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Investigation on the characteristics of a Non-Pneumatic tire with different spoke shapes

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Abstract
Non-pneumatic tires have gained significant popularity as a result of their distinct qualities and advantages over pneumatic tires. In this paper, based on ABAQUS commercial software, four different spoke structures have been introduced and investigated under static loading. Two of which are honeycomb structures that have been thoroughly researched in literature, and the two others are compared to them and a pneumatic tire as well. To identify the best model, Three different design parameters of NPTs have been studied: vertical stiffness, local stress in spokes, and mass of the model. It is found that the load-carrying capacity of the NPT models presented in this paper is higher than the PT. The hexagonal honeycomb model with 48 units had an average vertical stiffness of 26.6 percent higher than the pneumatic tire, while the NPT-A1 model had an average vertical stiffness of 21.7 percent higher. However, the former had a relatively higher mass. Having outperformed the pneumatic tires in terms of vertical stiffness, NPTs can be considered a potential replacement to pneumatic tires.

Keywords: Non-pneumatic tire, Honeycomb spokes, Vertical stiffness, Abaqus

Introduction

Tires play a critical role in the overall interaction between a vehicle and the ground, as well as the car's general stability. Pneumatic tires have been widely used in the automobile industry for over a century thanks to their unique characteristics, including low mass, vertical stiffness, and contact pressure [1]. However, there are a considerable number of downsides to pneumatic tires, specifically, being prone to puncture, frequent maintenance of air pressure, and a sophisticated manufacturing process. Due to the disadvantages mentioned above, a new form of tire known as non-pneumatic tires was developed, in which a spoke replaces the air pressure in conventional tires [2]. These types of tires include a number of flexible spokes, a rigid hub, a shear band layer with two reinforcements, and a tread. The shear band layer is sandwiched between the inner and outer ring, which are the reinforcements. The material used for reinforcements in this study and the literature is mainly high-strength steel. The shear band and the spokes are made of polyurethane, and the tread is made of synthetic rubber, both of which are modeled as hyperelastic material.

NPTs have received a lot of attention in recent years, and numerous researchers have worked to improve their performance by designing different structures for spokes and optimizing them. Designing an NPT is commonly done regarding its essential characteristics: vertical stiffness, mass, contact pressure. Rolling resistance is also an important factor for dynamic studies as it contributes to vehicle fuel consumption [3]. Honeycomb structures are among the most common structures used for spokes of an NPT thanks to their high out-of-plane stiffness to weight ratio, lightweight, good impact resistance and They are also utilized in automobile and aeroscope industries as well as military equipment [4, 5, 6]

In NPTs, the in-plane type of honeycomb is usually used. Changing the angle and thickness of the honeycomb cells was shown in several studies to have an impact on the overall model's performance [7].

The NPT's spokes are subjected to cyclic tension-compression loads, requiring a combination of resilience and stiffness to work well. Many studies have looked into the structural design and optimization of NPTs; for instance, Jin et al. [8] investigated the static and dynamic behavior of NPTs with three different honeycombs spoke structures and found that with the same wall thickness or the same reference load carrying capacity, maximum stress in the tread and spokes is much lower compared to conventional pneumatic tires. Kim et al. [9] studied the static contact behaviors of an NPT with hexagonal honeycomb spokes as a function of vertical loading and provided an optimal shape for spokes by comparison to a pneumatic tire. Ju et al. [10] investigated six hexagonal honeycomb spokes with varying cell angles and geometrical configurations. It was found that under uni-axial loading, those configurations with a highly positive cell angle have low local stresses as well as low mass. Zang et al. [11] proposed a design method for honeycomb structures based on the tangent method and evaluated six different hexagonal and circular honeycomb structures with varied densities.

The literature for spoke designs is not limited to honeycombs. Sim et al. [12] investigated the vertical stiffness characteristics of an NPT with a model provided by the manufacturer (Kumho Tire Co., Inc., Gwangju, Korea), and three variants of it were analyzed and compared.

There are also some studies conducted for dynamic analysis of NPTs, among which Zhang et al. [13] performed a comparative analysis of the static and dynamic performance of NPTs with three different finite element models and then compared the results to a pneumatic tire. Abdoul-Yazid et al. [14] examined a quasi-static 2D analysis of three different configurations of Michelin's Tweel, Resilient Technologies, and Bridgestone NPTs and found that the geometry of the spokes has a significant effect on the tire's behavior.

In this work, a finite element model for NPT is presented. Using ABAQUS/Standard, the static analysis and comparison between four different structures for spoke of the NPT are carried out, and key characteristics of an NPT, including vertical stiffness, mass, and contact pressure, are compared and studied. The objective of changing the spoke structures is to evaluate the value of design variables in order to improve the performance of the NPT.

Methodology

Geometric properties of the NPT

A 3D FE model is created using ABAQUS commercial software. This model comprises a tread, a shear band layer sandwiched between two reinforcements (inner ring and outer ring), lattice spokes, and a hub. The tread, shear band, and hub have inner diameters of 654, 635, and 432 mm, respectively. Figure 1. shows four different spoke structures that are used in this study. The corresponding thickness of the tread, reinforcement rings, shear band, and hub are 5, 0.5, 9, and 1 mm, respectively. The thickness of spokes in all cases is set to 5 mm. The width of the model is set to be 215 mm.

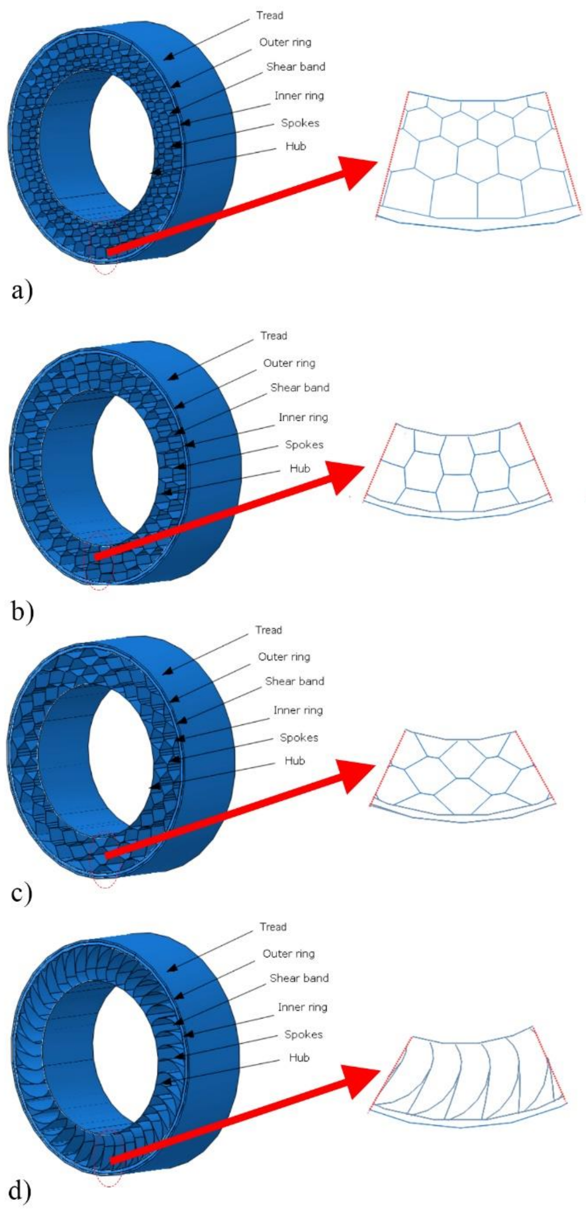

Figure 1. 3d FE models and their geometry: a) hexagonal honeycomb with 48 units, b) NPT-A1 c) NPT-C1, and d) Spoke pair model

The first structure, which is a hexagonal honeycomb with 48 units, is plotted by drawing concentric circles as guides for honeycomb walls so that they get smaller and smaller as we go toward the center of the tire. For this case, another model with 36 units was also studied, but the model with 48 units outperformed the other and therefore was chosen for the first structure. The second and third structures have been studied before by multiple researchers in the literature, including Jin et al. [8] and Ju et al. [10], but here they are used with a shear band layer, and a three-dimensional model is employed. These two structures were concluded as having the highest load-carrying capacity.

The fourth structure, which is a spoke pair model, is a modified version of the manufacturer (Kumho Tire Co., Inc) that is a non-honeycomb structure.

Material characteristics of the NPT

Shear band and the lattice spokes are both made up of polyurethane. The tread, which is the part that comes in contact with the ground surface, is made of synthetic rubber. Both of these materials are modeled as Ogden hyperelastic in ABAQUS. The corresponding strain energy functions and their coefficient used for modeling are presented in Equation (1) and Table (1).

$$W(\lambda_1, \lambda_2, \lambda_3)^n = \sum_{i=0}^{N} \frac{\mu_i}{\alpha_i} (\lambda_1{}^{\alpha_i} + \lambda_2{}^{\alpha_i} + \lambda_3{}^{\alpha_i} - 3) \quad (1)$$

Table 1. Polyurethane and Rubber hyperelastic Ogden strain energy function coefficients

	Polyurethane		Rubber	
i	$\mu_i(MPa)$	α_i	$\mu_i(MPa)$	α_i
1	13.546	1.513	13.356	1.633
2	-2.338	2.212	-6.631	1.9
3	0.093	-2.471	0.058	-2.456

Aluminum-alloy (Al 7075-T6; E=72 GPa, v = 0.33) is chosen for the hub. For two reinforcements, high strength steel (ANSI 4340; E=210 GPa, v = 0.29) is used.

Finite element simulation

Quad shell reduced integration (S4R in ABAQUS) elements are chosen for reinforcement rings, hub, and spokes. An 8-node 3D stress hybrid reduced integration element (C3D8RH in ABAQUS) is chosen for shear band and tread. The ground surface also has been meshed with R3D4 elements. A fully meshed model of an NPT with 48 hexagonal honeycomb units used for spokes is illustrated in figure 2.

For the contact properties between the tread and the ground surface, a tangential and normal behavior is defined, and for it, the friction coefficient was set to be 0.7 by using the penalty function formula. A surface-to-surface contact interaction is assigned between the outer surface of the tread and the ground surface. The ground surface was set to be a rigid part.

To apply the vertical load to the NPT, it is required to define a reference point at the center of the hub and then couple it to the inner surface of the hub by using a rigid kinematic coupling constraint. Tread, shear band, two reinforcement rings, spokes, and hub are all tied to each other with a tie constraint. While assigning the tie constraint, defining a master and a slave surface is needed. In this study, the surface with a bigger radius is always chosen to be the master surface, and the other is the slave.

Four different static loading of 1000, 2000, 3000, and 4000 N is applied at the tire's hub axle, which is a quarter of the typical car weight, which usually ranges from 400 to 1600 kg. Boundary conditions are applied at the hub axle to stop the model from rolling and allow only vertical movement at the center of the hub.

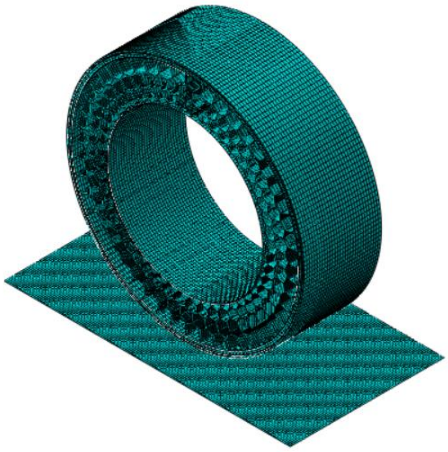

Figure 2. Meshed hexagonal NPT model with 48 units

Results and Discussions

Mesh independence study

For numerical analysis, especially those done by the finite element method, a mesh independence study seems essential. Figure 3 shows the mesh study done to verify the optimum mesh. Based on this study, A global seed size of 5mm seems to be optimum and is considered for the other analysis

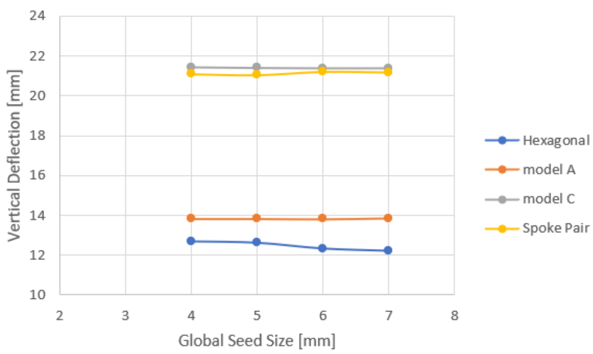

Figure 3. Mesh study under a vertical load of 3000 N

Effect of changing the spoke structure on the deflection of the tire and maximum

Under a load ranging from 1000 to 4000 N, the deflection and vertical stiffness of the tires are studied in this section. The deformed shape of the spokes under a vertical load of 4000 N is illustrated in figure 4.

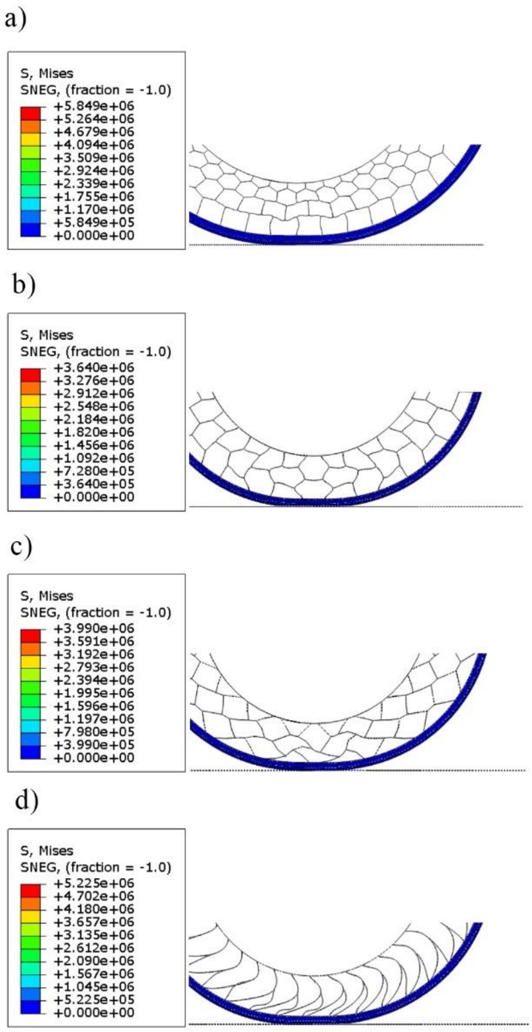

Figure 4. deformed shape of spoke structures and local stress in spokes [pa] under a vertical load of 4000 N: a) hexagonal honeycomb with 48 units, b) NPT-A1, c) NPT-C41, d) Spoke pair model

A comparison between the conventional pneumatic tire and the non-pneumatic tires that are presented in this study has been made and illustrated in figure 5. This figure shows that the hexagonal honeycomb model and NPT-A1 model outperformed the pneumatic tire in terms of having less vertical deflection and higher vertical stiffness.

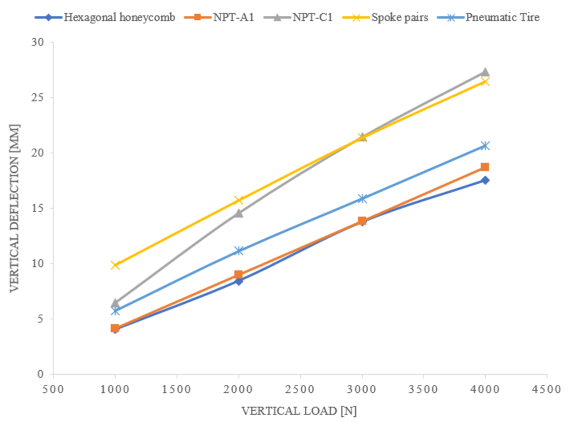

Figure 5. Comparison of tire bearing capacity between NPTs and deflections of a pneumatic tire [9]

Effect of changing the spoke structure on vertical stiffness and contact pressure

Vertical stiffness is an important factor in designing NPTs and is computed by Eq (2).

$$K = \frac{F}{\delta} \tag{2}$$

Where F is the vertical load applied at the center of the hub and δ is the deflection of the hub in the vertical direction. As shown in figure 6, It's clear that in two structures, namely, hexagonal honeycomb and NPT-A1 the vertical stiffness is higher than the values of a pneumatic tire with the same size, which is investigated by Kim et al. [9]. The vertical stiffness in these two structures is higher by an average of 26.6% in hexagonal honeycomb, and in the case of NPT-A1, it is higher by an average of 21.7% compared to the pneumatic tire. A closer look makes it clear that the vertical stiffness of pneumatic tires grows with an increase in vertical loading, which is not the case in NPT models presented.

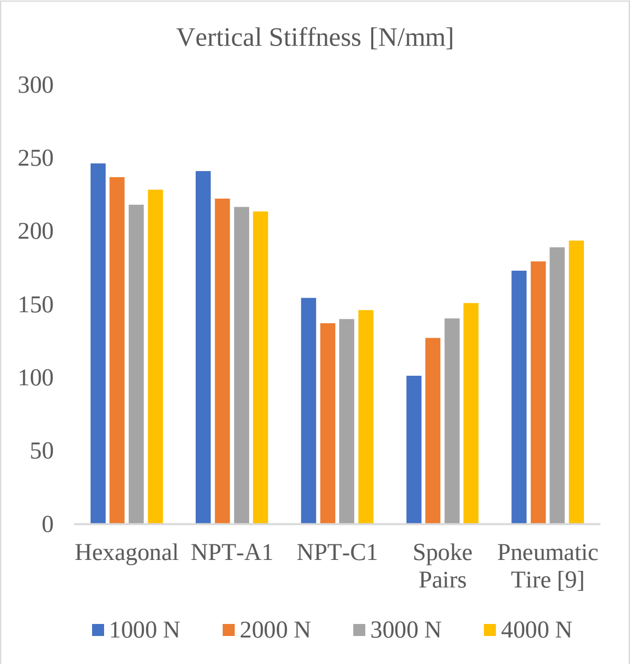

Figure 6. Vertical stiffness under different loadings of NPTs compared to a pneumatic tire

Comparing the mass of NPTs

By comparing the masses of NPT models, we find out that the mass of the hexagonal honeycomb model is the highest of the presented model. On the flip side, NPT-A1 has the lowest mass, and therefore, considering its relatively high vertical stiffness characteristics, it can be assumed the best-presented model. Figure 7 illustrates the masses of models.

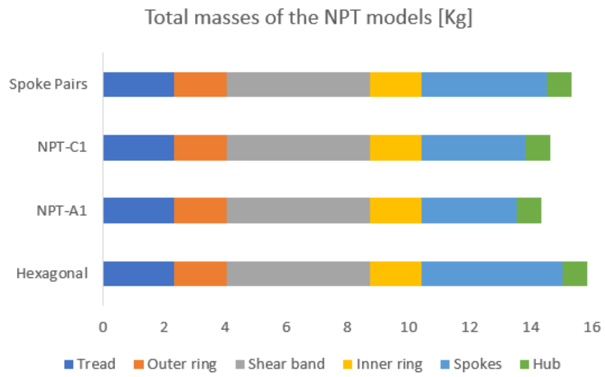

Figure 7. Comparing the mass of NPTs

Conclusions

Four three-dimensional finite element model of NPTs with varying spoke structure is presented in this study based on ABAQUS commercial software. A hexagonal honeycomb with 48 units, two typical honeycomb structures with different angles, which have been extensively studied in the literature, and a spoke pair model, which is a modified version of what is used in industry, are among the four models. The following are the key takeaways:

1. The spoke structure has a significant effect on the critical characteristics of an NPT. Among all the four presented models, the Hexagonal honeycomb model with 48 units and NPT-A1 showed promising results with an average of 26.6% and 21.7% higher vertical stiffness than a conventional pneumatic tire.
2. Among all the models, NPT-A1 has the lowest local stress in spokes, while the Hexagonal honeycomb structure has the highest local stress, which is explainable given its high density. The spoke pair model also has relatively sizeable local stress, which is due to its cell congestion.
3. Considering all of the related factors, it can be concluded that despite having a lower average vertical stiffness than the hexagonal honeycomb model, the NPT-A1 model is the optimal structure given its lower local stress and lower mass.

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