Development of a Transient Dynamic Finite Element Model for the Drum Testing of a Non-Pneumatic Tire

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Abstract
Non-pneumatic tire (NPT) or airless tire must be designed to meet the required performance such as weight, load carrying capacity and resistance to cyclic loading. The tire dynamic response is also needed to be observed since the tire are constantly subject to cyclic loading while rolling. Drum testing method is preferred over other rolling tire testing method since various factors from the vehicle suspension system and pavement structure are eliminated. This article aimed to develop the finite element (FE) model based on the transient dynamic approach for drum testing of NPT. The finite element model of NPT was created using Ogden hyperelastic material model. The FEM of NPT, which composed of Tread band and Spokes, was model using 3D hexagonal and 2D Quadrilateral elements respectively. The steel belt layers were modelled and embed using rebar elements and tying equation, respectively. The FE model of NPT was then assigned to contact with the rigid drum surface using Coulomb’s friction model. The finite element analysis of drum testing method of NPT as the drum was assigned to be rolling at speed of 11 km/hr. The NPT spoke deformations at each position and the angle was compared to the experiment to prove the validity of the model. The analysis results of spoke deformation were shown to be in a good agreement with the experiment at the average error of 3.51%. The developed FE model of NPT based on transient dynamic approach can be used to evaluate the important dynamic response of NPT during rolling and can be useful in designing the NPT.

1. Introduction
Recently, the non-pneumatic tire (NPT) or airless tire was developed to overcome the disadvantage of a traditional pneumatic tire. The traditional pneumatic tire has several disadvantages such as the required maintenance of inflation pressure periodically, and a possibility to be damaged or flattened. The latter can cause catastrophic damage if the tire went flat while driving [1]. The NPT has been studied and developed over the past decade. The NPT can be designed to exhibit conventional pneumatic tires performance regardless of tire size and inflation pressure. The TWEEL, which was recently developed by Michelin, is the first commercially available NPT. The TWEEL is consisting of three main
components which are 1) shear band, which can be described as a combination of tread and a solid sidewall inserted with steel belts, 2) polyurethane (PU) spoke structure, and 3) steel hub [2, 3].

The designing of NPT needs to be engineered carefully to meet the desired tire’s performance such as load-carrying capacity, riding comfort, rolling resistance, etc. The optimum design of NPT to have required load-carrying capacity and vertical stiffness can be achieved easily by mean of static finite element method (hereafter, FEM) with appropriated material models [4-6]. However, the dynamic characteristics of the NPT while rolling, which including cyclic stress, strain, deformation, rolling resistance, and riding comfort, are still needed to be observed. Normally dynamic characteristic of the rolling tire can be obtained by using a drum testing method. The method is performed by pressing an inflated tire against a drum with the desired load. The drum is rotated and tire’s interested properties can be measured and recorded. Drum testing method had an advantage when compared to the other rolling tire testing method since various factors from the vehicle suspension system and pavement structure are eliminated [7]. In recent years, finite element (FE) models of drum testing had been developed. The rotation system of drum and tire could be modelled by using transient dynamic analysis [8].

The tire, which is considered as a viscoelastic material, undergoes cyclic deformation while rolling. The stress and strain response under cyclic loading exhibit phase delay, which is the cause of hysteresis energy loss [9]. Thus, the development of the tire model with viscoelastic material is required to predict the dynamic characteristic of the rolling tire. The thermo-viscoelastic model of NPT with a lattice spoke was developed to predict rolling energy loss and the corresponding heat generation of NPT components. The Yeoh hyper-elastic model was obtained from the tension and compression tests, while viscoelastic material properties were obtained from dynamic mechanical analysis (henceforth, DMA) test. A 3-D stress analysis was performed using steady-state rolling analysis, then the cyclic strain energy was converted into heat to obtain temperature and compared with the experiments [10]. The effects of static and dynamic loading of NPT with honeycomb spoke was investigated using FEM. The three types of NPT with constant cell wall thickness but different cell geometries were numerically simulated to study the effects on deformation modes, stress distribution, load carrying capacity, and rolling resistance. While on dynamic loading, the effects of friction coefficient and angular velocity on rolling resistance were also studied. The maximum stress in spoke under dynamic loading was observed to be higher when compared to static loading [11].

This research aimed to develop the transient dynamic FE model for NPT. The Ogden hyperelastic model and generalized Maxwell’s viscoelastic model were used to modelling the elastic and inelastic behavior of NPT components. The spoke deformation obtained from finite element analysis (hereafter, FEA) then was compared with the drum testing experiment to validate the model. Lastly, the displacement at the center of the NPT and impact force was observed and recorded from the FEA.

2. Finite Element Modelling of Non-Pneumatic Tire

The commercial NPT Tweel, which was developed by Michelin, is selected to study the mechanical behavior and dynamic characteristic of NPT in this research. The Tweel 12N16.5 SSL ALL-TERRAIN model is shown in figure 1(a). The FE software MSC. Patran was used to model the FE model of NPT. The components of FE model of NPT, which composed of 4 main components, can be concluded as follows: 1) tread, 2) shear band, 3) belt layers, and 4) PU spoke. The FE model of NPT, its overall dimension are shown in figure 1(b) and figure 1(c) respectively, while the NPT components are shown in figure 2. The hybrid formulation or Hermann element was used to model the rubber components such as tread and shear band elements of NPT. The formulation was selected to prevent the excessive stress due to volumetric locking that may occur during compression of rubber material elements by mean of separated integration of pressure and displacement field. The spoke was then modelled using thick shell approximation. The details of elements used for each NPT components can be summarized as shown in Table 1. The spoke thickness was measured from the real spoke and assigned to each element differently based on actual thickness distribution, which the average thickness was found to be 5.8 mm. Additionally, the thicknesses at the outer and inner ring of the spokes were fixed at 6 and 7 mm, respectively corresponding to the real NPT.
The cross-section of shear band component including belt layers was obtained by means of waterjet cutting technique, which the belt layers were found to consist of 4 main layers which were 1) the outer layer, 2) the 1\(^{st}\) middle layer, 3) the 2\(^{nd}\) middle layer, and 4) the inner layer. The outer layer was composed of three sublayers while the inner layer was composed of two sublayers. The reinforcing bar or rebar element was used to develop the FE model of belt layers, which was then embedded into the rubber element using tying equation [12]. The value of the degrees of freedom of the nodes in the host body element was tied based on their iso-parametric location in the elements. The approximated number of wires per unit length of 0.3582 mm\(^{-1}\) was measured and assigned to the model. The cross-section of the shear band of the FE model and real TWEEL along with the embed belt layer position is shown in Figure 3.

![Figure 1](image1)

**Figure 1.** (a) The NPT Tweel 12N16.5 SSL ALL-TERRAIN model, (b) finite element model and (c) NPT’s overall dimension.

![Figure 2](image2)

**Figure 2.** Finite element model of NPT’s components.

| NPT’s Components | Element type   | Number of element | Averaged element length (mm) |
|------------------|----------------|-------------------|------------------------------|
| Tread            | Hexagonal      | 2,228             | 19.89                        |
| Shear band       | Hexagonal      | 11,904            | 16.15                        |
| Belt layers      | Quadrilateral  | 6,144             | 20.38                        |
| Spoke            | Quadrilateral  | 35,500            | 8.74                         |
3. Hyperviscoelastic Material Model

The Ogden hyper-elastic constitutive model was used to model nonlinear elastic behaviors of rubber tread, shear band, and polyurethane spoke. The general form of the Ogden hyperelastic model [13] can be expressed as shown in equation (1).

$$\ddot{W} = \sum_{n=1}^{3} \frac{\mu_n}{\alpha_n} \left( \lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3 \right)$$

Where \( \lambda_i \) is the principal value of the stretch tensor \( \dot{U} \), \( \mu_i \) and \( \alpha_i \) are hyperelastic material constants.

The inelastic behaviors of NPT components were modelled using the generalized Maxwell viscoelastic material model. The generalized Maxwell viscoelastic model can be express as follows:

$$G(t) = G_0 - \sum_{i=1}^{n} G_i \left( 1 - e^{-t/\tau_i} \right)$$

$$\tau_i = \eta_i / E_i$$

where \( G(t) \) is Shear Relaxation Modulus, \( G_0 \) is Shear Modulus at a time, \( t=0 \), \( G_i \) is \( i^{th} \) term of Shear Modulus, \( \tau_i \) is the \( i^{th} \) term of Relaxation Time (sec), \( E_i \) is Modulus of Elasticity, and \( \eta_i \) is viscoelasticity.

The parameters of Ogden hyperelastic and generalized Maxwell material model of tread and PU spoke, which are obtained and validated from mechanical testing in the previous research, are shown in Table 2 and 3, respectively [4, 10]. The compressive testing and tensile testing are performed on the cylindrical shape and dumbbell shape specimens, which are prepared from NPT’s tread and spoke respectively using waterjet cutting technique (figure 4) [5, 6]. In addition, linear elastic material with a modulus of elasticity (E) of 200 GPa and Poisson’s ratio of 0.3 was used to model the steel belt layers of NPT.

![Figure 3: Cross-section of the shear band with embed belt layers of (a) Tweel and (b) finite element model.](image)

![Figure 4: (a) Waterjet cutting technique, (b) flatted tread layer, (c) spoke (d) cylindrical-shaped specimen and (e) Dumbbell shaped specimen.](image)
Table 2. Hyperelastic constants of NPT components [4].

| Constant | Component       | Spoke       | Shear Band  |
|----------|----------------|-------------|-------------|
|          |                | 0.112983    | 1.15673     |
|          |                | -11.0664    | 1.06228     |
| 1        |                | 3.1488      | 5.37146     |
| 2        |                | -1.75206    | -2.31827    |

Table 3. Viscoelastic constants of NPT components [10].

| $i^{th}$ | $\tau_i$ | $G_i$   |
|----------|----------|---------|
|          |          | Spoke   | Shear Band |
| 1        | 0.2      | 0.125   | 0.2        |
| 2        | 0.02     | 0.125   | 0.2        |
| 3        | 0.002    | 0.125   | 0.2        |

4. Finite Element Modeling of Drum Testing on NPT

The FE model of NPT based on viscohyperelastic material model was brought into contact with the drum surface model. The drum surface model was defined as rigid, which means that the deformation did not occur. The Coulomb’s contact friction model with a friction coefficient of 0.8 was used to model friction between tread elements and drum surface. The tire was assigned to be pressed against the drum surface with a constant force of 14 kN. After the load was fully applied and the NPT was deformed, the drum surface was started to rotate with a velocity of 11 km/hr while the load was maintained at 14 kN. The drum testing experiment is shown in figure 5(a). The boundary conditions of the FE model of drum testing on NPT is shown in figure 5(b). The linear velocity could be converted into corresponding angular velocity as 7.0159 rad/sec. It should be noted that the static solution FEA was used during the load applying state, while the transient dynamic solution was applied during the rolling state. In addition, the high-speed video camera is set up to capture the deformation of spokes while the NPT is rolling at high speed (figure 6).

Figure 5. (a) Drum testing experiment on NPT and (b) finite element model of drum testing on NPT with boundary conditions.
Figure 6. The setting up of high-speed video camera on drum testing of NPT

5. Finite Element Analysis of rolling NPT

The FEA of drum testing of NPT was carried out using the transient dynamic finite element solution. The spokes deformation at various analysis time and rolling angle were collected as nodal coordinates. The recorded rolling angle position can be shown as a schematic diagram as shown in figure 7(a). The analyzed local stress at spoke and NPT deformation is shown in figure 7(b), which the maximum local stress at the node is shown to be 1.20 MPa. The deformed spoke coordinates were compared with experimental recording spoke position, which was recorded using a high-speed video camera to validate the accuracy of the model. The comparison of spoke deformation between the FEA and experiment at various rolling angle i.e. 0°, 30°, 60°, 90°, 120°, 150°, 180°, is shown in figure 8. The average error of spoke deformation analysis is calculated to be 3.51% compared to the experiment. Thus, FE model of NPT was shown to be accurate and can capture the mechanical behavior of the NPT while rolling. The impact force and displacement of NPT’s rolling center against the drum in the horizontal direction are plotted in figure 9. It should be noted that the displacement of the tire’s center using load 14 kN is 18.97 mm at the start of the dynamic solution/end of the static solution. The value of displacement at the center of NPT was shown to fluctuate between 17.55 and 19.80 while the impact force was shown to fluctuate between the 12.18 and 16.23 kN, respectively.

Figure 7. (a) The schematic diagram of the angular position of the collected spoke position and (b) local stress at spoke with load 14 kN at time 1.2 sec.
6. Conclusion
The transient dynamic FE model based on viscohyperelastic material model for drum testing of NPT was developed. The Ogden hyperelastic material model and generalized Maxwell’s viscoelastic was applied to model elastic and inelastic deformation of NPT, respectively. The FE model of NPT, which composed of Tread band and Spokes, was a model using 3D hexagonal and 2D Quadrilateral elements, respectively. The rebar elements and tying equation were used to model steel belt layers of the NPT. The FE model of NPT was then assigned to contact with the rigid drum surface using Coulomb’s friction model. The finite element analysis of drum testing method of NPT as the drum was assigned to be pressed with a load of 14 kN while rolled at the speed of 11 km/hr. The NPT spoke deformations at each position and angle were compared to the experiment to prove the validity of the FE model. The analysis results of spoke deformation were shown to be in a good agreement with the experiment at the average error of 3.51%. The developed FE model of NPT based on transient dynamic approach can be used to evaluate the important dynamic response of NPT during rolling and advantageous to use in further designing of the NPT.
Acknowledgments
This work was financially supported by Rubber Technology Research Center (RTEC), Mahidol University and the Thailand Research Fund (TRF) under the TRF Research Grant No. RDG60T0140.

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