Comparison of two different surface for rolling airless tire by finite element method

Chakrit Suvanjumrat\textsuperscript{1,2}, Ravivat Rugsaj\textsuperscript{1,2}, Juthanee Phromjan\textsuperscript{1,2,*}

\textsuperscript{1}Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom Thailand 73170
\textsuperscript{2}Laboratory of Computer Mechanics for Design (LCMD), Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom Thailand 73170

* Corresponding Author: juthaneephromjan@gmail.com

Abstract

Drum testing was carried out to determine rolling tire performance. The finite element method was used to model the drum testing instead. In order to yield accurate results, the generalized Maxwell’s viscoelastic material model with hyperelastic material model was employed to simulate the drum testing on the airless tire. However, it consumed a lot of simulation time because of the contact surface between tire and drum was difficult to compute by using a finite element method. The finite element model of rolling an airless tire on a flat surface was developed. The contact patch and spoke deformation were carried out to investigate the surface effects. The spoke deformation of rolling an airless tire on a flat surface was found to be in accord with the curvature surface of the drum. The flat surface showed little difference in the contact area against the drum. Particularly, it was found that the analysis time of rolling an airless tire on a flat surface was less than the drum 10.13 times.

Keywords: Airless tire, Finite element method, Rolling tire, Tire testing

1. Introduction

Nowadays, airless tires or non-pneumatic tires (NPT) have been developed to overcome the disadvantages of pneumatic tires such as maintaining air pressure for inflation being and easy to damage. An airless tire can be developed to achieve various performance requirements by designing the spoke structure. Rugsaj and Suvanjumrat [1] have studied the effect of NPT spoke structures by using a finite element method (FEM). The spoke structures were grouped into 4 main types including (1) curved spokes, (2) hexagonal honeycomb spokes, (3) auxetic honeycomb spokes and (4) interconnected mesh spokes. The finite element analysis (FEA) showed the interconnected mesh spoke had the highest vertical stiffness. Furthermore, the optimum number of interconnected mesh spokes was 24. The cell expanding of honeycomb spokes was studied [2]. It was found that the smallest cell expanding angle provided the lowest rolling resistance. However, the mechanical behavior of tire has to be studied in many ways for the complete tire development such as dynamic characteristics and contact patches. The drum testing method which is a popular laboratory method for investigating tire rolling behavior which had been carried out to test on solid tires. The contact force between drum surface and tire was...
studied. It was found that the contact force which occurred by using a solid tire was higher than the contact force which occurred by using a pneumatic tire under the same conditions [3]. Liang et al. [4] have studied pneumatic tire footprint geometry for tread wear investigation by using a tire static loaded machine and Tekscan (tire pressure measurement system). In agriculture, the contact distributions on soil which were passed by tractor tire and rubber track were compared [5]. The bigger contact area provided lower soil compaction. Furthermore, traction force is one of important parameter to study the tire-soil interaction which is used in tractor tire development. A soilbin-wheel tester was built for investigating rolling tractor tire behavior in the laboratory [6, 7]. In addition, a FEM is an alternative to an empirical tire patch. Phromjan and Suvanjumrat [8] have investigated the most suitable constitutive model for solid tire compression by varying 6 famous material models by finite element analysis. The Ogden model was found to be the most suitable material model when compared with experimental results. The load capability of solid tire was also studied by FEA [9]. In addition, effects of tire compression on soil were also studied by FEM and had performance for parameter control and lower costs. The soil pressure distribution by a tire was studied [10, 11]. It was found low inflation pressure could reduce topsoil compaction but the highest pressure occurred at the tire edge which could damage a pneumatic tire.

This research aimed to study the contact patch of airless tire (TWEEL). Then, the simulation model of rotated TWEEL airless tire on different surface was investigated. The proper rolling airless tire model which is achieved by this study will be used to develop the novel airless tires in the future.

2. Tire Testing Methods

2.1 Tire stiffness testing

A TWEEL airless tire, which was developed by Michelin, was used to study a tire patch on a flat surface. Figure 1(a) presents the tire stiffness tester (Ektron PL-2003) which is used to investigate the vertical deformation of TWEEL airless tire under compression load. Vertical displacement and vertical force were recorded by a position transducer and a load cell, respectively. In this research, the airless tire was pressed by the tester with a compression force of 14 kN which was a usage load. The tire was fixed on a mounting axle and compressed by a measurement table which was driven by a hydraulic motor with the displacement error less than ±0.1 mm.

2.2 Drum testing

A drum testing machine (KAYTON) was used to investigate the rolling tire's behavior in the laboratory. The diameter of the drum is 1.70 meters. The advantages of this method are that it uses less of the testing area and safer than field testing while providing accurate control conditions. The TWEEL airless tire was fixed on the mounting arm and moved to press on the rolling drum which controlled the tire speed at 11 km/hr. The accuracy of velocity measurement on the drum is ±1 km/hr. The compression load of 14 kN had been applied in the horizontal direction, while the TWEEL airless tire was pressed. The spoke deformation while the TWEEL airless tire rolls on the drum is detected by a high-speed video camera as shown in Figure 1(b).

Figure 1. The tire testing methods comprising of: (a) tire stiffness testing and (b) drum testing.
3. Finite Element analysis

The TWEEL airless tire 12N16.5 ALL TERRAIN composes of 4 main components including rubber treads, shear bands, Polyurethane (PU) spoke and steel rims. The TWEEL airless tire was cut by using the water jet cutting technique to prepare the specimen for material properties testing. The rubber tread was cut into a cylindrical shape for compression testing according to ASTM D575 while the PU spoke of the airless tire was cut into dumbbell shape for a tensile test according to ASTM D412. Computer Aided Design (CAD) and Computer Aided Engineering (CAE) methods were used to create the TWEEL airless tire model. The TWEEL’s diameter and width were 860 and 309 mm, respectively. The finite element (FE) model of the TWEEL was created and analyzed by using MSC.Patran and MSC.Marc software, respectively. These are the FE software. A hexagonal element was employed to create the tread and shear band model while belt layers and spoke models were created by quadrilateral elements. The steel belt layers were inserted into shear band by creating rebar element which were embedded using a tying equation.

The parameters of the Ogden hyperelastic model, equation (1), and generalized Maxwell material model, Equation (2) and (3), which are suitable to describe material properties of airless tire components, are presented in Table 1 and Table 2, respectively [12].

To validate the FE model, the TWEEL airless tire model is compressed by using a rigid flat plate according to tire stiffness testing as shown in Figure 2. The Hermann element was selected to prevent the excessive stress due to volumetric locking.

\[ W = \sum_{n=0}^{3} \mu_n \left( \lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3 \right) \]

where \( W \) is the strain energy density per unit volume, \( \lambda_i \) is the principal value of the stretch tensor while \( \mu_i \) and \( \alpha_i \) are material constants.

\[ G(t) = G_0 - \sum_{i=1}^{n} G_i (1 - e^{-t/\tau_i}) \]

\[ \tau_i = \eta_i / E_i \]

where \( G(t) \) is shear relaxation modulus, \( G_0 \) is shear modulus at initial time (t=0), \( G_i \) is \( i^{th} \) term of shear modulus, \( \tau_i \) is \( i^{th} \) term of relaxation time (s), \( E_i \) is modulus of elasticity and \( \eta_i \) is viscoelasticity.

| Component          | Ogden’s constant |
|--------------------|------------------|
|                    | \( \mu_1 \)       | \( \mu_2 \)       | \( \alpha_1 \) | \( \alpha_2 \) |
| Tread and Shear Band| 1.15673          | 1.06228          | 5.37146       | -2.31827       |
| Spoke              | 0.112983          | -11.0664         | 3.1488        | -1.75206       |

| \( i^{th} \) | \( \tau_i \) | \( G_i \) |
|-------------|------------|-----------|
| 1           | 0.2        | 0.125     |
| 2           | 0.02       | 0.125     |
| 3           | 0.002      | 0.125     |
The boundary conditions of a rotated TWEEL airless tire on a drum surface according to drum testing methods are presented in figure 3(a). The diameter ratio between the drum and TWEEL airless tire was 2. Multipoint constraints (MPCs) were performed to mimic the rim which were tied together at tire center. Two steps to simulate the transient tire testing model were performed. The first step, the rigid drum was moved to press the tire model with a compression force of 14,000 N. The final step, the rigid drum was rotated at a speed of 11 km/hr. The tire model was induced to rotate at the desirable speed by using a contact algorithm. The friction coefficient between tire and surface was found to be 0.8 [13].

The boundary conditions of the rotated TWEEL airless tire on a flat surface are presented in Figure 3(b). The rigid rim was controlled by a FE node at the tire’s center. In this case, a rigid flat surface was fixed while the airless tire model was moved to compress on the rigid flat plate with a compression force of 14 kN. After that, the airless tire model was rotated with a velocity of 11 km/hr. These boundaries were controlled on a rigid rim. The transient dynamic FEM was carried out by using the implicit method. The solution of transient FE implicit analysis is calculated by the single step Housbolt method as written by the following equations.

\[ u_{n+1} = u_n + \gamma \Delta t \dot{u}_n + \gamma_i \Delta t u_{n+1} \]
\[ u_{n+1} = u_n + \Delta t \dot{u}_n + \beta \Delta t^2 \ddot{u}_n + \beta_i \Delta t^2 \dddot{u}_{n+1} \]

where \( u \) is the time-dependent displacement field, \( \gamma_i \) is a defined constant, \( t \) is time and \( \beta \) is a constant.

![Figure 2](image1)

**Figure 2.** The FE model of the compression of the TWEEL airless tire on flat surface, (a) boundary conditions and (b) an isometric view.

![Figure 3](image2)

**Figure 3.** The boundary conditions of the rolling TWEEL airless tire on: (a) drum surface and (b) flat surface.
4. Results and Discussion

4.1 Validation

According to tire stiffness testing, the vertical force and deformation of the compressed TWEEL FE model were recorded. Figure 4(a) presents the comparison between the simulation and the experiment of the TWEEL airless tire deformation. The average tire stiffness of the experiment and the simulation were 951.01 and 846.42 N/mm, respectively. The simulation result had a good accord with the experimental result. It had an average error of less than 11%. The deformation of TWEEL airless tire model is presented in Figure 4(b). The maximum and minimum displacement were presented in yellow and blue, respectively. The result showed that the maximum deformation occurred on the compressed spokes. At the same time, the upper spokes which were not compressed, were stretched instead. That cooperation structure was one of the advantages of airless tires.

The spoke deformation at various rolling angle was detected by collecting nodal coordinates of spoke shown in Figure 5(a). Image processing using a high-speed video camera was performed to collected spoke positions from the experimental results. The comparison of spoke deformations at 30°, 60°, 90°, 120°, 150° and 180° is presented in Figure 5(b). The simulation results of the TWEEL airless tire rolling on a drum surface showed a good accord when compared to the experimental results. It had an average error of 3.51% with simulation time of 329.71 hours [13]. The simulation with the drum surface consumed a lot of simulation time due to complex contact and small-time step for analysis. Then, the FE model of the rotated TWEEL airless tire on flat surface was developed to reduce these complexities. The spoke deformation at each rolling angle between a rolling airless tire on a flat and drum surface was also found to be in a good accord. The deformation of spoke of TWEEL airless tire testing which was modelled on a flat surface was different on drum surface of 1.14%. The rolling airless tire on a flat surface model was found to have the advantage of using less analysis time than the drum surface model by 10.13 times.

Figure 4. (a) The vertical displacement vs. compression force graphs and (b) the deformation of FE model under a compression force of 14 kN.

Figure 5. (a) The schematic diagram of collected rolling angle and (b) comparison of spoke deformation at various rolling angles.
4.2 Comparison of two different surface for rolling airless tires

Footprint analysis is an important criterion to indicate tire-road adhesion ability and tread wear. The footprint area (FA) is an overall contact area of a tire on the ground. On the other hand, the contact area (CA) is an actual contact area [14]. In this research, the contact area of rolling TWEEL airless tire model on flat surface was compared against the rotated model on drum. Figure 6 shows the comparison of contact patches on the different floor surface. At the initial state, the TWEEL airless tire was compressed by a compression force of 14,000 N. The contact area of TWEEL airless tire which was compressed by the drum was smaller than flat surface. This showed the effect of curvature on the surface of a drum. After the tire model was rotated at 90 degrees, the footprint still happened like in the initial position. It was found that the difference of contact patch at initial and 90 degrees could be neglected. The result indicated that contact area which occurred from the rolling tire model on a flat surface was a little bit bigger than the rolling on a drum surface. The contact area on a flat surface was different from the drum surface by just 56.78 cm$^2$.

In the stress analysis case, it was found that the stress distribution of the TWEEL airless tire rolling on flat surface was extensive with an analogous contour under a constant compression load of 14,000 N. The intense stress of TWEEL airless tire rolling on a drum surface is a little bit higher than the flat surface (Figure 7). The value of stress was separated as color bars which were placed beside each color contour plot.

![Figure 6](image_url)

**Figure 6.** Footprint of the rolling TWEEL airless tire on: (a) drum surface and (b) flat surface.

![Figure 7](image_url)

**Figure 7.** Contact stress of the rolling TWEEL airless tire on: (a) drum surface and (b) flat surface.
The effect of the curvature surface of the drum was found to be the reason for the different stress which could be observed at the center of contact patches. The arc of the rigid drum surface compressed the tread of the TWEEL airless tire model. The average difference of contact area and maximum stress of both models was only 26.97% and 14.22%, respectively. There are two criteria to indicate performance of these models. The overall results of the FE model of the rolling TWEEL airless tire on a flat surface were accepted to save computing time.

5. Conclusion
The TWEEL airless tire, which was created to overcome the disadvantages of a conventional pneumatic tire, was studied. Knowledge of the static and dynamic behavior of a tire is essential in complete tire development. To study tire static behavior, tire stiffness testing was performed and used to validate the TWEEL airless tire FE model. The vertical stiffness of the TWEEL tire model had a good accord with that of the experiment. Next, the TWEEL airless tire model was extended for the purpose of a dynamic behavior study. The FE model of rolling TWEEL airless tire on a flat surface was developed to provide high accuracy while having little simulation cost. A transient dynamic FE model with a visco-hyperelastic material model was developed. The spoke deformation and footprint analysis presented a good compatibility between the two different surfaces. The calculating time of the rolling tire on flat surface was 10.13 times less than the FE model of rolling a TWEEL airless tire on a drum surface. To achieve a desirable tire performance, the FE model of rolling a TWEEL airless tire on a flat surface in this research will be used to study various rolling airless tire parameters in the future.

Acknowledgments
This work was supported by Rubber Technology Research Center (RTEC), Mahidol University and the Thailand Research Fund (TRF) under the TRF Research Grant No. RDG60T0140.

References
[1] Rugsaj R and Suvaranjumrat C 2020 Mech. Based Des. Struct. Mach. DOI:10.1080/15397734.2020.1777875
[2] Xiaochao J Cheng H Xueling F Yongle S Jinan L and Chunsheng L 2018 Compos. Struct. 187 27-35
[3] Phromjan J and Suvaranjumrat C 2018 J. Mech. Sci. Technol. 32(4) 1539-1548
[4] Liang C Wang G An D and Ma Y 2013 Chin. J. Mech. Eng.-En. 26(3) 506-511
[5] Ansorge D and Godwin R. J 2007 Biosyst. Eng. 98 115-126
[6] Tiwari V K Pandey K P and Sharma A K 2009 J. Terramechanics 46 293-298
[7] Mardahi A Shahidi K and Maslak H K 2010 J. Food Agric. Environ. 8(2) 642-646
[8] Phromjan J and Suvaranjumrat C 2018 Engineering Journal 22(2) 141-155
[9] Phromjan J and Suvaranjumrat C 2018 Key Eng. Mater. 777 416-420
[10] Omar G Ciro E I C Elvis L B Carlos A R M and Miguel H S 2016 J. Terramechanics 63 61-67
[11] Farhadi P Golmohammadi A Malvajerdi A S and Shahgholi G 2019 Comput. Electron. Agric. 162 793-806
[12] Rugsaj R and Suvaranjumrat C 2019 Int. J. Automot. Technol. 20(4) 801-812
[13] Rugsaj R and Suvaranjumrat C 2020 IOP Conf. Ser., Mater. Sci. Eng. 886 012056
[14] Phromjan J and Suvaranjumrat C 2020 IOP Conf. Ser., Mater. Sci. Eng. 886 012049