the tire is repeatedly deformed under the action of load stress, which causes the hysteretic loss of the tire material to deform; and the other is the heat energy. Change the friction between the tire and the ground to generate heat [9-10]. Research on tire temperature field has been started very early in foreign countries. Although my country also attaches great importance to the problem of tire temperature affecting tire service life, there is little research work in this area,
especially the temperature rise characteristics of retreaded tires and the impact on tire mechanics. The impact of performance has not yet been published.

In recent years, the rapid development of mining, construction and other industries has caused the demand for vehicle tires to increase day by day. Vehicle tires are usually operated in open-pit mining areas such as earth and stone, with large carrying capacity, frequent starting and braking, and sharp stones. The impact force is large, resulting in a shorter service life of engineering tires, and thus a large number of waste tires are produced. Therefore, the secondary retreading and reuse of waste engineering tires can further extend the service life of engineering tires, conducive to saving rubber resources and promoting green environmental protection, and "black pollution" will be effectively transformed into "black energy". At present, the research of foreign developed countries, such as the United States, Japan, South Korea and my country, mainly focuses on the tire retreading industry status and related policy analysis, the development of truck tire retreading process equipment system, truck tire retreading technology, and the quality of finished truck tire retreading. In terms of evaluation, new tire tread modification and enhancement technology of trucks, there are few studies on the macro and micro mechanical properties of retreaded vehicle tires. Engineering retreaded tires are frequently used on uneven roads and will produce large vibrations. The resonance phenomenon must be paid attention to during use. Therefore, this paper conducts the radial stiffness method vibration modal analysis on the vehicle retreaded tires, and obtains the natural frequency and natural vibration of the tire under the two working conditions of wheel constraint and ground contact constraint, and provides the structural design, performance and performance of the engineering retreaded tire. Dynamic performance and failure mechanism analysis provide important theoretical guidance.

2. Computer geometric model of vehicle retreaded tires

2.1. Mathematical model of heat transfer in retreaded tires

The heat generation of retreaded tires due to the secondary adhesion of the tread layer during the rolling process due to the asynchronous stress and strain of each layer is a steady-state temperature field problem. This problem can be solved by the following second-order thermal conductivity differential equation.

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial \theta}{\partial y}\right) + Q = 0$$

(1)

In the formula: $k_x$, $k_y$ are the thermal conductivity in the x and y directions; $\theta$ is the temperature; $Q$ is the heat generation rate per unit volume.

To solve the above differential equations, boundary conditions must be attached. The boundary conditions in this study are the first and third types of boundary conditions [2].

2.2. Discrete equation of radial stiffness method

In order to use the radial stiffness method to solve the steady-state temperature field, the retreaded tire structure needs to be discretized. After the discretization, the temperature can be expressed as:

$$\theta = \sum_{i=1}^{N_e} N_i(x,y) \theta_i = N \theta_e$$

Where $N_e$ is the number of nodes in each element; $N_i$ is the C0 type interpolation function; N is the element interpolation function matrix, $N = [N_1, N_2, \ldots, N_{n}]$; $\theta_e$ is the nodal temperature matrix.

This paper takes 26.5R25 retreaded tires as the main research object. According to the distribution characteristics of the material structure of the retreaded tires, the characteristics of stretching, rotation and bending in the Pro/E Wildfire software are used to construct a three-dimensional geometric model. The constructed three-dimensional assembly model of grounding conditions is mainly composed of
tread, cushion rubber, belt layer, old carcass, sidewall, toe rubber, traveller and ground. The tread grooves of the engineered retread tires studied in this paper are relatively narrow (the groove area only accounts for about 5% of the total tread area). The effect of the tread pattern on the performance is ignored, and the pattern is simplified.

3. Vehicle retreaded tires and ground contact model

26.5R25 retread tire and ground contact The model is described using frictional contact model, and the penalty function method is applied to construct it. The ground is set as the rigid target surface and the tire tread is the flexible contact surface. The tire is subjected to a combination of radial force and tangential force. The radial force is described by equation (1), and the size is related to the radial contact stiffness and the distance between the tread and the ground. The tangential force can be described by formula (3). The size is related to the state of the tread. When the tread is in an adhesive state, its size is related to the tangential stiffness and the elastic deformation of the tread; when the tread is in a sliding state, Its size is related to sliding friction coefficient and radial force.

\[
f_r = \begin{cases} K_n C (C \leq 0), \\ 0 (C > 0) \end{cases}
\]

(2)

\[
f_s = \begin{cases} \frac{K_t \eta'}{\mu f_n}, \\ f_n \end{cases}
\]

(3)

Where: \( f_r \) is the radial force, N; \( f_s \) is the tangential force, N; \( K_n \) is the normal contact stiffness, N/mm; C is the distance between the tread and the ground, mm; \( K_t \) is the tangential stiffness, N/mm; \( \eta' \) is the elastic deformation of the tread, mm; \( \mu \) is the sliding friction coefficient.

4. Radial stiffness method analysis model of vehicle retreaded tires

The tire traveller part, the wheel, and the ground solid unit are all fixed and restrained, and the wheel center point only restricts the degrees of freedom in the X and Z directions. The material parameters of the tread, cushion rubber, sidewall, toe rubber, and traveler have been tested and tested, as shown in Table 1, and the material parameters of the old carcass and belt have been tested and tested, as shown in Table 2. The Mooney-Rivlin model is used to simulate the surface, cushion rubber, sidewall and toe rubber. The traveler is simulated by Solid unit. The old carcass and belt are simulated by Layer unit, and the Lanczos method is used to solve the calculation.

Table 1. Material parameters such as tread

| Material   | Modulus of elasticity/MPa | Poisson's ratio | Density/(kg/m3) |
|------------|----------------------------|----------------|-----------------|
| Tread      | 7.26                       | 0.48           | 1790            |
| Buffer glue| 5.94                       | 0.48           | 1020            |
| Sidewall   | 10.36                      | 0.48           | 1240            |
| Toe gum    | 12.14                      | 0.48           | 1370            |
| Traveller  | 2.12e5                     | 0.29           | 7850            |

Table 2. Material parameters of the old carcass and belt

| Material   | Modulus of elasticity/MPa | Shear modulus/MPa | Poisson's ratio | Density/(kg/m3) |
|------------|----------------------------|-------------------|-----------------|-----------------|
| Old carcass| 9.704 6.96 6.96 6.04 3.26 | 3.26 0.398 0.398 0.48 | 4580            |
| Belt       | 1.58e5 2.62 2.62 9.88 2.58 | 2.58 0.344 0.344 0.48 | 6480            |
5. Vibration modal analysis of wheel restraint conditions

The first 20 natural frequency distributions obtained under wheel restraint conditions are shown in Figure 1, and the natural frequency variation curves of each order are shown in Figure 2. It can be seen from Figure 1 and Figure 2 that the natural frequency of the first 20 orders of retreaded tires ranges from 4.3652 to 24.794 Hz, and the frequency increases approximately linearly with the increase of the stage. Among them, from the 12th to the 13th order, the vibration frequency has a large sudden change, and the increase the amplitude is up to 5Hz, and there is no obvious change from the 18th to 20th order vibration frequency.

![Figure 1. Natural frequency distribution of each order](image1.png)

![Figure 2. Natural frequency change curve of each order](image2.png)

The obtained 1~4th order mode shapes are shown in Fig.1, and the 5~8th order mode shapes are shown in Fig.2. It can be seen from Figure 1 that the 1st to 4th order vibration shapes gradually increase, among which the 1st to 2nd order vibration deformation is closer, the 3rd to 4th order vibration deformation is closer, and the 1st to 4th order maximum vibration shapes are 41.905, 42.692, 56.385 and respectively. 56.559, the vibration directions of the 1st to 4th modes are the tires in each radial direction outwards, the tire Z-axis negative direction outwards, the tire Y-axis positive and negative directions outward, and the tire Z-axis positive and negative directions outward. It can be seen from Figure 2 that the vibration deformation of the 5th-6th order is relatively close, and the 7-8th order vibration deformation changes greatly. The maximum vibration modes of the 5th-8th order are 44.224, 43.845, 57.734 and 52.83, respectively, and the vibrations of the 5th-8th order are respectively 44.224, 43.845, 57.734 and 52.83. The directions are the positive and negative directions of the tire Y axis outward, the positive and negative directions of the tire Z axis outward, the positive and negative directions of the tire Y axis outward, and the tire Z axis positive and inward bending of the tire surface, and the tire Z axis positive and negative directions. The tire is bent outwards and the tire Y-axis is positively inward in the tire surface. The 5 to 8 vibration modes mainly occur in the tire sidewall direction.
Comprehensive analysis of each order mode shape and change law, each order mode shape law is shown in Table 3, and the change of the mode shape is shown in Figure 3. From Table 3 and Figure 3, it can be seen that the first 20 modes of retreaded tires and wheels are mainly elliptical, triangular, and quadrilateral. Among them, the second to fifth and 11th to 20th modes have large changes. Enough attention should be paid to the structural design and dynamic performance analysis of engineering retreaded tires.

Table 3. Maximum mode value and mode of each order

| Order | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-------|------|------|------|------|------|------|------|------|------|------|
| Max mode value | 41.905 | 42.692 | 56.385 | 56.559 | 44.242 | 43.845 | 57.734 | 52.830 | 61.822 | 55.741 |
| Mode shape | Round shape | Round shape | Oval | Oval | Round shape | Round shape | Oval | Oval | Round shape | Round shape |
| Order | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Max mode value | 63.923 | 55.741 | 76.497 | 59.381 | 45.006 | 78.739 | 57.641 | 59.161 | 48.015 | 79.016 |
| Mode shape | triangle | triangle | quadrilateral | quadrilateral | Round shape | Round shape | Round shape | Oval | Oval | Oval |

Figure 3. Variation curve of each order mode shape

Comprehensive analysis of each order mode and change law, each order mode and mode value are shown in Table 4, and its mode change curve is shown in Figure 4. It can be seen from Figure 4 that the first 20 modes of retreaded tires under static grounding conditions are mainly circular, elliptical, triangular, quadrilateral, and pentagonal. The first 14 modes are generally increasing, among which the first 3 modes are equal, the 14th mode reaches the maximum value, and then decreases, the 3rd to 5th modes have a larger increase, and the 5th to 7th modes basically the same.
6. Conclusion
Since a retreaded tire (cold retread) is a layer of new tread material attached to the used carcass, the bonding area between the tread and the old carcass is the fragile layer of failure during the use of the tire. Through the numerical simulation and experimental analysis of the thermal and thermal-structure coupling field of 11R22.5 retreaded tires commonly used in transportation vehicles, it is shown that the temperature at the interface between the tread and the carcass of the retreaded tire increases with the increase of vehicle speed, and the tire deformation value. And the flexural stress increases with the increase of temperature, and the deformation is approximately linear with the speed of the vehicle. When the vehicle speed is greater than 80 km/h, the stress, deformation and temperature of the interface will reach high values, which will easily cause the tire to produce internal micro-shear along the retreaded fragile layer, that is, the interface will produce microscopic tearing cracks, indicating that the retreaded tire is in under the long-term high-speed state of the highway, there is a danger of delamination and tearing of the tread.

References
[1] Wang, Q., Jiang, L., & Xiaojie, Q. I. (2020). Simulation and experimental study on load-bearing deformation characteristics of 11r22.5 vehicle retreaded tire. Mechanical Engineering Science, 2(1), 2429-2445.
[2] Karita, N. (2016). Retreaded tire manufacturing method and tires suited therefor, 23(1), 34-37.
[3] Modern, Tire, Dealer, & group. (2017). Low-cost imports affected new and retreaded tires. Modern Tire Dealer, 107(1), 21-38.
[4] Abdella, G. M., Kim, J., Khalifa, K, & Hamouda, A. (2019). Penalized conway - maxwell - poisson regression for modelling dispersed discrete data: the case study of motor vehicle crash frequency. Safety Science, 120, 157-163.
[5] Jian, S., Rashidi, T. H., & Dixit, V. (2017). An analysis of carsharing vehicle choice and utilization patterns using multiple discrete-continuous extreme value (mdcev) models. Transportation Research Part A Policy & Practice, 103, 362-376.
[6] Wong, L. H. (2018). Performance analysis of vehicle assembly line using discrete event simulation modelling. International Journal of Business Excellence, 14(2), 189-195.
[7] Hti, I. (2015). Prediction of vehicle transactions and targeted advertising using vehicle telematics, 8(1), 31-42.
[8] Kamyat, C., Raksiri, C., & Masakasin, R.. (2020). A development of automatic builder machine for retreaded tire manufacturing. IOP Conference Series Materials Science and Engineering, 26(4), 638-654.
[9] Montani, M., Vitaliti, D., Capitani, R., & Annunciario, C. (2020). Performance review of three car integrated abs types: development of a tire independent wheel speed control. Energies, 8(5), 710-716.

Figure 4. Variation curve of each order mode shape
[10] Khanse, K. R., Siramdasu, Y., & Taheri, S.. (2016). Development of a simulink-carsim interaction package for abs simulation of discrete tire models. Tire Science and Technology, 44(1), 2-21.