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Influence of Spoke Parameters on Load Capacity of Non-Pneumatic Tires Using Orthogonal Study and Analysis of Variance

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Abstract
This study aims to investigate the relationship between the static characteristics of non-pneumatic tires (NPTs) and spoke design parameters using the finite element (FE) method. A three-dimensional FE model of the NPT was established. The influence of different ranges of stress and strain on the calculation accuracy of the Neo-Hookean and Yeoh constitutive models was analyzed. Subsequently, the main design parameters—spoke thickness, spoke number, and arc curvature—were selected according to the geometric characteristics of the spokes. The effects of these three parameters on the vertical stiffness, maximum spoke stress, overall maximum stress, and maximum and average contact pressures were examined using univariate and multivariate analysis methods. The range and variance analysis results indicated that the spoke thickness, spoke number, and arc curvature had a significant effect on the vertical stiffness. Finally, the relationship between the vertical stiffness and product of the spoke thickness and number was obtained using a nonlinear fitting method. When the arc curvature of the spoke was less than 5 m^{-1}, the errors between the calculated and simulated vertical stiffness did not exceed 5%. This observation can be used to facilitate the rapid design of spoke parameters under different load capacity requirements.

Keywords Finite element method · Non-pneumatic tires · Spoke parameter design · Analysis of variance

1 Introduction

Pneumatic tires (PTs), which have been developed for more than a century, are highly engineered composite structures in vehicle components. However, PTs have several disadvantages, such as blowout, maintenance of air pressure, and complicated manufacturing processes (Gent & Walter, 2006).

Non-pneumatic tires (NPTs) can overcome these disadvantages and achieve suspension performance, better handling, and better driving comfort. Tweel NPTs, introduced by Michelin in 2006, are a representative example of NPTs. A variety of patents on structural design, new elastomer material and process molding have been proposed (Cron et al., 2020; Rhyne et al., 2007, 2020). Tweel NPT was designed to exhibit the desired characteristics (such as low energy loss, vertical stiffness, contact pressure, and mass) of PTs without specifying an inflation pressure value (Rhyne & Cron, 2006). Tweel NPT usually consists of four components: a tread, a shear band, spokes and a hub. The research on NPT focused on establishing accurate numerical simulation models and exploring the influence of tire structure on performance.

Several simulation studies were conducted to guide the structural design and optimization of Tweel NPTs. For instance, Ju et al. (2013) developed two-dimensional FE models of NPT with and without aperture holes in a shear band structure using a viscoelastic material model. The vertical stiffness and rolling resistance were then analyzed to investigate the potential of the NPT design with low rolling resistance while maintaining satisfactory performance, such as in terms of vertical stiffness and manufacturability. The effects of geometric and material parameters on the overall performance of the NPT were further investigated by the same researchers. They found that the spoke thickness, shear band thickness, and shear modulus of the polyurethane (PU) spoke were the most important design parameters (Veeramurthy et al., 2014). Aboul-Yazid et al. (2015) and Kucewicz et al. (2017) both used FE method (FEM) simulations to investigate the contact pressure, vertical tire stiffness, and stresses of different configurations of

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