Analysis and Research on Radial Stiffness of Main-auxiliary Spring Structure Wheel

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Abstract. In order to improve the traditional pneumatic rubber tire performance of puncture-proof, explosion prevention and environment adaptability, a main-auxiliary spring structure wheel was propesed. The new wheel composed base on metal helical spring mutual woven and interwined. By analyzed the system structure,combined with radial force of the main spring when it contact ground,the mechanical model of the wheel was established and its force was analyzed then it radial static loaded. Finite element model of wheel was established and simulated, different structural parameters of the main spring influence on radial stiffness was analyzed.

1. Introduction

Because of its material and structural properties, the traditional pneumatic rubber tire exist the following problems:anti-destruction capability is weak and difficult to resist sharp objects puncture; the presence of standing wave phenomena at high speeds easily lead to blow-out; high and low temperature environment alternately results tire performance significantly dropped.

For the problems that pneumatic rubber tires existence, non-pneumatic tire of new materials and new structure had become one of the hot current research in the tires field[1,2]. There are typical Tweel tire[3], honeycomb structure tire[4], Spring Tire[5], AirFree Concept tire [6].

2. Wheel Structure Design

The wheel consists of main spring, spring-net, rim, fixing belt and fixing ring, as shown in Fig.1.Main spring end to end into a ring by welded, placed in the rim arcuate recess, and the wire of the main spring snaped into the recess of the fixing belt one to one correspondence, fixed by the fixing belt; Fixing belt was composed by six metal circle with same structure, of which the inner recesses of the fixing belt is corresponding to the wire angle and pitch of main spring when it bend into a ring,fixing belt is fixed through the threaded hole on the rim, restricted the main spring circumferential and radial movement; Auxiliary spring twice the circle number of the main spring, take the structure form of one end tight and the other end freedom,convolution and interlaced with each other around the wire and its space of the main spring formed a laced toroidal structure.The tight end ensure that auxiliary spring can be easily fixed by fixing ring and the freedom end ensure that the auxiliary spring adjacent to each other can be interlaced; Fixing ring fixed the auxiliary spring-net from both sides of the rim through the threaded hole, and constrain the relative movement of the auxiliary spring-net.

3. Main Spring Radial Force Analysis

3.1 Mechanical Model

The mechanical action between each part of the wheel is complex, and its difficult to directly analyze its radial stiffness. But then the wheel static radial loaded, its mainly force is borne by the main spring, thus simplified the wheel mechanical model as follows:

(1) Ignore the influence of the main spring pitch, simplified the main spring as metal ring which its number of laps, pitch,mean diameter are same with the main spring;

(2) Ignore effects of radial stiffness by the spring-net.

Simplified wheel main spring mechanical model as shown in Figure 2.

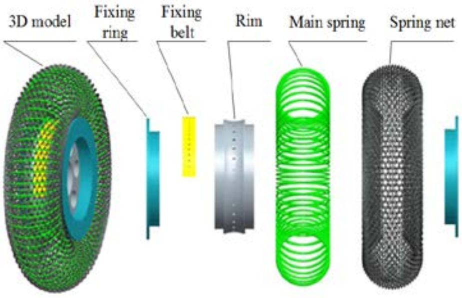


Fig.1 Main-auxiliary spring structure wheel model

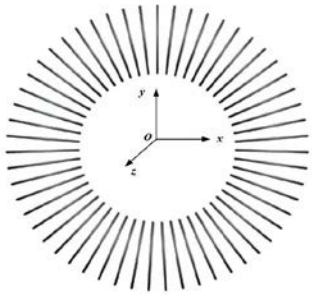


Fig.2 Simplified mechanical model

3.2 Ring Forced Analysis

Main spring simplified model use the same structural parameters ring as the forced element. Combined with its symmetry, take half of ring for the force analyzed. Under the action of the radial force P, the force of arbitrary cross-section of the ring as shown in Fig.3.

Since the cross-sectional dimensions of the ring is much smaller than the radius of curvature, strain energy caused by axial force and shear can be ignored, only consider the moment impact .

Moment of arbitrary cross-section:

$$M = PR_1 \sin\varphi$$

The strain energy:

$$U = \int_0^{\pi} \frac{M^2(\varphi)}{2EI} R_1 d\varphi = \frac{\pi R_1^3}{4EI} P^2 \quad (1)$$

Where E is the Elastic Modulus of main spring; I is moment of inertia that the ring cross section to the neutral axis, its value is $\frac{\pi d_1^4}{64}$.

Assume that δ is the displacement under the force P, in the displacement of the δ ,the work that P done was

$$W = \frac{1}{2} P\delta \quad (2)$$

According to the energy conservation law:

$$U = W \quad (3)$$

By equation(1)~(3):

$$\delta = \frac{\pi R_1^3}{2EI} P \quad (4)$$

That is, in the case of small deformation, vertical deformation and radial load of ring show linear relationship. Take $K = \frac{2EI}{\pi R_1^3}$, by the Hooke's law:

$$P = K\delta \quad (5)$$

In the ring grounding process the ith lap of ring deformation is ΔL_i, force is N_i, and then:

$$N_i = K\Delta L_i \quad (6)$$

According to the forced symmetry of the wheel, the contact ground number of the ring then the wheel static loaded is odd or even , and then analyzed the odd case.

3.3 Simplified Model Forced Analyzed

Forced diagram is shown in Fig.4. Take the radial force that the wheel suffered is F, and its value is the resultant force of each spring ring suffered along the vertical direction. The ratio of F and deformation of the wheel at the lowest point of the wheel is the radial stiffness.

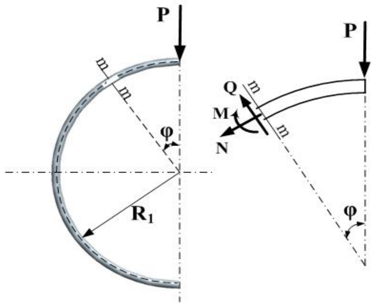


Fig.3 Ring forced diagram

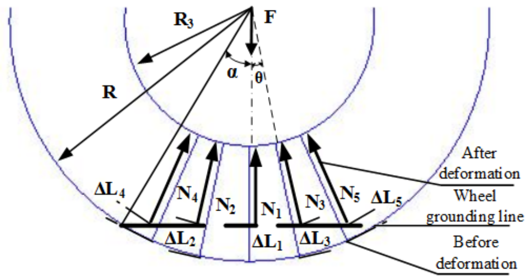


Fig.4 Forced Diagram

By the static equilibrium equation:

$$\begin{bmatrix} \sum X \\ \sum Y \end{bmatrix} = \begin{bmatrix} 0 & \sin\theta & -\sin\theta & \cdots & \sin\frac{n-1}{2}\theta & -\sin\frac{n-1}{2}\theta \\ 1 & \cos\theta & \cos\theta & \cdots & \cos\frac{n-1}{2}\theta & \cos\frac{n-1}{2}\theta \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \\ \vdots \\ N_i \end{bmatrix} = \begin{bmatrix} 0 \\ F \end{bmatrix} \quad (7)$$

Where θ is the angle between adjacent ring, and its value is 6.54º

By the main spring forced symmetry:

$$\begin{cases} N_2 = N_3, \cdots \ N_{i-1} = N_i \\ \Delta L_2 = \Delta L_3, \cdots \ \Delta L_{i-1} = \Delta L_i \end{cases} \quad (8)$$

Under radial load, with increasing of the deformation, the contact ground laps of main spring growing as 2 arithmetic, the main spring grounded angle α, contact ground laps n, the largest deformation ΔL increases gradully, by the deformation coordination relationship:

$$\begin{cases} (\mathrm{R} - \Delta \mathrm{L}_2)\cos\theta = \cdots = (\mathrm{R} - \Delta \mathrm{L}_{i-1})\cos\frac{i-1}{2}\theta = R\cos\alpha \\ R\cos\alpha = \mathrm{R} - \Delta \mathrm{L}_1 \end{cases} \quad (9)$$

Wherein R is the sum of rim radius diameter, the main spring wire diameter and mean diameter.

By equation of (6)~(9):

$$F = \begin{cases} KR(1-\cos\alpha) & i = 1 \\ KR\left[(1-\cos\alpha) + \cdots + 2(\cos\frac{i-1}{2}\theta - \cos\alpha)\right] & i = 3, 5, \cdots \end{cases} \quad (10)$$

Assumed the maximum grounded angle is 18º, take α for different values, the main spring grounded radial stiffness can be obtained respectively.

4. Radial Stiffness Simulation

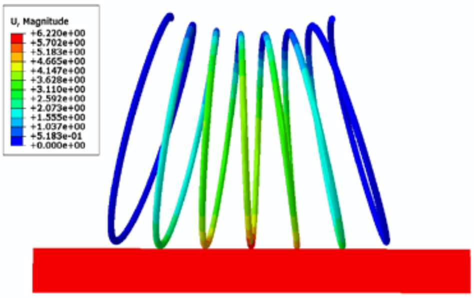
4.1 Setting of Simulation Conditions

Material parameters: the elastic modulus E is 1.96 × 10^{11}Pa, Poisson's ratio μ is 0.3. Meshing: use amendment 10-node secondary tetrahedral elements (C3D10M) which suitable for contact and large deformation analysis. Contacting Methods: the ground and the main spring use surface-surface Coulomb contact model.Set the ground rigid, contact surface as master, set the main spring soft body, the contact surface as slave. Boundary conditions: in order to make the results easier to convergence, set the area that the main spring contact with the rim fixed constraint, and applied perpendicular upward displacement to the ground.

4.2 Simulation Results

Fig.5 is radial deformation figure of the main spring applied to the ground vertically upward displacement.As the ground radial displacement increased, the main spring grounded laps grow. When the application of the maximum radial displacement of 6.22mm, have 5 ring grounded. In the grounded ring, the intermediate ring radial deformation is largest and along the sides gradually reduced. Each grounded ring the grounding point have the maximum amount of deformation and along the vertical upward direction gradually decreased, fixed point in the main spring became zero.

From the ground contact reaction force and vertical displacement can obtined curve that radial force varied with the change of displacement, and compared with the calculation result shown in Figure 6.



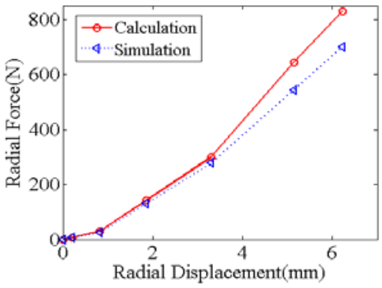
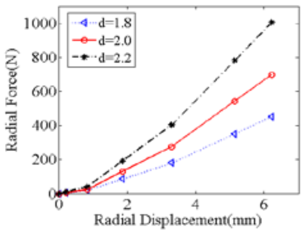


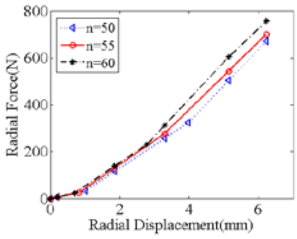
Fig.5 Radial deformation figure　　　Fig.6 Comparison of calculation and simulation

From simulation result as shown in Fig. 6 it can be concluded that the radial stiffness of the main spring magnify as deformation increased, and periodic increased then the grounding number of laps increased. Compared with calculation result, both stiffness have same trend, the simulation result are smaller than the theoretical calculation.

4.3 Effect of Structural Parameters on the Radial Stiffness

To analyze the diferent structural parameters influence of the stiffness of the wheel,select the wire diameter(d), laps of ring(n) and mean diameter(D) for study,kepping two of the structural parameters constant and change the other,obtain the wheel radial stiffness contrast curve shown below. It can be concluded that changed structural parameters of the main spring the wheel radial stiffness changed, as increased of the main spring wire diameter, number of laps and the decreased of the mean diameter, the radial stiffness of the wheel increased.





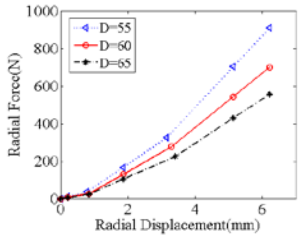


Fig.7 Different wire diameter　　Fig.8 Different lap　　Fig.9 Different mean diameter

5. Summary

This paper designed a main-auxiliary spring structure wheel use helical spring as basic component. Combined with 3D model of new wheel, established simplified mechanical model of the wheel then it static radial loaded, and analyzed the wheel grounded mechanical characteristics. Established the finite element model of the wheel, simulated the wheel radial stiffness and comparison with theoretical calculation, two results have same trend.

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