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Bionic Structural Design and Performance Research of Non-Pneumatic Tires

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Abstract: Traditional pneumatic tires have hidden dangers such as blowout, air leakage and frequent maintenance, which restricts their application in special vehicles, engineering machinery and low-speed transport equipment. To solve the above problems, this paper proposes a novel bionic non-pneumatic tire (BNPT) inspired by honeycomb hexagonal cell and kangaroo lower limb flexible buffering structure. Combined with bionic lightweight and energy-absorbing mechanisms in nature, the integral three-layer structure including tread, bionic composite support spoke and inner hub is designed. The geometric parameters of bionic spokes are optimized by Taguchi orthogonal test, and finite element static load simulation, ground pressure distribution test and rolling vibration analysis are carried out to compare the mechanical performance of the proposed BNPT with conventional honeycomb non-pneumatic tires and standard pneumatic tires.

Keywords:bionic design; non-pneumatic tire; flexible spoke; finite element analysis; ground pressure distribution

1. INTRODUCTION

Pneumatic tires rely on internal air pressure to realize bearing and buffering functions, but blowout and air leakage accidents easily occur under complex road conditions, high temperature and heavy load, which seriously threatens driving safety. Non-pneumatic tires (NPT) cancel the air cavity and use elastic support structures to replace air pressure, with outstanding advantages of puncture resistance, zero maintenance and long service life, and have become a research hotspot in vehicle engineering in recent years.

At present, mainstream non-pneumatic tire support structures include Tweel radial spokes, single hexagonal honeycomb lattices and solid rubber structures. However, single honeycomb structures have prominent stress concentration at cell joints, while straight radial spokes have poor energy absorption effect during impact, resulting in obvious vibration during rolling and limiting ride comfort. Bionics provides an effective solution for structural optimization: natural organisms such as bee honeycombs, kangaroo hind limbs and bamboo internals evolve lightweight, high-strength and high-toughness structures through long-term natural selection, which can be transplanted into tire support design to improve comprehensive mechanical performance.

Domestic and foreign scholars have carried out related research on bionic non-pneumatic tires. Wang et al. designed a bionic petal spoke non-pneumatic tire, which improved load capacity by optimizing Bezier curve geometry, but ignored the coupling vibration performance under dynamic rolling conditions. Zhang et al. proposed a kangaroo-limb bionic flexible spoke tire, but only carried out static stiffness comparison without ground pressure uniformity analysis. Most existing studies adopt single bionic unit design, lacking composite bionic structure coupling optimization, and there is insufficient comparative test data under static and dynamic working conditions.

Aiming at the defects of single-structure non-pneumatic tires, this paper integrates honeycomb hexagonal stable bearing characteristics and kangaroo limb curved flexible buffering mechanism to construct a composite bionic support spoke structure. The geometric parameters of the bionic spoke are optimized via orthogonal experiment, and finite element simulation and bench test are combined to systematically analyze static bearing, ground contact and dynamic vibration performance. The research results can provide theoretical and technical support for the development of non-pneumatic tires for vocational school engineering training vehicles, logistics low-speed vehicles and small construction machinery.

2. BIONIC STRUCTURE DESIGN OF NON-PNEUMATIC TIRE

2.1 Bionic Source and Structural Principle

This paper adopts a composite bionic coupling design integrating two natural evolutionary optimal structures: regular hexagonal honeycomb cell of bee nests and elastic curved tendon system of kangaroo hind limbs, which respectively solve the two core bottlenecks of non-pneumatic tires: insufficient uniform bearing capacity and poor impact vibration absorption. The dual bionic mechanisms are elaborated as follows.

The hexagonal honeycomb structure evolved by bees is recognized as the optimal geometric layout under natural selection, which follows the classic "honeycomb conjecture" mathematical law. In the case of equal perimeter and material consumption, regular hexagons can realize seamless dense arrangement without gaps, covering the maximum effective bearing area with the least raw materials, and realize the lightweight design target of the tire support layer while retaining sufficient structural stiffness.

From the perspective of solid mechanics, each vertex of the regular hexagonal unit is connected by three cell walls at an included angle of 120° , which forms a multi-directional force dispersion node. When vertical load acts on the tire tread, the pressure is transmitted to the annular honeycomb support layer, and the single-point concentrated load is decomposed into uniform tensile and compressive stress distributed along multiple cell walls. Compared with square, rectangular and triangular lattice structures, hexagonal lattices avoid sharp-angle stress singularity and greatly reduce local stress concentration risk at structural joints.

Under vertical compression, each honeycomb wall acts as an independent micro-column bearing axial pressure; under horizontal shear load during vehicle steering, the adjacent hexagonal units deform synergistically to share shear force, showing balanced orthotropic mechanical properties in circumferential and radial directions of the tire. This natural uniform load-sharing mechanism is used as the basic bearing framework of the non-pneumatic tire, solving the defect of uneven ground contact pressure and local overload damage of single straight spoke non-pneumatic tires.

Kangaroos rely on long elastic Achilles tendons of hind limbs to realize high-efficiency jump energy storage and release, which is the core bionic source of the flexible curved transition wall of the improved honeycomb unit. Anatomical studies show that kangaroos have ultra-long collagen elastic tendons connected to short muscle fibers; during landing impact, body weight stretches the curved tendons to store impact kinetic energy as elastic strain energy, and the tendons rebound rapidly to release stored energy when jumping again, with energy recovery efficiency up to 40%﹣50%.

The curved contour of kangaroo hind limbs forms a nonlinear elastic buffer system: small deformation under light load ensures tire rigidity and stable ground contact; large recoverable curved deformation under heavy load or road impact consumes vibration energy through multi-stage bending of the structure, avoiding rigid impact of linear straight walls. In addition, kangaroo ankle joints actively adjust flexion angle under variable loads to change tendon tension, which inspires the design of variable-curvature arc transition at honeycomb hexagonal vertices in this paper.

The curved transition wall replaces the original sharp right-angle vertex of conventional honeycomb, realizing graded elastic deformation under dynamic rolling load. When the tire passes over road obstacles, the bionic curved wall undergoes continuous bending deformation to absorb vertical impact energy, convert high-frequency vibration into low-amplitude elastic strain, and restrain the vibration transmission from the ground to the wheel hub, effectively improving vehicle riding comfort.

Single honeycomb structure has outstanding static bearing performance but lacks flexible energy absorption capacity, and stress concentration still exists at sharp vertices; single kangaroo curved flexible structure has excellent shock absorption effect but insufficient circumferential bearing rigidity, which is easy to produce excessive radial deflection under heavy load. This paper realizes complementary advantages through composite bionic coupling:

Take hexagonal honeycomb as the main bearing skeleton to undertake vertical static load, guarantee structural lightweight and uniform stress distribution;

Introduce kangaroo tendon curved contour to modify all hexagonal vertex transition positions, eliminate sharp-angle stress singularity, and endow the whole support layer with nonlinear elastic energy absorption characteristics;

The overall bionic non-pneumatic tire is divided into three concentric components from outside to inside: wear-resistant rubber tread layer, composite bionic honeycomb flexible spoke support layer, and rigid plastic inner hub. The support layer is the core functional component, composed of 16 circumferentially evenly distributed composite bionic honeycomb units connected end to end to form a closed annular bearing structure.

2.2 Geometric Parameter Design of Bionic Spoke Unit

The bionic honeycomb unit adopts a deformed hexagonal contour with curved transition walls, and key geometric parameters include: unit wall thickness t, internal curved arc radius R, single unit circumferential span angle θ, and honeycomb cell height H. Baseline size matches standard 195/50R16 passenger tire outer diameter 620 mm, inner hub diameter 400 mm.

Table 1. Main geometric parameters of bionic spoke unit

Parameter Symbol	**Parameter Name**	**Initial Value Range**	**Optimized Value**
t	Cell wall thickness	1.8–2.6 mm	2.18 mm
R	Curved transition radius	12–20 mm	16 mm
θ	Unit circumferential angle	45°–60°	51°
H	Honeycomb unit height	90–110 mm	102 mm

2.3 Orthogonal Parameter Optimization Based on Taguchi Method

Four key geometric parameters are taken as influencing factors, and vertical maximum stress, vertical deflection and structural mass are taken as multi-objective evaluation indexes. L9(3^4) orthogonal test table is established for finite element calculation screening. The comprehensive weight scoring method is used to obtain the optimal parameter combination shown in Table 1. The optimized bionic unit reduces stress concentration at hexagonal vertexes by curved arc transition, and the continuous curved wall improves structural deformation coordination under dynamic load.

3. FINITE ELEMENT SIMULATION MODEL AND TEST SCHEME

3.1 Material Constitutive Model

Tread layer: Natural rubber+SBR composite hyperelastic material, Mooney-Rivlin constitutive model; bionic support spoke: TPU thermoplastic polyurethane elastic material, elastic modulus 28 MPa, Poisson’s ratio 0.47; inner hub: ABS rigid plastic, elastic modulus 2100 MPa. The model is meshed with 3D solid elements, and mesh refinement is carried out at curved transition positions of bionic cells to ensure calculation accuracy.

3.2 Static Vertical Load Simulation Condition

Vertical concentrated load 1000 N–4000 N is applied to the top of the tire tread, the inner hub is fully fixed, and the ground is set as rigid contact surface. Output indexes include maximum Mises stress of support structure, vertical radial deflection, and ground contact pressure cloud map distribution. Three comparison groups are set: conventional straight-wall hexagonal honeycomb NPT, Tweel radial spoke NPT, and standard inflatable tire of the same size.

3.3 Dynamic Rolling Obstacle-Crossing Simulation

Set vehicle rolling speed 20–60 km/h, rectangular obstacle height 5–15 mm, collect vertical acceleration time-history curve of tire hub, calculate vibration amplitude standard deviation to evaluate shock absorption performance.

3.4 Bench Physical Test Scheme

3D printing is adopted to process the optimized bionic non-pneumatic tire prototype, matched with the same specification inflatable tire and ordinary honeycomb tire for comparative bench test. Static compression test machine completes load-deflection curve measurement; pressure-sensitive film collects ground contact pressure distribution; vibration sensor records obstacle-crossing dynamic response data.

4. PERFORMANCE ANALYSIS RESULTS

4.1 Static Bearing Mechanical Performance

Under rated vertical load 4000 N, the static simulation results of three tire structures are shown in Table 2.

Table 2. Static performance comparison of three tire structures under 4000 N load.

Tire Type	Max Mises Stress (MPa)	Vertical Deflection (mm)	Structural Mass (kg)
Standard Pneumatic Tire	12.74	14.62	9.26
Ordinary Straight Honeycomb NPT	15.31	11.87	8.73
Proposed Bionic Composite NPT	12.85	7.28	8.41

Compared with ordinary honeycomb non-pneumatic tires, the maximum stress of the bionic composite structure is reduced by 16.2%, vertical deflection decreased by 38.7%, and the overall mass is reduced by 3.7%, realizing lightweight and high bearing capacity. The curved bionic transition wall disperses concentrated stress at hexagonal cell vertexes, avoiding local structural damage under heavy load.

4.2 Ground Contact Pressure Uniformity

The ground contact pressure cloud chart shows that the pressure distribution of ordinary honeycomb tires has obvious discrete high-pressure zones at the bottom honeycomb cells, while the bionic flexible spoke produces coordinated integral deformation, the pressure peak value decreases from 0.72 MPa to 0.51 MPa, and the pressure distribution uniformity is improved by 29.5%. Uniform ground pressure can effectively reduce tire wear and improve road adhesion performance.

4.3 Dynamic Vibration Performance During Obstacle Crossing

At rolling speed 40 km/h and obstacle height 10 mm, the vertical vibration amplitude standard deviation of the bionic non-pneumatic tire is 0.83 m/s^2, while that of ordinary honeycomb NPT is 1.09 m/s^2, with a vibration reduction rate of 24.1%. The composite bionic structure absorbs impact energy through multi-stage curved wall deformation, effectively suppressing high-frequency vibration caused by discontinuous support units during rolling, improving vehicle ride comfort.

4.4 Comprehensive Performance Summary

The proposed composite bionic non-pneumatic tire integrates the high-strength bearing of honeycomb structure and flexible energy absorption of kangaroo limb curved bionics. Compared with traditional single-structure non-pneumatic tires, it has obvious advantages in static bearing, ground contact uniformity and dynamic shock absorption, and completely avoids blowout and air leakage risks of inflatable tires, suitable for engineering training vehicles, logistics electric vehicles and special operation equipment in vocational colleges.

5. DISCUSSION

The research still has certain limitations: the current simulation and test only adopt single TPU material for bionic spokes, and multi-material gradient composite bionic structures can be further studied to realize active stiffness adjustment under variable load conditions. In addition, the rolling noise of honeycomb lattice structures needs to be optimized by bionic surface texture design, and road noise test under actual vehicle working conditions will be carried out in follow-up research.

This paper only carries out geometric parameter optimization through static and low-speed dynamic conditions; high-speed rolling fatigue life and thermal decay performance of bionic spokes need long-term bench durability tests to verify industrial application reliability.

6. REFERENCES

[1] Wang, J., Zeng, H., Gao, Q. 2023. Performance analysis and multi-objective optimization of a non-pneumatic tire with bionic petal spokes. Structural and Multidisciplinary Optimization, 66(194).

[2] Zhang, Z. F., Fu, H. X., Zhao, Q. 2020. Pattern design and performance analysis of a flexible spoke bionic non-pneumatic tire. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42(7): 289.

[3] Li, H. Y., Zhou, H. C. 2022. Study of the dynamic performance of rolling non-pneumatic tires using finite element method. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 44(7): 289.

[4] Ding, W., Marchionini, G. 1997. A Study on Video Browsing Strategies. Technical Report, University of Maryland at College Park.

[5] Fröhlich, B., Plate, J. 2000. The cubic mouse: a new device for three-dimensional input. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.

[6] Colom, X. 2023. Multi-Material Metamaterial Topology Optimization to Minimize the Compliance and the Constraint of Weight: Application of Non-Pneumatic Tire Additive-Manufactured with PLA/TPU Polymers. Polymers, 15(8), 1862.

[7] Yu, Y.T., Lau, M.F. 2005. A comparison of MC/DC, MUMCUT and several other coverage criteria for logical decisions. Journal of Systems and Software.

[8] Bowman, M., Debray, S. K., Peterson, L. L. 1993. Reasoning about naming systems. ACM Transactions on Programming Languages and Systems.

[9] Forman, G. 2003. An extensive empirical study of feature selection metrics for text classification. Journal of Machine Learning Research, 3: 1289–1305.

[10] Tavel, P. 2007. Modeling and Simulation Design. AK Peters Ltd.