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Analysis of Mechanical Characteristics of Non-Pneumatic Tyres

A. M. G. Binuri SENADHI[a], Bodhita BHATTACHARJEE[b,1], VIPIN[c]

[a,b,c]*Department of Mechanical Engineering, Delhi Technological University, Delhi, India*

Abstract. This research paper provides an analysis for the deformation and vertical stiffness of non-pneumatic tyres (NPT) due to different vertical loads. The non-pneumatic tyres are developed for replacing traditional pneumatic tyres. These tyres do not use air to support the load and subjected to hard conditions and rough terrain. The non-pneumatic tyres are used for heavy load-carrying capacity, vertical stiffness, contact pressure, and rolling. The mechanical characteristics of NPT are studied by using a 3D modelling software - Fusion 360 and analysed by using Finite Element Analysis (FEA) on the simulation software - Ansys.

Keywords. Non-pneumatic tyres, vertical stiffness, deformation.

1. Introduction

The tyres are an essential element of automobiles. However, the standard pneumatic tyres have various drawbacks since they risk severe damage or flatting if the tyre traverses diverse obstructions. The NPT was developed to show the required features of the conventional tyres without the need of inflation pressure. It can be designed to have desired contact pressure, vertical stiffness and flank stiffness on the overall geometry and material without any limitations to their size and pressure, affecting riding comfort. Non-pneumatic tyres, also called Tweel, have a robust internal centre point connected to the shaft of the vehicle that is encompassed by polyurethane spokes. The non-pneumatic tires guarantee overall performance better than that feasible with traditional pneumatic technology because of their shear band configuration, brought suspension and reduced moving obstruction. The ride comfort and load conveying limit offered by it is close to that of pneumatic tyres and because of the absence of pressurized air cavity it cannot be penetrated.

Jin et al. [1] have investigated the static and dynamic behaviours of the honeycomb spoked NPT by varying the reference load carrying capacity or the wall thickness of the honeycomb. The study showed that the stress level of an NPT is higher under dynamic load than that of static loading but is still lower than that of a conventional tyre. They suggest adopting a smaller cell expanding angle and wall thickness for an optimal NPT. Hu et al. [2], have proposed a tyre model to determine vertical mechanical properties of a tyre. Study shows the variation of vertical stiffness of a tyre from loading to unloading which results hysteresis loss. Rugsaj and Suvanjumrat [3] tested the mechanical properties of NPTs by employing experimental tests in the laboratory. They compare the vertical stiffness of the NPT to that of conventional tyres using the same size and appropriate inflation pressure. Prabhuram et al. [4] compared three dissimilar NPTs with a conventional tyre in mechanical properties. Results show that NPTs characteristics surpass the ones of conventional tyres. They suggest 3D printing for manufacturing composite tyres for commercial purposes. Jafferson et al. [5], have proposed unique designs to use in NPTs. The paper compares different lattice structures in terms of weight, material cost and performance and suggest 3D printing to manufacture NPTs as well as conventional tyres. Patel et al. [6], have used integration of geometry to analyze the deformation of complex geometries including NPTs and conventional tyres. Study showed the need of a new Absolute Nodal Coordinate Formulation for modeling such complex structures. Gasmi et al. [7] have developed a quasi-static, two-dimensional analytical model to study a rigid and frictionless NPT. The mathematical model was created by varying bending stiffness, circumferential stiffness, radial load and circumferential load and validated by experimental results of vertical stiffness, rolling resistance of an NPT. In their paper model, Sanjeev et al. [8], NPTs with common elastic materials in track and polyester in place of nylon for the body. A comparison was made amidst different spoke designs with varied materials and that resulted the tire with a rounder structure showed less twisting than other structures. Mohan et al. [9] have created three different CAD models of hexagonal honeycomb structured NPT, keeping the cell angle and the ratio of inclined length to cell height as critical factors. They conducted simulations and concluded that the NPT with a giant cell-sized honeycomb spoke exhibited maximum deflection, minimum stress concentration, and minimum contact pressure under static conditions. Sim et al. [10] investigated the variation of the vertical stiffness property of an NPT with the shape of the spoke. Results showed that the vertical stiffness of the fillet applied model was the most appropriate. Zang et al. [11] adopted a porous rhombus structure to investigate the mechanical characteristics of an NPT under compounded pavement surrounding. Obstacles were used to emulate the pavement conditions, and the height has been varied throughout the study. Numerical analysis showed that the obstacle's height is inversely proportional to the maximum stress on NPT and satisfied with the analytical results.

Moving towards the material, Mgbemena et al. [12] designed and analysed a conventional P195/55 R16 85H tyre model and designated the factors defining rubber vulcanizates' linear isotropic elastic behaviour. The results showed that the tyre material produced from Natural Rubber/Organomodified kaolin functions appreciably under static structural analysis. Shashavali et al. [13], designed and analyzed a airless tyre to be used in a four-wheeler. After analyzing many thermal, static and structural properties, study choose Nylon 4-6 over Nitrile Rubber as the preferable material from the manufacturing point of view. Ludvigsen et al. [14], have carried out a Multiphysics analysis on airless tyres to compare the pressure profile with conventional tyres. The study showed NPTs have a more evenly distributed pressure profile compared that of a conventional tyre. Evenly distributed yet concentrated pressure increase the grip which reduces the chances of sliding over snow in low temperatures. The Paper concludes by proving NPTs are more suitable to use in winters. Samarini et al. [15], show how NPT’s unique properties are used in autonomous planetary rovers. A numerical study is used to describe wheel’s complex geometry with deformations and to compare kinematics and tractive forces. Mazur and Rykov [16] discussed the ability of polyurethane made airless tyres to self-purify. The experiment has carried out full-scale models to test the ability of flexible spokes to remove dirt during rolling. The experiment showed that the degree of purification from wet clay and snow was 90-95% and 80-85%, respectively. It testified that flexible spokes are not a limiting factor to use airless tyres on heavy load vehicles.

This paper aims to study the mechanical characteristics of a NPT, also known as airless tyre using FEA. The first commercial NPT Tweel introduced by Michelin was examined using a vertical tyre and drum testing machines.

2. Methodology

Non-pneumatic tyres, also called Tweel, are a mix between of a tire and haggle and do not have any regular wheel centre gathering. TWEEL, invented by Michelin, consists of two main segments, (a) circular shear beam and tread and (b) elastic spokes attached to a hub. Transmission of energy within the poly-resin spokes helps decrease the "bounce" produced by pneumatic tires while delivering good handling properties. They are developed to behave and perform like pneumatic tires, without causing downtime and inconvenience by getting flat tires. In this paper the mechanical characteristics of an NPT Tweel tyre was studied using FEA.

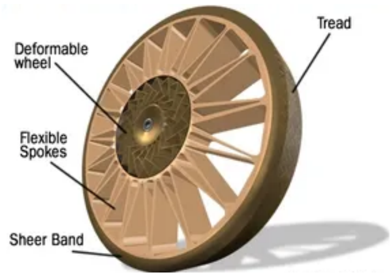


Figure 1. NPT Tweel.

Three-dimensional modelling software – Fusion 360 was used to model the commercial NPT Tweel 12N16.5 (overall diameter 33.1", section width 12.1") ALL TERRAIN airless radial tyre designed by Michelin.

Low alloy aluminium was used as the inner hub material, the mechanical properties are shown in Table 1. Polyurethane was applied as the spoke material, the mechanical properties of which are shown in Table 1.

Table 1. Mechanical properties of materials used.

Property	Low alloy aluminium values	Polyurethane values
Density (kg/m^3)	2770	1210
Elastic modulus (MPa)	71000	35
Poisson's ratio	0.33	0.48
Yield strength (MPa)	280	145
Shear modulus (MPa)	2669	11.8

Figure 2. 3D model of NPT Tweel 12N16.5.

3. Analysis

Proper mesh and geometry settings are essential for accurate finite element analysis. In addition, the results may differ significantly based on boundary conditions. Therefore, setting the correct boundary conditions is critical. A remote force was applied on the surface of the tyre to represent the vertical load of the vehicle. A rotational velocity was given to the tyre and the central hub was made rigid. Vertical load was varied at 4 kN to 32 kN at an increment of 2 kN, while the velocity was kept at 11 km/h to determine the deformation at different loading conditions. These results were then used to calculate the vertical stiffness of the NPT by taking an average of the obtained values. Then a suitable mesh was generated for obtaining the results.

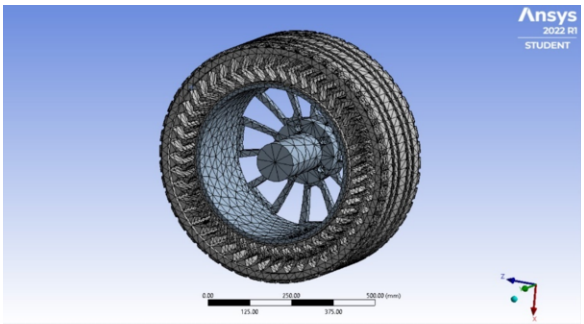
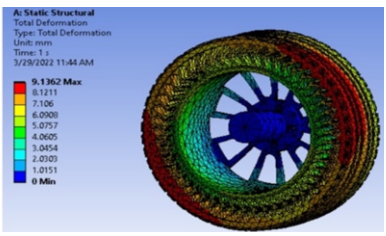


Figure 3. 3D model of NPT Tweel 12N16.5 with meshing.

4. Results And Discussions

The following results were obtained from the analysis as -

1. The FEM results of total deformation were obtained at the constant speed of 11 km/hr by varying the vertical load from 4 kN to 32 kN at the increment of 2 kN.



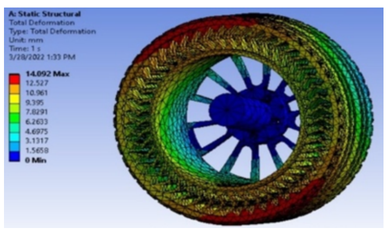
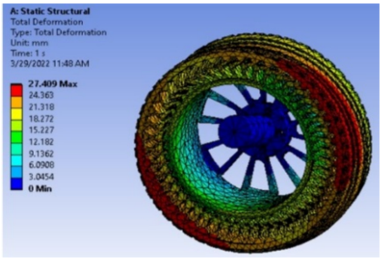


Figure 4. Deformation for 8 kN load. **Figure 5.** Deformation for 16 kN load.



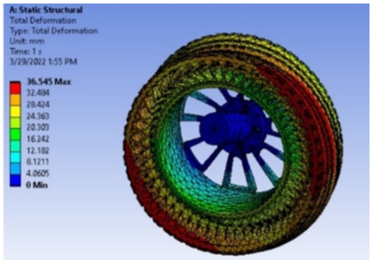


Figure 6. Deformation for 24 kN load. **Figure 7.** Deformation for 32 kN load.

From the obtained simulations it is evident that the tyre experiences the maximum amount of deformation on the upper and lower part of the tyre which were in direct contact with the vertical load and the ground, respectively. It can also be observed that the part of the entire structure which experiences the least amount of deformation is the central hub as well as the inner part of the spokes.

2. Deformation results of FEM analysis –

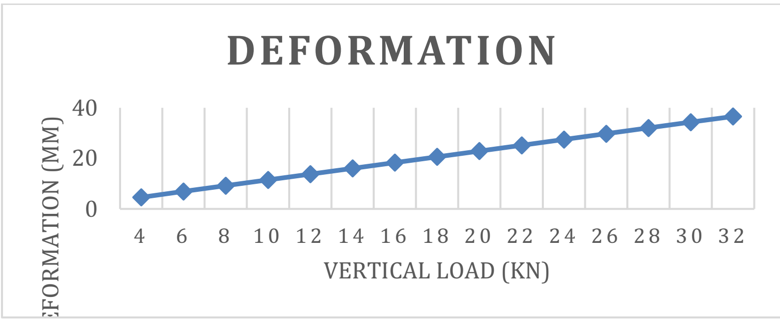


Figure 8. Variation of Deformation with vertical load.

By visualising the deformation vs vertical load graph (Fig 8.) we can see that deformation is linearly dependent with positive slope upon the vertical load applied to the NPT. The graph also confirms that deformation suffered by the non-pneumatic tyre is directly proportional to the vertical load experienced by it.

3. Stiffness results of FEM analysis -

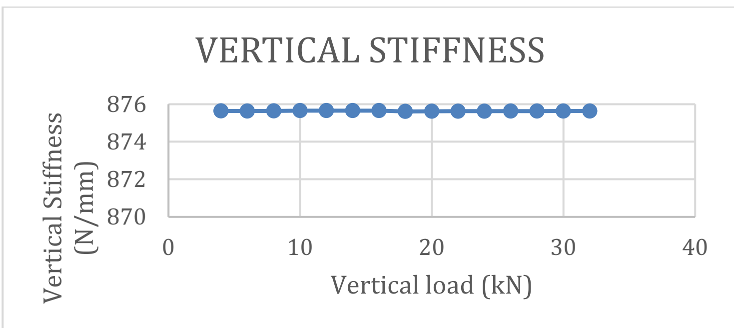


Figure 9. Variation of Vertical stiffness with vertical load.

The vertical stiffness of the tyre is dependent on the vertical load applied and the displacement it suffers because of it. Thus, when vertical load is applied on a conventional tyre, it can cause the stiffness of the tyre to change, which in turn can affect the overall performance of the tyre. We have analysed the behaviour of non-pneumatic tyres for the same in our research paper. By visualising the vertical stiffness vs vertical load graph (Figure 9.) we can see that vertical stiffness is linearly dependent with zero slope upon the vertical load applied to the NPT. The graph also confirms that vertical stiffness suffered by the non-pneumatic tyre is independent of the vertical load experienced by it. The value of vertical stiffness as obtained from the graph is 875.635 N/mm which is in accordance with the experiment performed by Rugsaj and Suvanjumrat (2020) [3] in their paper.

5. Conclusion

Following conclusions were drawn by the analysis,

1. FEA simulations using Ansys were employed to study the mechanical characteristics of non-pneumatic tyres.
2. A linear variation of deformation from 4.57 mm to 36.55 mm with vertical load was observed when the vertical load was varied from 4kN to 32kN at an increment of 2kN.
3. Average vertical stiffness was achieved at 875.635 N/mm based on the values of deformation for different vertical loads.

6. References

[1] Jin X, Hou C, Fan X, Sun Y, Lv J, Lu C. Investigation on the static and dynamic behaviors of non-pneumatic tires with honeycomb spokes. Composite Structures. 2018;187:27–35.
[2] Hu H, Yang Y, Gu Z, Song L, Ma X, Zhang S. Study on vertical mechanical properties of tyre based on hysteresis–rolling characteristics. Vehicle System Dynamics. 2021;1–20.
[3] Rugsaj R, Suvanjumrat C. Mechanical characteristics of airless tyre by laboratory testing. IOP Conference Series: Materials Science and Engineering. 2020;773(1):012037.
[4] Prabhuram T, Sundaram SC, Jegadeeswer S, Kannan VS. Static analysis of different spoke structure of airless and conventional Tyre. IOP Conference Series: Materials Science and Engineering. 2020;923(1):012017.
[5] Jafferson JM, Sharma H. Design of 3D printable airless tyres using ntopology. Materials Today: Proceedings. 2021;46:1147–60.
[6] Patel MD, Pappalardo CM, Wang G, Shabana AA. Integration of geometry and small and large deformation analysis for vehicle modelling: Chassis, and airless and pneumatic tyre flexibility. International Journal of Vehicle Performance. 2018Dec19;5(1):90–127.
[7] Gasmi A, Joseph PF, Rhyne TB, Cron SM. Development of a two-dimensional model of a compliant non-pneumatic tire. International Journal of Solids and Structures. 2012;49(13):1723–40.
[8] Sanjeev kumar R, Vetrivel kumar K, Ramakrishnan T. Design optimization of Airless Tyre - Numerical Approach. IOP Conference Series: Materials Science and Engineering. 2021 Feb 1;1057(1):012032.
[9] Mohan A, Johny CA, Tamilarasu A, Bhasker JP, Ravi K. Design and analysis of non-pneumatic tyre. IOP Conference Series: Materials Science and Engineering. 2017 Nov;263:062061.
[10] Sim J, Hong J, Cho I, Lee J. Analysis of Vertical Stiffness Characteristics Based on Spoke Shape of Non-Pneumatic Tire. Applied Sciences. 2021 Mar 7;11(5):2369.
[11] Zang L, Wang X, Chen Y, Li Y, Jin H, Yang G. Investigation on mechanical characteristics of non-pneumatic tire with rhombus structure under complex pavement conditions. Simulation Modelling Practice and Theory. 2022;116:102494.
[12] Mgbemena CO, Boye TGE, Emovon I. Static analysis of a tire sidewall developed from tailored organomodified kaolin/natural Rubber Vulcanizates. Journal of Advanced Engineering and Computation. 2017;1(2):106.
[13] Shashavali S, Reddy CR, Yadiki GK. Design and Analysis of Four Wheeler Airless Tire. International Journal of Advanced Technology and Innovative Research. 2016 Dec;08(22):4298–305.

[14] Ludvigsen S, Andleeb Z, Khawaja H, Moatamedi M, Alzahabi B. Multiphysics Analysis of Contact Pressure Profile of Airless tires as compared to Conventional Tires. IJM. 2020Nov.15;14(4):399-425.
[15] Samarini E, Shabana AA, Grossi E, Somà A. Integration of geometry and analysis for the study of continuum-based airless tyres of planetary wheeled robots. International Journal of Vehicle Performance. 2020;6(4):446.
[16] Mazur VV, Rykov SP. The Ability of Airless Tires to Self-Purify. IOP Conference Series: Earth and Environmental Science. 2021 Mar 1;666(4):042012.