Design of bio-inspired irregular porous structure applied to intelligent mobility products

October 2022

Supplementary Material

The structures in Table. S1 show parameters obtained by authors in the field of non-pneumatic tires.

Linear structures with a slight curvature [1, 2] show excessive structural deformation in the middle part of the tire, obtaining an extensive structural effort, being the lower spokes the most affected. Due to the chaotic structure of the Voronoi pattern, the in its structural deformation remains homogeneous. It should be emphasized that the homogeneity of the sample, is established by the density index in the total volume *(vT)*, the number of seeds in point *(pT)*, and the thickness of the trabecula *(eT)*. Another feature, for example, the trabecular rounding index has distributional properties compared to those in vertical termination. Voronoi-type chaotic structures have excellent damping properties and energy dispersion performance. The pore size gradient is one of the key reasons ensures a superior performance.

According to a group of researchers from the University of Helwan in Egypt [3], tires with curved elastic structures show that the vertical arrangement of their spokes generates a significant decrease in mechanical strength. In the same way, the curved structure causes the vertical stiffness to decrease, as well as a maximum deformation under mechanical loads.

As shown in Table. S1, the rhombic structure has a minimum deflection value once subjected to a pressure of 30 psi. This structure has an optimal design [4] The hexagonal structure proposed at the Rajiv Gandhi Institute of Technology in India [5], was studied to compare torque resistance, lateral stiffness and lateral torque resistance between a conventional tire, and the proposed one in the research. Concerning torsion and lateral resistance, the model obtained maximum results, whereas the lateral stiffness showed a low value. The proposed model of reticular pattern Voronoi exhibits high resistance to torsion as well. Voronoi´s strength is due to the trabeculae´s randomness.

As suggested by the Department of Mechanical and Industrial Engineering in Indonesia [6], which studies the distribution of pressure and deflection in the field of airless tires, as the thickness of the structural spokes of a tire increases, a low concentration of Von Misses Stress value exists. The aforementioned characteristic results in a better distribution of stress under higher loads. The authors of this research state that the point of highest stress concentration occurs in those locations where the hexagonal cells join. Therefore, the most effective output of the optimization suggests the placement of variable-type rounding on the trabecular joints of the Voronoi-type cell to create a resistant structure. Voronoi cells can be controlled with the visual programming module by adapting degrees of porosity and density in the sample; this represents an advance in the placement of gradients from the same cell for different purposes. The tightly packed and interlocking units lead to a cell that behaves like a monolithic structure; the thrust is equally distributed over the trabecular joint reducing the stress on a specific area. The Voronoi cell can transfer the Von Misses stress to the subsequent cell, where once again, it is uniformed distributed to the surrounding cells.

The Robotic Institute of Beihang University in China provides two new structures [7] in which the radial arrangement of crossed arcs and rectangular cells, respectively, is observed. In this study, the researchers propose that the optimal cross-arch structure meets a higher tread thickness. This authors suggests that the higher the thickness, the lower the radial deformation will be. They point out that if a tire increases the number of cells in its arrangement, the degree of wear decreases. A higher number of cells distributed on the sample provides better mechanical stability. Added to its variable of randomness, the Voronoi cells proposed in free directions on its three-dimensional axis execute excellent torsion and overturning.

The Korean Aerospace University, in conjunction with the University of North Texas, developed a proposal of hexagonal structure [8]. In the analysis of the study, the researchers established that a structure with better stress distribution has a 45° angle in the cell unit. Later, in the simulation using FEM, it was confirmed that the structure presented low levels of Von Mises stress, but the vertical deflection showed high values of displacement. From this study it can be concluded that a greater opening angle in the cells, allows the airless tire to have a better flexibility performance, however, compared to the structures studied in this research, the buckling parameters remain in a higher value. Additionally, in a previous study carried out by these institutions, it is indicated that the hexagonal structure [9] presents vertical displacement values close to those of a traditional tire. Furthermore, it is mentioned that the displacement increases when constant speed is applied in the center of the hub.

Concerning the proposed Voronoi type lattice pattern, it presents an angle opening higher than 128°, the cell formed by irregular convex polygons allows the Von Mises stress distribution to be lower, it is established that the cell density gradient provides properties of rigidity and flexibility.

On the other hand, the College of Mechanical and Power Engineering, China carried a study where the anti-chiral gradient structure is proposed. This research shows that tires with this structure have a slightly uniform deformation. Besides, the deformation concentrates on the middle structure of the tire. With increasing load, the displacement does not remain static but is distributed circumferentially. Therefore, as the load increases, the internal ligaments of the structure move and begin to converge. As a consequence, the deformation is limited, and the structure reaches the maximum displacement. According to these authors [10], the deformation of the experimental tire without air presents consistent conditions for its application in the industrial sector. Concerning the Voronoi-type lattice unit, the trabecular units move slightly, redistributing the load over the body.

In a recent study published by the School of Creative Arts and Engineering [11] in the United Kingdom, a hexagonal pneumatic model is presented. The airless tire was subjected to numerical analysis to define the parameters that influence the mechanical behavior of hexagonal structures. This research states that the parameters of cell density and cell length, when increased, generates a decrease in Von Mises stress within each cell. As a consequence, the structure´s density reduces as well. Therefore, the optimal output is the increase of cells to reduce stress. However, if the density increases to ensure better performance, the tire´s weight will also increase. So, the authors remark the necessity to balance cell density and tire weight. Meanwhile, the structure with the Voronoi reticular pattern presents the same principle applied in the aforementioned study. The reticular pattern structure of Voronoi shows that an increase in the density variable causes the solid trabeculae to have an increased rigidity index as well. On the other hand, the trabeculae with low rigidity have low density together with a broader deformation point.

Finally, the mechanical properties of the Voronoi reticular pattern illustrate the application of natural components for performance in functional products. The skeletal structure is found in a great diversity of organisms. The structural optimization of the sample makes the external and internal tensions as uniform as possible throughout the structure. The CAD software design proposal allows the reconfiguration of stress zones by readjusting the equilibrium point at high-stress points.

References

[1] Ma J, Summers J, Joseph P. Dynamic impact simulation of interaction between non-pneumatic tire and sand with obstacle. SAE Technical Paper; 2011.

[2] Żmuda M, Jackowski J, Hryciów Z. Numerical research of selected features of the non-pneumatic tire. In: AIP Conference Proceedings. vol. 2078. AIP Publishing LLC; 2019. p. 020027.

[3] Aboul-Yazid A, Emam M, Shaaban S, El-Nashar M. EFFECT OF SPOKES STRUCTURES ON CHARACTERISTICS PERFORMANCE OF NON-PNEUMATIC TIRES. International Journal of Automotive & Mechanical Engineering. 2015;11.

[4] Pramono AS, Effendi MK. Optimization in airless tires design using backpropagation neural network (BPNN) and genetic algorithm (GA) ap-

proaches. In: AIP Conference Proceedings. vol. 2187. AIP Publishing LLC; 2019. p. 050001.

[5] Pewekar MM, Gaikwad SD. Strength Validation of Hexagonal Cellular Spoked Non-Pneumatic Tires for Automobiles through Finite Element Analysis. International Journal of Scientific Research in Science and Technology (IJSRST). 2018;4(5):1044–1055.

[6] Sriwijaya R, Hamzah R. The effect of surface contact on the pressure distribution and deflection of airless tires. In: AIP Conference Proceedings. vol. 2187. AIP Publishing LLC; 2019. p. 050021.

[7] Meng F, Lu D, Yu J. Flexible Cellular Structures of a Non-Pneumatic Tire. In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. vol. 50152. American Society of Mechanical Engineers; 2016. p. V05AT07A005.

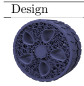
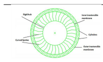
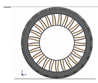
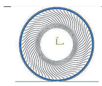
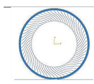
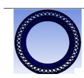
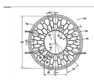
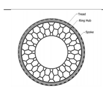
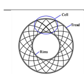
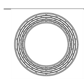
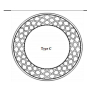
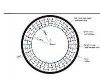
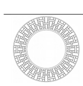
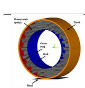
[8] Kim K, Ju J, Kim DM. Static contact behaviors of a non-pneumatic tire with hexagonal lattice spokes. SAE International Journal of Passenger Cars-Mechanical Systems. 2013;6(2013-01-9117):1518–1527.

[9] Lee C, Ju J, Kim DM. The dynamic properties of a non-pneumatic tire with flexible auxetic honeycomb spokes. In: ASME International Mechanical Engineering Congress and Exposition. vol. 45240. American Society of Mechanical Engineers; 2012. p. 605–615.

[10] Wu T, Li M, Zhu X, Lu X. Research on non-pneumatic tire with gradient anti-tetrachiral structures. Mechanics of Advanced Materials and Structures. 2020:1–9.

[11] Ganniari-Papageorgiou E, Chatzistergos P, Wang X. The Influence of the Honeycomb Design Parameters on the Mechanical Behavior of Non-Pneumatic Tires. International journal of applied mechanics. 2020;12(03):2050024.

Table 1: Comparison of structures applied to airless tires in the state of art

Design	Structure	Properties	Deliverables	Reference
	Voronoi	The process of constructing artificial bone with porous gradient structures Porous scaffolds with gradient distribution of porosity	The highest deformation of nodes occurs at edges of contact with the surface based on the gradient deformation Density is defined by the area of material need when suffering a stress deformation Variable radios of the Voronoi cell provide mechanical resistance to energy distribution Strong cell structure CAD controls the stress relief via simulation of material needs	This work
	Segmented Cylinder	Shear band of segmented cylinders Spring steel to form the inner and outer membranes Curved spokes	Spokes show deformation in the lower part Spokes are highly tensioned in the upper part When rolling, the cylinders are in contact with the ground When rolling at a lower speed, the tire shows more deformation at shocking with an obstacle	[1]
	Radial lines	25 pairs of spokes connected to an inner and outer ring made of PU Michelin Tweel Model	The deformation of the vertical spokes occurs in the lower part Under the load of 20kN, the elastic geometry suffers higher stress in the middle of the bottom spokes. As the load increases, the area of contact with the ground becomes deformed, which causes the tire to flat The distance between the inner and outer ring, which its normal value is 133mm, decreases to 118 mm at a vertical load of 20kN	[2]
	Curved radial lines	The spokes have a special curvature This enables them to: Flex effectively without twisting while providing the strength of pneumatic tires	The tire showed: A low vertical stiffness of 79.76 N/mm under a load of 3000 N A high value of deflection of 37.61 mm	[3]
	Curved radial lines	This model has a different hub diameter, which generates a different curve The purpose of the spokes is to have low stiffness PU spokes	At a vertical load of 3000N, the tire showed: A vertical stiffness of 158.7 N/mm A deflection of 18.9 mm	[3]
	Rhombic	Spoke thickness of 4 mm The rhombic angle of 107.778° Polyurethane L100 Tire Width of 135 mm Outside diameter of 798.6 mm	At a pressure of 30 psi: The tire showed a deflection of 5.824 mm The tire showed a total stress of 9.287 Mpa	[4]
	Hexagonal	Wall thickness of 5 mm Tire width equal to 172 mm Hexagonal unit cells	Under a load of 4500 N, the structure shows a deflection of 16.1 mm Under a load of 1400 N, the tire presents a lateral deflection of 62.476 mm The tire has excellent torsional stiffness but low lateral stiffness	[5]
	Hexagonal	Hexagonal unit cells	Von Mises stress rise when the angle of surface inclination grows Fatigue is less probable to occur when the tire is exposed to low angle inclination surfaces If the thickness of the spoke increases, a better distribution of Von mises stress is obtained	[6]
	Cross section	Tread thickness of 1.2 mm 30 cell structure	Large tread thickness Low radial deformation Strong cell structure.	[7]
	Rectangle	15 cell structure Tread thickness of 0.8 mm	Not able to be under large loads Large radial deformation Low radial stiffness	[7]
	Hexagonal	Inner ring radius 177.4 mm Outer ring radius 277mm Lattice spokes and shear band made of PU Cell angle of 45°	The maximum value of deflection is 25.77 mm at a vertical force of 4000N Von Mises stress of 5.97 Mpa Uniform distribution of stress Strong spokes with minimum probability to collapse Great performance of flexibility	[8]
	Auxetic honeycomb	Inner diameter of 262 mm Outer diameter of 272 mm PU spokes Synthetic rubber tread 30° spoke	Under a load of 3000 N, a vertical displacement of 16 mm occurs, just like a traditional pneumatic At a speed of 60 km/h, a deflection of 22.3 mm is appreciated At a speed of 80m/h, a vertical deflection of 22.4 mm occurs.	[9]
	Anti tetrachiral auxetic	The diameter of the tire is 205 mm The diameter of the spokes is 18 inches 36 rows of gradient anti-tetrarchical structures in the radial direction	When displacement had reached 15 mm, the layer began to converge 20 mm was the limit of displacement under a load of 250 kN	[10]
	Hexagonañ	Cell Width of 36.66 mm Cell length of 26.25 mm Cell thickness of 3.20 mm Cell angle of 15.76° The cell density of 20 The outer diameter of 430.8 mm	Vertical displacement of 27.66 mm at a load of 3000 N General Von Misses Stress of 415 Mpa Increase of cell length or/and cell density decreases Von Mises stress	[11]