The Effect of Bank Angle on the Pressure Distribution and Deflection of Non-pneumatic Tires

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Abstract. A certain amount of road angle is necessary to reduce the risk of run-off-road and head-on crashes. Following the rapid development of non-pneumatic tires (NPT) in the past years, pressure distribution and deflection analysis of NPT while operating on flat and inclined road angles are analyzed using the Finite Element Method. The results showed that a higher stress concentration of spokes is evident at an elevated bank angle. Simultaneously, a more significant load combined with bank angle increment resulted in a higher displacement magnitude. This study aims to enable the designer to create an NPT design that could adapt to different bank angles.

1. Introduction

Pneumatic tires are currently the most popular type of tires available in the market. The fact that they can withstand contact pressure and provide buffering function due to internal inflation pressure supplied by air serves as the primary reason for its popularity. However, the dependence on air means that this type of tire requires air pressure maintenance and is susceptible to puncture. The disadvantages lead to the development of non-pneumatic tires (NPT), a single unit comprised of a rigid hub, deformable polyurethane spokes, and a tread band, by several tire manufacturers worldwide.

Figure 1. Vehicle operation under certain road bank angle.

Several works have been carried out to explore different aspects of NPT. Sassi et al. [1] examined the design aspects of NPT and imply that good radial stiffness can be achieved by introducing cuts in tire design. Another research conducted by Aboul-Yazid et al. and Mohan et al. [2][3] analyzed rolling resistance, contact pressure, von Mises stresses, and mass value aspects to determine the characteristics performance of 4 different spokes structures. Zmuda et al. [4] developed a numerical model of NPT and was further validated by experiments. More specific research on NPT’s spokes was conducted by Ju et al. [5] and Mathew et al. [6] by varying honeycomb spokes design and introducing diamond structure. However, since tire cells dynamically engage with the road surface, it is crucial to consider the stress distribution and deflection of NPT. Two previous research in this area has been published by Sriwijaya...
and Hamzah. The former [7] suggests that tension deviation occurs in NPT, especially when applied in high velocity, while the latter [8] [9] concludes that road inclination angle increment will be followed by increases in pressure distribution, deflection, and the tendency of spoke failure. Road bank angle, a phenomenon where the outer edges of curved are raised above the inner edge to provide sufficient centripetal force as shown in figure 1, is commonly applied in highway construction so vehicles can make a safe turn. An extreme case of road bank angle utilization can be seen on velodrome construction. By considering road topography, this research aimed to better understand NPT’s pressure distribution and deflection under three different bank angles. Finite Element Analysis (FEA) using Abaqus® software is chosen to evaluate the environment due to its effective yet inexpensive method.

2. Modeling

2.1. Non-pneumatic tires
A 3D model of NPT made by Sriwijaya and Hamzah (figure 2) is referred for this research. The design utilizes honeycomb structures and consists of 3 layers. The inner and outer ring are made of polyurethane (PU) and connected by honeycomb spokes, while high-strength steel (HSS) is selected for ring hub material. Treads are attached to the outer rubber layer. Relevant properties of each material are provided in table 1.

2.2. Road topography
This paper analyzes three different bank angles (0°, 1.8°, and 2.7°) in this paper to simulate practical applications. Illustrations of the tire under each bank angle are provided in figure 3.

3. Finite element analysis
The NPT model is imported to FEA software. Abaqus®/ CAE 6.11 software is chosen to carry out the structural analysis. The numerical research was conducted for five load conditions: 1, 2, 3, 4, and 5 kN. Bank angles were also varied at 0°, 1.8°, and 2.7° during the simulation.
**Table 1.** Material properties of HSS, PU, and rubber.

| Properties                | AISI 4340 Steel | PU       | Rubber   |
|---------------------------|-----------------|----------|----------|
| Density (kg/m³)           | 7,800.00        | 1,200.00 | 1,150.00 |
| Young’s Modulus (GPa)     | 210.00          | 32.00    | 11.90    |
| Yield Stress (Mpa)        | 1,240.00        | 145.00   | 16.00    |
| Poisson’s Ratio           | 0.29            | 0.49     | 0.49     |

**4. Findings and discussion**
Figures 3 to 6 show the results of static analysis of von Mises stress distribution on three different bank angles under the highest load (5 kN). The analysis was performed on the overall NPT system, shown by figure 4(a), figure 5(a), and figure 6(a). A separate analysis of von Mises stress was also carried out for both NPT’s tread shown by figure 4(b), figure 5(b), figure 6(b), and NPT’s spokes demonstrated by figure 4(c), figure 5(c) and figure 6(c).

**Table 2.** Yield stress of NPT’s assembly, tread, and spoke.

|              | Assembly | Tread | Spoke |
|--------------|----------|-------|-------|
| Yield stress (MPa) | 710      | 145   | 16    |

**Figure 4.** Von Mises stress distribution of (a) NPT, (b) tread, and (c) spokes under 0° bank angle.

**Figure 5.** Von Mises stress distribution of (a) NPT, (b) tread, and (c) spokes under 1,8° bank angle.
Based on the results obtained, it can be inferred that stresses were well distributed around the overall NPT system and NPT’s tread, although slightly higher tension was observed at the bottom part of the structures. However, NPT’s spokes analysis results showed that significantly higher von Mises pressure distribution occurred at the spokes’ joint area, which indicated the area with high-pressure concentration. Maximum von Mises stress of spokes are 8.748 MPa for $0^\circ$ angle, 8.641 MPa for $1.8^\circ$ angle, and 10.809 MPa for $2.7^\circ$ angle. Von Mises stress of different load and bank angle induced in system assembly, tread, and spokes are shown in figure 6, while yield stress of each component is presented in table 2. Based on the visual observation of the simulation, it is also suggested that the deformation of spokes is higher at the lower part of the NPT.

Maximum stress obtained at different load and bank angles is recorded and plotted into line graphs, as shown in figure 7. It is clear that both tread and spokes can withstand maximum stress with quite a large margin within the experimented load. However, the pressure absorbed reached its yield strength when 5 kN of load was applied to the system, with the highest stress concentration shown at the ring hub. Materials with the highest yield stress determine the yield stress property for each analysis. Therefore, yield stress for the entire NPT system is obtained from AISI 4340 steel with a yield stress of 710 MPa.

Each graph indicated that the increase of load is always followed by a linear increase in stress distribution, either for NPT’s system, tread, or spokes. Consequently, the highest stress is always produced at 5 kN load.

The effect of bank angle on stress distribution can also be inferred from figure 7. An increase of bank angle complemented with higher load give the most significant increase in stress concentration at spokes. On the contrary, the amount of stress reduced at a higher bank angle while the whole system was investigated. Bank angle gave negligible influence towards the stress concentration of NPT’s tread.
Figure 8. (a) Displacement measurement method; (b) NPT’s displacement at different loads.

Displacement of NPT’s data is obtained by measuring the shifted center of gravity at each axis (x, y, z) and illustrated by figure 8(a). Two red dots are utilized to represent each center of gravity. The magnitude of displacement rises exponentially with the increasing load given to the NPT. It is evident that although the displacement of NPT at 0° bank angle is significantly higher than inclined angles, the gap quickly narrowed down as higher load applied to the system.

5. Conclusions
The increment of road bank angle supplemented with a high load applied to NPT resulted in increasing magnitude of both displacement and von Mises stress. In contrast to the NPT’s thread, NPT spokes are determined to be the most vulnerable part of coping with inclined bank angle. It is also vital to notice that the bank angle’s inclination gave more influence on NPT’s spokes than other parts of NPT. Authors recognized that further research by taking more variables into account is required to simulate real-world terrain better.

6. References
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