

Effects of Material Properties on Static Load-Deflection and Vibration of a Non-Pneumatic Tire During High-Speed Rolling

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ABSTRACT

The Michelin Tweel tire structure has recently been developed as an innovative non-pneumatic tire which has potential for improved handling, grip, comfort, low energy loss when impacting obstacles and reduced rolling resistance when compared to a traditional pneumatic tire. One of the potential sources of vibration during rolling of a non-pneumatic tire is the buckling phenomenon and snapping back of the spokes in tension when they enter and exit the contact zone. Another source of noise was hypothesized due to a flower petal ring vibration effect due to discrete spoke interaction with the ring and contact with the ground during rolling as the spokes cycle between tension and compression. Transmission of vibration between the ground force, ring and spokes to the hub was also considered to be a significant contributor to vibration and noise characteristics of the Tweel. Previous work studied spoke vibration, ground vibration and related geometrical factors on a two-dimensional (2D) Tweel model. In the present work, a three-dimensional finite element model of a non-pneumatic tire (Tweel) is considered which uses a hyperelastic Marlow material model for both ring and spokes based on uni-axial test data for Polyurethane (PU). Changes in the shear modulus on vertical stiffness and vibration of spoke and ground force reaction for a non-pneumatic tire during high-speed rolling are studied. A three-dimensional finite element model with hyperelastic Marlow material properties for both ring and spokes based on uni-axial test data for Polyurethane (PU) is used for the numerical experiments. In order to study the effect of changes in shear modulus for the ring and spokes while keeping the ratio of volumetric bulk modulus to shear modulus unchanged, the value of shear modulus is varied from unchanged to plus/minus 25% for the Mooney-Rivlin

and Neo-Hookean models obtained from a nonlinear least-squares fit of the uni-axial stress-strain data. For tensile stresses and strains, the Mooney-Rivlin best matches the original Marlow material model, compared to the simpler Neo-Hookean model. However, for large compressive stresses, the Mooney-Rivlin model diverges significantly from the results obtained with Marlow properties. The simple Neo-Hookean model is able to fit the Marlow curve better for compression, but is less accurate in tension. As a result of decreasing shear modulus in the ring of the non-pneumatic tire, the vertical displacement in the static load-deflection curves increases upon loading. The softer Neo-Hookean model resulted in decrease in stiffness when compared to the Mooney-Rivlin and original Marlow model. The effects of material changes on spoke vibration as measured by changes in perpendicular distance and vibration in ground interaction measured by FFT frequency response of vertical reaction force during rolling are also reported. Results show a trend where the vibration decreased when the stiffness of the Mooney Rivlin and the Neo Hookean models was increased from +25% to -25%. Conversely, the vibration increased when the stiffness decreased between the extreme limits. However, in several of the material models for the ring and spokes, the unchanged stiffness gave the lowest vibration amplitude, suggesting that an optimal value is somewhere between the plus/minus 25% stiffness limits.

INTRODUCTION

Interest in non-pneumatic wheels has a long history; notably for use on the NASA lunar rover wheels [1] and other specialized applications such as all-terrain and military vehicles, including the honeycomb wheel structure proposed in the NPT [2]. Non-pneumatic extra-terrestrial wheels include the Apollo toroids constructed of piano wire which

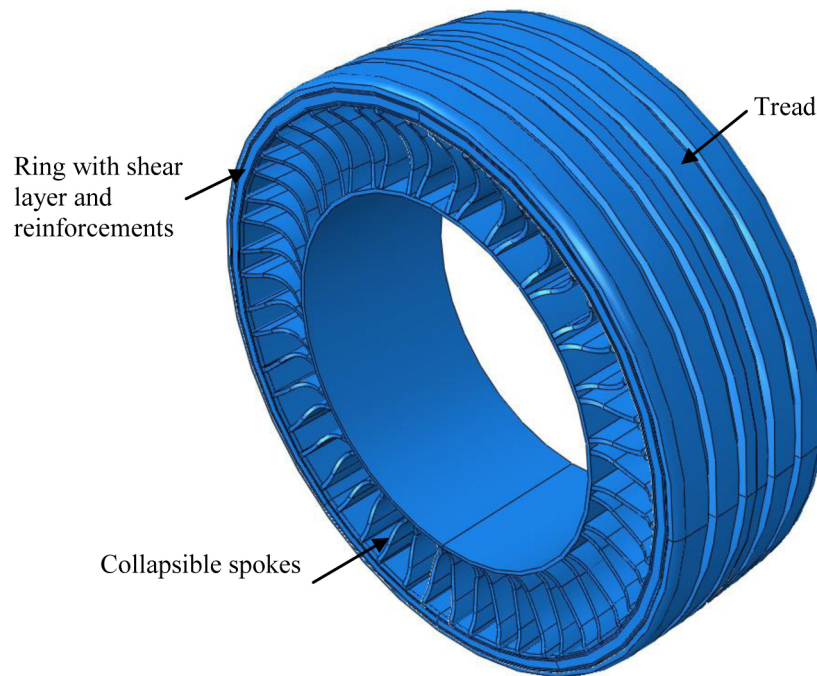


Figure 1. Tweel tire geometric model used in the present analysis

have limited endurance and the Mars' rovers that are made of nearly solid billets with low mass to function ratio and low compliance. More recently, the ATHLETE (All Terrain Hex Limed Extra Terrestrial Explorer) robot [3,4] based on a wheel-on-limb vehicle concept, and designed for a top speed of 10 kph, has adopted a wheel prototype inspired by the Michelin Tweel, a non-pneumatic structure that retains the important characteristics of the traditional tire while removing many of the design limitations [5]. The design of the Tweel relies heavily on the low shear modulus and incompressibility of polyurethane.

The Tweel design allows the wheel's effective contact pressure to be largely independent of load and distributed uniformly across the ground contact area. Since lunar wheels must perform over wide temperature ranges, non-polymeric materials, such as metals and textiles operating in the 100-400K range were proposed, while exhibiting relatively low energy loss from obstacle impacts and allowing for a tunable vertical stiffness that is independent of contact pressure.

To improve functional performance for potential use on standard automobiles at highway speeds, the Tweel is designed using polyurethane (PU) materials for improved endurance. Using this approach, the Michelin Tweel tire structure described in [5] has recently been developed and tested on several different automotive test tracks. The Michelin non-pneumatic tire structure consists of three basic parts [5]: a circular deformable shear beam, thin elastic collapsible spokes, and a hub which may be rigid or flexible.

The Tweel stiffness properties and contact pressure during loading is affected by several geometric and material parameters, including ring thickness, reinforcement type, and spoke geometry. Cooling after molding places the spokes in pretension.

As with other previous non-pneumatic tire designs, the problem of noise, vibration, and harshness (NVH) during high-speed rolling of the Tweel must be addressed. During high speed rolling in initial testing, early prototypes showed high noise levels at frequencies above 100 Hz. One of the potential sources of vibration during rolling of the Michelin Tweel is the buckling and snapping back of the spokes in tension when they enter and exit the contact zone. Another source of noise was hypothesized due to a flower petal ring vibration effect due to discrete spoke interaction with the ring and contact with the ground. Transmission of vibration between the ground force, ring and spokes to the hub was also considered to be a significant contributor to NVH characteristics. Previous work has studied spoke vibration, ground vibration and related geometrical factors on a two-dimensional (2D) Tweel model for automotive applications at highway speeds. In the present work, a three-dimensional finite element model of the Michelin Tweel is considered which uses a hyperelastic Marlow material model for both ring and spokes based on uni-axial test data for Polyurethane (PU). Figure 1 shows the Tweel tire geometry used in the present work.

In the Tweel structure, the ring is constructed from a relatively low shear modulus material that deforms

predominately in shear due to the imbedding of inextensible membrane reinforcements. The number of inextensible reinforcing membranes in the circumferential direction can varied for design, but a minimum of two is required to create the shear beam behavior. The shear ring can be made from rubber-like elastomers or relatively low modulus polyurethane reinforced with steel cable or other high stiffness reinforcement materials. The shear ring is connected to a hub with flexible spokes which collapse when compressive in the ground contact zone and then regain tension as the spokes pass around the top of the wheel during rolling. Typically, the spokes and ring are molded together and both materials are polyurethane. [Figure 2](#) shows a prototype Tweel design used for testing at Clemson University and Michelin.



Figure 2. Prototype Tweel tire used for testing at Clemson University and Michelin.

In [7,8], the noise was hypothesized to be due to the buckling phenomenon of the spoke when entering and leaving the contact zone and the resulting vibration during the tension phase of the spoke as it passes around the top portion of the rotating wheel. In [11,12] another source of noise was hypothesized due to a flower petal ring vibration effect due to discrete spoke interaction with the ring and contact with the ground during rolling as the spokes cycle between tension and compression. Transmission of vibration between the ground force, ring and spokes to the hub was also considered to be a significant contributor to vibration and noise characteristics of the Tweel.

In [6], spoke dynamics was investigated by analyzing a single 3D spoke in ABAQUS. The 3D spoke was tied to the hub center using different connector elements and was rotated. A 3% static tensile strain was imposed on the spoke and was

then accelerated to a speed of 80 km/hr. The research work in [7,8] involved the development of a computational procedure for simulating high speed rolling of a planar Tweel in contact with a rigid plane. In addition, the spoke vibration frequencies were monitored and the spoke length vs. time profile was obtained. This served as an input boundary condition for a 3D Tweel spoke model in order to capture both in-plane and out-of-plane vibrations. From the computational procedure, it was concluded that the spoke vibrations were not significantly affected by the thickness of the spoke. In [9,10], changes were made to the model step procedures to more accurately represent the cooling and loading phases during steady state rolling using ABAQUS/Explicit. In addition, a single 3D spoke model was analyzed under high speed rolling conditions. From this analysis, it was concluded that scalloping the edges of the spoke with lateral profiling drastically reduced the vibration amplitude but did not have a strong effect on the dominant frequency. An optimal amount of scalloping was suggested and physical testing confirmed the effect of reduced vibration and noise with scalloping.

In [11,12], important spoke and ring (geometric) parameters were considered for vibration and were studied using Taguchi's Robust Parameter Design and orthogonal arrays. To evaluate every combination, sets of output parameters such as perpendicular distance of the spoke from a virtual plane, ground reaction forces due to vibration of the Tweel and ring vibration were monitored and compared. In [13], a systematic study of the effects of spoke angle deviations from radial lines (DeRad) was performed using Taguchi's Robust Parameter Design Method and Orthogonal Arrays. In [13,14], effects of a new alternate spoke pair design concept wherein even and odd numbered spoke pairs have different thickness, curvature, or combinations of both were examined. On comparing with a reference model having uniform spoke thickness, the alternating spoke pair model with plus/minus 5% difference in thickness between the odd and the even spoke resulted in reducing the RMS and maximum amplitudes, and also broadened the excitation frequencies of the ground force reaction. Combining thin spokes with large curvature within a pair and thick spokes with small curvature within the other spoke pair was shown to produce an effective design which reduces the amount of vibration in both the spoke and ground interaction.

As stated earlier, all of these studies were performed with a 2D planar finite element model of the Tweel structure or a single 3D spoke with boundary conditions supplied by the signal derived from the 2D models. While many of the geometric features of the Tweel are planar and projected in the width dimension to form a 3D structure, some components are not entirely planar, such as the spokes and tread which have a taper across the width dimension. In addition, the grooves in the tread can only be captured in a 3D model of the Tweel. In [15], a procedure for extending the

analysis of 2D planar models to a complete 3D Tweel model is given. A spoke pair geometric part model is created and instanced and then tied to the ring and hub structure. The internal reinforcements are modeled as solid cylinders that are then embedded into the host ring structure [15]. In the present work, a complete 3D static and dynamic Tweel model based on the model in [15] is used for analysis of Tweel stiffness and vibration during high-speed rolling.

In the previous simulations, including [15], the analysis procedure consisted of a nonzero initial rotation speed applied to all points on the Tweel structure followed by a simultaneous cooling and vertical ground push-up step to the desired load position using no friction. The conditions were then held constant for steady-state rolling with constant speed and zero acceleration. This allowed for a steady-state rolling condition to be achieved without starting from rest and accelerating up to steady speed, resulting in significantly reduced compute time. This procedure produces ground force signals which are very sensitive to vibrations present in the rolling tire, and thus serve well for parameter studies. In addition experimental noise results confirmed that the reduced ground force signal did correspond to reduced levels of noise and vibration [15]. While these procedures give effective results for studying steady-state rolling, they do not allow for the possibility of a ground which includes obstacles. To allow for the possibility of simulation of rolling over ground obstacles in future studies and to account for the effects of friction, in the present work a new analysis procedure is developed which includes friction contact and actually rolls the Tweel tire across a fixed ground.

Both geometric and material properties play an important role in the performance of the Tweel tire. In previous work, geometric factors were studied on the vibration of spokes and ground force interaction of a rolling non-pneumatic tire. In this present work, material factors are considered. Changes in material properties on static load-deflection curves, and vibrations of spoke and ground force reaction during rolling are studied. As stated earlier, in the present study, a complete 3D finite element model of a non-pneumatic tire was considered using a Hyperelastic Marlow material model for both ring and spokes based on uni-axial test data for Polyurethane (PU). In order to study the effect of changes in shear modulus for the ring and spokes while keeping the ratio of volumetric bulk modulus to shear modulus unchanged, the value of shear modulus is varied from Mooney-Rivlin and Neo-Hookean models obtained from a least-squares fit of the uni-axial stress-strain data. A total of 6 different material models are examined together with the original Marlow model. The 6 material models are divided into 2 sets and each set has 3 levels (unchanged and plus/minus 25% change in shear modulus). In addition to static load-deflection curves which are important for vehicle design integration, the effects of material changes on spoke vibration as measured by changes in perpendicular distance of spoke displacements

from a virtual spoke plane and vibration in ground interaction measured by FFT frequency response of vertical reaction force during rolling are also reported.

In summary, the objectives of the present work are: (i) compute the shear modulus and bulk modulus for Mooney-Rivlin and Neo-Hookean hyperelastic material models obtained from nonlinear least-squares fit of uni-axial test data for the spoke and ring polyurethane material. (ii) Quantify the change in instantaneous tangent slope modulus for stress-strain curves, and change in vertical stiffness from a load-deflection test, based on changing the shear modulus by plus/minus 25% in the derived Mooney-Rivlin and Neo-Hookean models. (iii) Demonstrate the new analysis startup analysis procedure for computing spoke and ground vibration during steady-state rolling at high-speeds, (iv) Assess the amount of increase or decrease in spoke vibration amplitude and ground force resultant vibration during steady rolling, due to changes in shear modulus in the ring.

THREE DIMENSIONAL FINITE ELEMENT MODEL OF TWEEL

The Tweel design is molded from polyurethane (PU) and described earlier consists of four different parts: (1) Ring, (2) Reinforcements to create a shear layer in the ring, (3) Spokes, and (4) Outer Tread. The ring is a composite structure consisting of a shear beam and inextensible reinforcements embedded inside the ring structure. The reinforcements have high stiffness and strength in the circumferential direction. The section of the ring inside the inner reinforcement is called the inner coverage while the section of the ring outside the outer reinforcement is called the outer coverage. Attached to the outer ring coverage, a rubber tread is also modeled. The tread establishes contact with the ground and provides traction. The collapsible spokes connect the outer ring and the inner hub modeled as rigid. The spokes have curvature and are aligned to deviate from radial lines. The spokes are paired and placed at equal intervals along the circumference of the Tweel. The PU material forms the bulk of the Tweel including the spokes and ring regions, i.e., inner coverage, outer coverage and shear beam layers of the ring.

Figure 3 shows the complete 3-D Tweel finite element model including tire tread with mesh distribution used in the present study. The geometric parameters are summarized in Table 1. Figure 4 shows the finite element model of a collapsible spoke pair which is copied in equal intervals around the circumferential direction. Figure 5 shows the finite element model of the Tweel shear ring with embedded reinforcements. In previous studies the spoke length, curvature and amount of edge scalloping have a large influence on the vibration characteristics of the Tweel tire. For static analysis in Abaqus/Standard, the mesh of the shear ring, collapsible spokes and the reinforcements use 8-node hybrid brick elements (C3D8H). Reinforcement surfaces are

modeled with 4-node, quadrilateral elements (SFM3D4). For dynamic analysis in Abaqus/Explicit, 8-node linear hexahedral brick elements with reduced integration and hourglass control (C3D8R) are used for the ring and spokes and with 4-node and quadrilateral with reduced integration (SFM3D4R) for the reinforcement surfaces. The ring is modeled has 8 elements thru the thickness, 6 elements across the tire width, and 1200 elements around the circumference with equal spacing of 3.33 elements per degree. The collapsible spokes of the Tweel are meshed with 4 elements thru the thickness, 12 elements along the tire width, and 24 elements along the spoke length. For the dynamic rolling analysis, a contact model is defined in ABAQUS / Explicit. The mechanical constraint formulation between the rigid ground surface and the deformable tread is defined by a penalty contact method with a tangential interaction property defined a friction coefficient value of 1. A rigid kinematic coupling constraint is defined such that the outer surface of the hub is coupled to a reference node at the hub center; see [Figure 6](#).

Table 1. Tweel Structure Geometric Parameters.

Parameters	Tweel Model
Outside Diameter	584 mm
Inside Diameter	422 mm
Tread Thickness	5 mm
Ring Thickness	15 mm
Outside Coverage	8.3 mm
Inside Coverage	3 mm
Number of Spoke Pairs	25
Spoke Thickness	4.2 mm
Width	210 mm

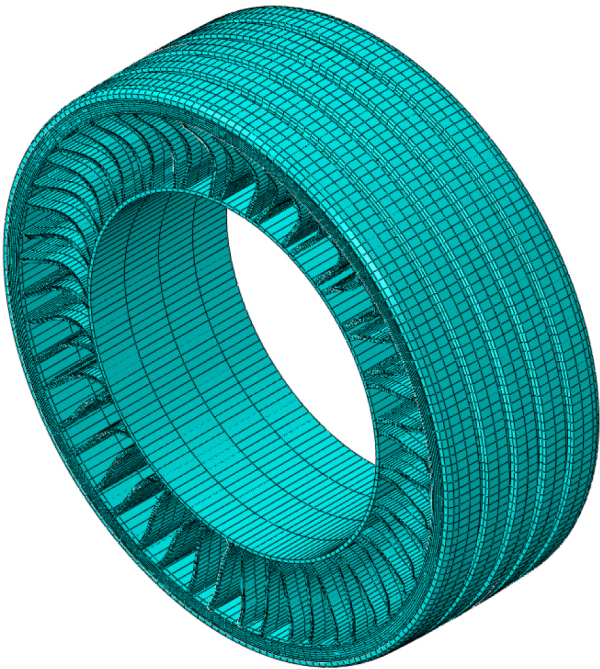


Figure 3. 3D Tweel Tire Finite Element used for analysis

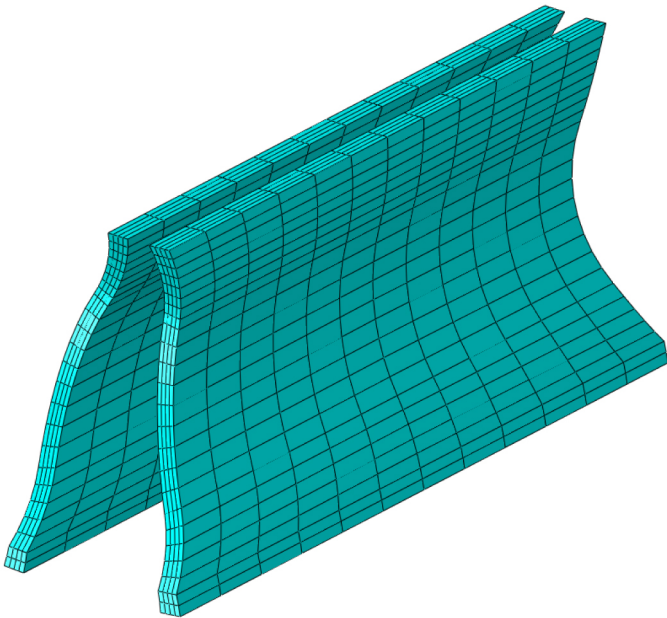


Figure 4. Finite Element model of Tweel Spoke Pair