Experimental Analysis of Radial Tire Stiffness and Grounding Characteristics

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Abstract. The radial tire was tested by the tire comprehensive testing machine to analyze the stiffness characteristics and grounding characteristics of the tire under different tire pressure and vertical load. The results show that the stiffness of different directions changes when the tire pressure increases. The longitudinal stiffness increases slightly and the torsional stiffness increases when the vertical load increases. As the vertical load increases, the tread impression changes from the ellipse to the approximately rectangle, and the area of the tread impression is slightly increased. As the tire pressure increases, the area of the tread impression is significantly reduced.

1. Introduction
The car as a whole consists of many different components, and the tire is the only medium in contact with the road surface. The tire which supported by the rim is a combination of steel wire and rubber [1]. During the driving process, the tires and the suspension bear the impact of the driving together, which guarantee the safety of the whole car and the occupants. During the start-up process of the car, the tire can help the car to gain more power from the advancement process and maintain stability throughout the process; during the process of car braking, the tire acts as a medium to the longitudinal braking force of the car, and the car is quickly decelerated while ensuring safety; during the turning of the car, the tire will exert sufficient centripetal lateral force on the car to maintain good ride comfort; during the bumping process, the damping effect of the tire is buffered. The vibration and impact from the road surface keep passengers comfortable [2]. The literature [2] simulates the grounding characteristics and static stiffness of tires under different inflation pressures and vertical loads. The literature [3] studies the lateral stiffness of tires under static conditions, and the literature [4] studies the experimental conditions of longitudinal and lateral tires. Literature [5] studied the variation of grounding marks under different loads.

This paper tests the impact of different tire pressure and vertical load on the tire stiffness and grounding characteristics by using the Unicon UP-2092 tire comprehensive testing machine, in order to select more reasonable parameters to optimize tire performance and provide a certain mechanical reference for tire design.
2. Test equipment and method
The equipment used in the test is the Youken UP-2092 tire comprehensive testing machine, which is mainly composed of the main machine and the auxiliary machine. The main part includes three parts: tire rigidity and tire tread mark detection area, servo system and tire decoupling test area [6]. The tire comprehensive testing machine and test bench are shown in Figure 1. The auxiliary part is a cabinet type, which includes a computer, a servo control system, a basic electrical control system and a measurement system. The test performs the device control, data analysis, and output of the final result through the slave operation. The tire strength detection and analysis software of UP-2092 tire comprehensive testing machine is based on Windows operating system analysis software PL2000. The control of the test instructions is realized by the PL2000 software, and the results of the test detection and analysis are obtained in the main interface.

In the stiffness characteristic test, after the tire is inflated to the preset tire pressure, it is fixed on the UP-2092 tire comprehensive testing machine. The vertical load is applied to the tire through the software program, and then the force is applied in different directions of radial, lateral and torsion. Then obtain the relationship between the displacement and the load in each direction and observe the change of the stiffness characteristics. When the grounding property test is performed, the load in the vertical direction is also applied to the tire. The pressure sensitive paper placed on the test bench in advance will leave the tread mark of the tire, and the stamped image of the scanned image will be analyzed by PL2000 software.

3. Analysis of stiffness characteristics under different working conditions
The main functions of the tire include bearing the car and the load, transmitting the forces in different directions to the ground, adapting the car to different road conditions, cushioning the noise and improving the ride comfort [7]. Therefore, the performance of all aspects of the tire has also received more attention, and the tire stiffness characteristics are one of them.

The inflated tire has a certain load carrying capacity and also has a certain elasticity. The tire elasticity mainly includes radial (vertical) elasticity, longitudinal (circumferential) elasticity, lateral (transverse) elasticity and torsional elasticity, which represented by static stiffness, longitudinal stiffness, lateral stiffness and torsional stiffness these four parameters [5]. For the convenience of calculation, a coordinate system is set for the tire. The tire rolling direction is set to the x direction, the tire axial direction is set to the y direction, and the vertical direction is set to the z direction [8]. Tire stiffness characteristics are an important parameter to measure the overall performance of a tire.
3.1. Research on static stiffness characteristics

The part in which the tire does not contain the belt is called the tire body. When subjected to a certain vertical load and only longitudinally moved on a horizontal rigid road surface without rolling, due to the vertical force $F_z$ of the road surface, the belt has a vertical movement amount $z$, and the static stiffness $G_z$ of the tire can be expressed as

$$G_z = \frac{dF_z}{dz}$$

Before the test, the tire pressure was charged to 150 kPa, and then vertical loads of 3000N, 4000N, 5000N and 6000N were applied to the tires, and four sets of test data with the same tire pressure and different vertical loads were obtained. The tire pressure was then increased to 200 kPa, 250 kPa, and 300 kPa, and the same test procedure was repeated. The data is organized into a scatter plot with a smooth line. Figure 2 shows the radial load and radial displacement under different vertical loads when the tire pressure is constant.

![Fig. 2 Relationship between radial load and radial displacement under different vertical loads](image-url)
In the static stiffness test, the tire is only subjected to a vertical force, so the slope of the curve does not change as the vertical force changes. When the tire pressure is constant, the static stiffness characteristic curves under different vertical loads are almost completely coincident, which is clearly reflected in the images at 200 kPa, 250 kPa and 300 kPa tire pressure. However, in the image with a tire pressure of 150 kPa, the curves corresponding to different vertical loads are not completely coincident. Due to insufficient tire pressure, the radial load during the test does not necessarily change with the increase of the radial displacement for the first time. As the displacement increases, the road surface gradually exerts a vertical force on the tire and increases, so the curve on the image does not necessarily pass through the origin. However, the slope of the corresponding curve under different vertical loads is consistent, which means when the tire pressure is constant, the change of the vertical load does not affect the static stiffness characteristics of the tire.

![Relationship between radial load and radial displacement under different tire pressures](image)

**Fig. 3** Relationship between radial load and radial displacement under different tire pressures

The test data is collated to obtain the curve of Fig. 3, which shows the relationship between the radial load and the radial displacement under different tire pressures when the vertical load is constant. Under the same radial displacement, the larger the tire pressure, the larger the radial load of the corresponding tire; and under the same radial load, the larger the tire pressure, the smaller the radial displacement of the corresponding tire. When the vertical load is applied to the tire, the increase of the static stiffness of the tire is nonlinear. When the load is gradually increased to a certain extent, the radial load and the radial displacement show a linear relationship. The slope of the curve increases with the increase of the tire pressure. This means that the static stiffness of the tire increases as the tire pressure increases and increases linearly as it increases to a certain extent.
3.2. Study on longitudinal stiffness characteristics

Longitudinal stiffness refers to the ratio of the longitudinal force of the tire to the vertical non-smooth simulated road surface, which is longitudinally moved and not rolled, on the horizontal non-smooth simulated road surface, and the longitudinal movement caused by the tire [4]. When the tire is subjected to a certain vertical load, it is longitudinally moved on a horizontal rigid road surface. Due to the longitudinal force \( F_Y \), the longitudinal displacement of the tire is \( y \), and the transverse stiffness \( G_Y \) of the tire can be expressed as

\[
G_Y = \frac{dF_Y}{dy}
\]

The longitudinal stiffness test is carried out by the tire grounding model. A vertical load of 3000 N is applied to the vertical direction of the tire to cause relative radial displacement between the tire and the ground. Then a force is applied to the ground in the direction of the tire. During the test, the tire does not roll and the ground moves relative to each other. Fixed vertical load test the relationship between the longitudinal load of the tire and the longitudinal displacement at the tire pressures of 150 kPa, 200 kPa, 250 kPa and 300 kPa. Then increase the vertical load to 4000N, 5000N and 6000N, and repeat the same steps, organize the data to obtain the relationship between the vertical load and the tire pressure change in Fig. 4.

![Graphs showing the relationship between longitudinal load and longitudinal displacement under different tire pressures](image)

**Fig. 4** Relationship between longitudinal load and longitudinal displacement under different tire pressures
Under the same longitudinal displacement, the longitudinal load of the tire will increase with the increase of the tire pressure; under the same longitudinal load, the longitudinal displacement of the tire will decrease as the tire pressure increases. The peak at which the curve eventually reaches the vertical load no longer increases, which is the value of the longitudinal load corresponding to the tire slip. The greater the vertical load, the smaller the difference in longitudinal load that causes the tire to slip under different tire pressures, and the greater the difference in slope of the curve. The greater the load, the more pronounced the effect of tire pressure on the longitudinal stiffness of the tire. Overall, the greater the vertical force, the greater the longitudinal load corresponding to the tire slip; the greater the tire pressure, the greater the longitudinal stiffness of the tire.

Fig. 5 is a graph showing the relationship between the fixed tire pressure and the vertical load. When the tire pressure is insufficient, the magnitude of the vertical load has no effect on the longitudinal stiffness of the tire. When the tire pressure is sufficient, the longitudinal load increases with the increase of the vertical load under the same longitudinal displacement; under the same longitudinal load, the longitudinal displacement decreases with the increase of the vertical load. This is because as the vertical load increases, the pressure between the tire and the ground and the corresponding friction increase. The load required to move the same displacement increases, and the same load can only move smaller displacements. The greater the vertical load on the tire, the greater the longitudinal load required to achieve slip. For tires with insufficient air pressure, the longitudinal...
stiffness is not affected by the vertical load; for tires with sufficient air pressure, the longitudinal stiffness increases with the increase of the vertical load, but the increase trend is not obvious.

3.3. Study on transverse stiffness characteristics
Lateral rigidity refers to the tire that bears a certain vertical load, and only laterally moves and does not roll on the horizontal non-smooth simulated road surface, the ratio of the lateral force to the tire and the resulting lateral movement [7]. The lateral stiffness of the tire is one of the main influencing factors of the dynamic response characteristics of the vehicle, and it is an important characteristic of the tire. When the tire is subjected to a certain vertical load, lateral movement on a horizontal rigid road surface, due to the lateral force $F_x$, the tire produces a displacement $x$ of parallel movement, the lateral stiffness $G_x$ of the tire can be expressed as

$$G_x = \frac{dF_x}{dx}$$

The lateral stiffness test is also to apply a vertical load of 3000 N in the vertical direction to the tire and then apply a lateral load to the ground. The relationship between the lateral load and the displacement at the tire pressures of 150 kPa, 200 kPa, 250 kPa, and 300 kPa was tested under a condition of a constant vertical load. Then the vertical loads will be set to 4000N, 5000N and 6000N and the same steps will be repeated. The resulting curve is shown in Fig. 6.

![Fig. 6 Relationship between lateral load and lateral displacement under different tire pressures](image_url)
Under the same displacement, the lateral load of the tire increases with the increase of the tire pressure; under the same lateral load, the lateral displacement of the tire decreases with the increase of the tire pressure. The smaller the tire pressure, the more the lateral stiffness curve tends to change linearly; the greater the tire pressure, the greater the lateral stiffness of the tire [9], and the greater the lateral load value required for the tire to slip. During the increase in tire pressure, the tendency of the curve to increase the slope decreases. The tire pressure is increased to a certain extent, and the lateral stiffness is no longer affected by the tire pressure. In the test of loading the 6000N vertical load, the curve of the tire pressure of 250 kPa and 300 kPa showed a small fluctuation, which was due to the slippage of the tire during the test. It is indicated that in actual driving, the larger the tire pressure and the larger the load, the more likely the tire is to slip laterally.

![Graphs showing relationship between lateral load and lateral displacement under different vertical loads](a)150kPa (b)200kPa (c)250kPa (d)300kPa

**Figure. 7** Relationship between lateral load and lateral displacement under different vertical loads

Fig. 7 is a graph showing the relationship between the fixed tire pressure and the vertical load. The first half of the corresponding curve under different vertical loads almost coincides, and the lateral stiffness does not change due to the change of the vertical load. The stable peak is not the same in the second half of the curve, and increases as the vertical load increases. Under certain conditions of the tire pressure, when the tire is subjected to a larger vertical load, the lateral load required for the slip is greater.
3.4. Study on Torsional Stiffness Characteristics

The torsional stiffness characteristic is the elasticity of the tire rotating about the vertical axis and is used to describe the relationship between the torsion angle of the tire and the torque. The tire was placed on the test rig and placed under load, and then the test rig was rotated about the vertical axis. Let the torque at this time be $M_Y$ and the torsion angle be $\alpha$, then the torsional stiffness $G_{mY}$ of the tire can be expressed as

$$G_{mY} = \frac{dM_Y}{d\alpha}$$

To perform the torsional stiffness test, first apply a fixed vertical load to the vertical direction of the tire and then apply a torsional load to rotate the test rig (ground). Under the condition that the vertical load is constant, the corresponding data is obtained by changing the size of the tire pressure. Then increase the vertical load appropriately and repeat the same test procedure, and the resulting curve relationship is shown in Fig. 8.

![Fig. 8 Relationship between torque and torsion angle under different tire pressures](image)

When the vertical load is 3000 N and the tire pressure is 150 kPa, the tire immediately deforms (displacements) as the torque increases, and the amount of deformation increases as the torque increases. This is due to the lack of maximum static friction between the tire and the test bench, and the small torque can deform the tire. In the case of tire pressures of 200 kPa, 250 kPa, and 300 kPa, the tire does not start to deform as the torque increases. This is because the torsional force applied at the
The beginning is smaller than the maximum static friction between the tire and the test bench, and it is necessary to load a value greater than the maximum static friction force to deform the tire. At a certain torsion angle, the higher the tire pressure, the smaller the corresponding torque; at a certain torque, the higher the tire pressure, the larger the corresponding torsion angle. In the case where the torsional force is sufficient, as the tire pressure increases, the contact area of the tire with the ground decreases, and the twist angle required to generate the twist is smaller. The higher the tire pressure, the less torque is required to make the tire slip. The curve is not completely smooth, because during the actual test, the tire slips with the rotation of the test bench. Under the condition that the vertical load is constant, the larger the tire pressure is, the smaller the torsional rigidity of the tire is.

**Fig. 9** Relationship between torque and torsion angle under different vertical loads

Figure 9 is a graph showing the relationship between the fixed tire pressure and the vertical load. Under insufficient tire pressure (150 kPa), the vertical load has little effect on the torsional stiffness. Under sufficient tire pressure, the greater the vertical load, the greater the torsional stiffness of the tire, and the more torque the tire needs to slip. Big. At higher tire pressures (300 kPa), the smaller the vertical load, the smaller the torsion angle required to overcome the friction to increase the torque; and under insufficient or normal tire pressure, the different vertical loads overcome the friction. The twist angle required to increase the torque is the same. At the same torsion angle, the torque increases as the vertical load increases; at the same torque, the torsion angle decreases as the vertical load increases. In general, the torsional stiffness of the tire increases as the vertical load increases.
4. Analysis of grounding characteristics under different working conditions

Grounding characteristics are one of the basic properties of tires. The durability, wear performance and driving performance of the tires are closely related to each other [10, 11]. Tire ground contact characteristics can be divided into the tire ground-contact geometry and mechanical properties of two types of tire, the contact area of the former is described wherein the shape of the latter is described wherein the mechanical contact area [12]. Tread footprint analysis of geometric features static analysis, with pressure-sensitive recording paper under the test procedure tread footprint, and then scans 256 gradations BMP format image. Fig. 10 shows an image recorded on a pressure sensitive paper, and Fig. 11 shows an image scanned on a computer. Analysis software tread, the tread area can be measured in different directions transverse, longitudinal section of the pressure value, the pressure value at any point of the tread surface, etc. [6]. In the process parameters tire pressure, vertical load changes and the like, the shape of the footprint of the tire, the area will also change [13]. Through analysis, the tire pressure change of the tire cut surface under different working conditions can be obtained.

Repeat the same steps as the static stiffness test, and measure 16 sets of tire tread marks with different vertical loads of 3000N, 4000N, 5000N and 6000N under different tire pressures of 150 kPa, 200 kPa, 250 kPa and 300 kPa. The tread marks on the pressure sensitive paper were scanned with a gray scale by a scanner, and then the analysis image was subjected to tread pressure analysis using the analysis software. Pressure of less than 0.35MPa preset region shown in white, is greater than 0.91MPa area shown in red. 0.35MPa to 0.91MPa to 0.07MPa between each additional different colors represented by the color of the tread footprint can be clearly observed in particular on the distribution of footprint pressure. Figure 12 compares the tire footprint of tires with the same tire pressure and different vertical loads.
The grounding area of the tire is mainly determined by the radius of curvature of the crown and the amount of tire sinking [14]. Under certain circumstances the tire pressure, as the vertical load increases, the amount of sinking of the tire increases, the footprint tread area will increase. Among them, the width of the printed mark changes little and the length changes greatly. In addition to the change in area, the shape of the impression will vary. When the vertical force is small, the shape of the print tends to be elliptical; as the vertical force increases, the shape of the print is more similar to a rectangle. The relative size of the pressure at each point of the tread was observed by pressure treatment of the tread marks. It can be seen from the image that the change of the vertical force has

**Fig. 12** Tire footprint under different vertical loads
less influence on the pressure of each part of the tread, and the pressure on both sides of the crown is larger than the intermediate force of the crown.

Figure 13 compares the tire footprint of tires with the same vertical load and different tire pressures. As the tire pressure increases, the maximum pressure at the ground will also increase. When the tire pressure is low, pressure concentration occurs on both sides of the crown. This is when the tire's air pressure is small, because the radial stiffness of the tire is small, the center of the tread is concave during the grounding process, and the center of the crown will produce a "warping" phenomenon [15]. As the tire pressure increases, the center of the crown will also have a concentration of pressure. The
pressure distribution throughout the tire grounding becomes more uniform, and the phenomenon that the grounding pressure is more concentrated on both sides of the crown is also alleviated. In the process of increasing the tire pressure, the grounding width changes little, the grounding length becomes smaller, and the tread surface area of the tire is reduced [16]. When the tire pressure is too high, some tires will not be grounded. When the tire pressure is too low, the grounding area of the tire will increase accordingly, but the pressure distribution will be uneven, and the pressure will accelerate the shoulder wear. Inflated tires not only have a large grounding area, but also cause excessive deformation and overheating of the tires, which can cause great damage to the tires. Compared with the change of the tire pressure, the change of the tread shape caused by the change of the vertical force is smaller, that is, the shape of the tread is less affected by the tire pressure. As the tire pressure increases, the pressure at each point on the tread increases. If the tire pressure is too high or too low, the tire grounding pressure will be more concentrated on the shoulder. Therefore, applying a suitable tire pressure to the tire can make the pressure distribution more uniform, which is more conducive to prolonging the service life of the tire and improving the safety of the vehicle.

5. Conclusion
The stiffness characteristic test mainly investigates the effects of tire pressure and vertical load on the static stiffness, longitudinal stiffness, lateral stiffness and torsional stiffness of the tire.

1) Tire pressure has a significant effect on static stiffness, longitudinal stiffness, lateral stiffness and torsional stiffness. Static stiffness, longitudinal stiffness and lateral stiffness increase with increasing tire pressure, and the torsional stiffness decreases with increasing tire pressure.

2) The magnitude of vertical load has little effect on static stiffness, longitudinal stiffness and lateral stiffness. The longitudinal stiffness of transverse stiffness and lateral stiffness and tire pressure will not change with the increase of vertical load. The longitudinal stiffness when the pressure is sufficient increases slightly as the vertical load increases. In contrast, the vertical load has a more significant effect on the torsional stiffness, and the torsional stiffness increases as it increases.

3) During the torsional stiffness test, the tire will slip due to the rotating tire of the test bench, which is difficult to simulate during the simulation.

The grounding characteristic test mainly explores the influence of tire pressure and vertical load on the size and pressure distribution of the tire footprint.

1) The vertical force mainly affects the shape of the tread mark, and the tire pressure mainly affects the area of the tread mark. As the vertical load increases, the tread impression changes from an elliptical shape to an approximately rectangular shape, especially when the tire pressure is small. When the tire pressure is constant, the vertical load increases, and the area of the tread mark slightly increases; when the vertical load is constant, the tire pressure increases, and the area of the tread mark is significantly reduced.

2) The greater the vertical load, the more obvious the phenomenon of pressure concentration on both sides of the crown.

3) When the tire pressure is small, the pressure is mainly concentrated on both sides of the crown. As the tire pressure increases, the center of the crown will also exhibit pressure concentration, and the overall pressure distribution becomes more uniform.

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