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THE DYNAMIC FINITE ELEMENT MODEL OF NON-PNEUMATIC TIRE UNDER COMFORTABLE RIDING EVALUATION

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ABSTRACT: The Non-Pneumatic Tire (NPT) has design potential to have desired mechanical characteristic upon usage requirements. The NPT also has no restriction on inflation pressure, maintenance, and less damage possibilities due to flat while driving. The optimum design of NPT to have required load carrying capacity and vertical stiffness can be easily achieved by mean of static Finite Element Method (FEM) with appropriated material models. However the models to predict dynamic response such as tire structure to road pavement interaction, shock absorption and ride comfort are still needed. This paper aims to develop FEM to study dynamic characteristics and evaluate the ride comfort property of the NPT. The FEM of NPT, which composed of Tread band and Spokes, was 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 visco-hyperelastic constitutive model was used to model the mechanical behavior which depends on time of the NPT's components. The FEM of NPT was then assigned to traverse across cleats with different heights to study the effect of obstacle on tire-road interaction and dynamic response of NPT. The impact force history and deformation behavior of NPT at any given time was analyzed. The results were compared to discuss the validity of the model to capture important dynamic characteristic that considered useful in designing of NPT to have ride quality challenging the commonly used pneumatic tire.

Keywords: Non-pneumatic tire, Finite element method, Tire-road interaction, Ride Comfort, Impact force

1. INTRODUCTION

The basis function of pneumatic tire, which is an important vehicle component, is to provide the vehicle to road interface, to support vehicle load, to provide road surface friction, and to absorb road irregularities. In that regards, the design of pneumatic tire requires some performance parameters such as the riding comfort, handling and traction criteria to be engineered to meet desired characteristic. However, the pneumatic tires have several disadvantages since the tire possess the risk to undergo severed damage or flatted if the tire traversing across various types of critical obstacles [1]. The Non-Pneumatic Tire (NPT) or airless tire was developed to overcome these disadvantage. The NPT was designed to exhibit desired characteristics of the pneumatic tires without requirement of the inflation pressure. The first available commercial NPT is TWEEL developed by Michelin. The Tweel, consists of two main components which are 1) circular shear beam and tread 2) elastic spokes which connected to a hub. The NPT can be designed to have required vertical stiffness and contact pressure upon spoke geometry and material without limit to size and pressure, unlike traditional pneumatic tire. The non-pneumatic tire's lateral stiffness which affects handling and cornering can also be independently optimized with vertical stiffness which affects the riding comfort [2].

The vehicle stability and ride comfort is important tire performance especially on off road vehicle which traversing over various type of irregular terrain and obstacles. The transient dynamic characteristic of a tire has significant effect on vehicle handling stability. However the transient dynamic effect is difficult to study due to its highly non-linear behaviors. The effects of obstacle geometric factors during tire-obstacle collision was study using soil-bin facility equipped with a single-wheel tester. The various obstacle shapes along with different depth were varied in the experiments which operation condition of wheel traversing such as speed and load were controlled. The maximum and minimum induced impact force were observed from highest triangular shape and trapezoidal shape obstacle respectively [3]. Normally transient dynamic characteristic of the rolling tire can be determined by using drum testing method. However the drum testing method has limitation if the effects of pavement surface, roughness, or obstacles such as cleat or ditch are interested. The Finite Element Method (FEM) can be used to simulate the tire behavior during rolling under critical conditions. A

FEM of tire was developed to perform tire enveloping tests in transverse obstacles of different sizes using explicit dynamic solution in finite element software ABAQUS. The tire transient dynamic behavior was investigated by analyzing the effects of tire rolling velocity and obstacle height on spindle force, dynamic stiffness, and tire deformation. [4]. The 3D FEM based on dynamic transient approach of Mechanical Elastic Wheel (MEW) traversing over a ditch was developed to study transient dynamic characteristic of MEW. The radial stiffness and footprint of MEW were analyzed and compared with the experiment to validate the model accuracy. A dynamic analysis of MEW over a ditch was conducted using ABAQUS. The equivalent stress and contact stress was analyzed to study effects of rolling speed [5].

The tire, which is considered as viscoelastic material, undergoes cyclic deformation during rolling on the road surface. The stress and strain field under cyclic loading exhibit phase delay between strain and stress time histories, which is the cause of hysteresis energy loss [6]. Thus, the development of thermomechanical model with viscoelastic material is required to predict the dynamic characteristic of the rolling tire. NPT, which components are made from low viscoelastic energy loss materials, can be a good option for developing tires with low rolling resistance. 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 hyperelastic model was obtained from the tension and compression tests, while viscoelastic material properties were obtained from Dynamic Mechanical Analysis (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 temperature distribution from the experiments [7]. 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 [8].

Design of NPT is needed to consider the tire performances which dynamic characteristic such as tire–road interaction, rolling resistance, and riding comfort, play an important factor. This paper aimed to develop the 3D FEM of NPT based on viscohyperelastic material model that can be used to predict NPT performances regarding dynamic characteristic.

2. FINITE ELEMENT MODEL OF NON-PNEUMATIC TIRE

The commercial NPT Tweel 12N16.5 SSL ALL TERRAIN airless radial tire developed by Michelin (Fig.1), which is the first available NPT, was selected to study the mechanical behavior and characteristic of NPT. The FEM of NPT was modeled using the FE software MSC.Patran. The NPT model composed of 4 main components which can be concluded as follows: 1) tread, 2) shear band, 3) belt layers, and 4) polyurethane spoke. The FEM of NPT along with its overall dimension and components is shown in Figs. 2,3, and 4 respectively. The hybrid formulation or Hermann formulation was used to model the tread and shear band elements of NPT. The formulation utilized the separated integration of pressure and displacement field, which can be used to prevent volumetric locking that may occur during loading of rubber material elements. The thick shell approximation is used to model the spoke. The details of elements which are used in modeling of NPT which shown in Table 1. The thickness of each shell elements was assigned differently based on the actual thickness distribution measured from the real spoke. The thicknesses at outer and inner ring of the spoke were 6 and 7 mm, respectively, while the averaged thickness of the spokes could be calculated relating to the spoke weight that was 5.8 mm.

The belt layer consisted of four main layers which were 1) the outer layer, 2) the 1st middle layer, 3) the 2nd 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 belt layer model was developed using reinforce bar or rebar element [9]. The rebar elements of the belt layer were embed into the rubber element using tying equations. The value of the degrees of freedom of the nodes in host body element was tied based on their isoparametric location in the elements.

The cross section of shear band of the FEM and real TWEEL along with the embed belt layer position is shown in Fig. 5. The details of the elements using in each layer are described in Table 2.

Fig.1 NPT Tweel 12N16.5 SSL ALL TERRAIN.

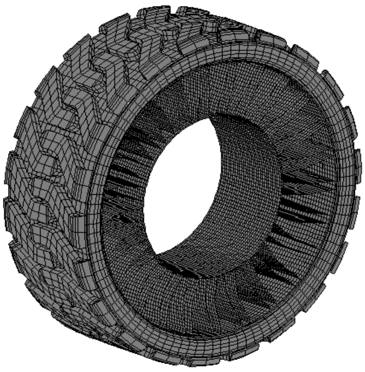

Fig.2 Finite element model of non-pneumatic tire.

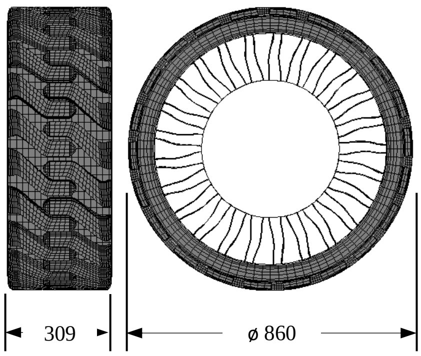

Fig.3 Overall dimension of NPT's FEM.

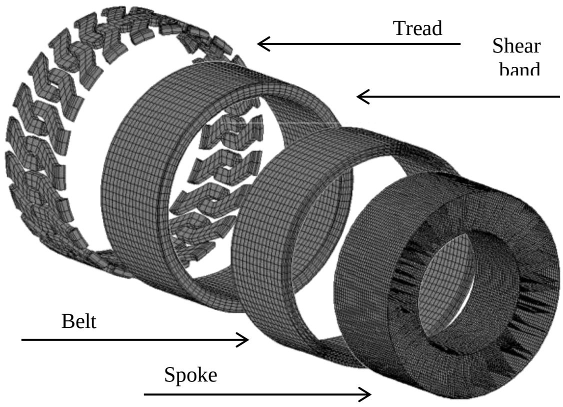

Fig.4 Components of FEM of NPT.

Table 1 Details of elements used in FEM of NPT

	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

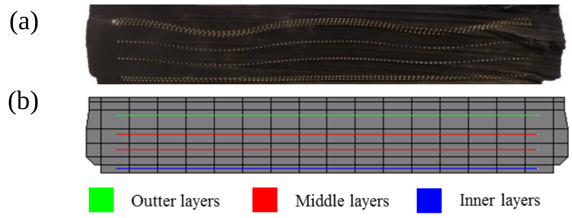

Fig.5 Cross section of shear band with embed belt layers of (a) FEM (b) TWEEL.

3. HYPERVISCOELASTIC MATERIAL MODEL

The Ogden hyperelastic constitutive model was used to model nonlinear elastic behaviors of rubber tread, shear band, and polyurethane spoke.

The general form of Ogden hyperelastic model [10] can be expressed as Eq. (1):

$$ {}_{0}^{t}\tilde{W} = \sum_{n=1}^{3} \frac{\mu_n}{\alpha_n}\left(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3\right) \quad (1) $$

where λ_i are the principal value of the stretch tensor ${}_{0}^{t}U$, μ_i and α_i are material constants. The inelastic behaviors of NPT components were modeled using the generalized Maxwell viscoelastic material model. The generalized Maxwell viscoelastic model can be express as Eq. (2), (3).

$$ G(t) = G_0 - \sum_{i=1}^{n} G_i\left(1 - e^{-t/\tau_i}\right) \quad (2) $$

$$ \tau_i = \eta_i / E_i \quad (3) $$

where $G(t)$ is Shear Relaxation Modulus, G_0 is Shear Modulus at time, $t=0$, G_i is ith term of Shear Modulus, τ_i is ith term of Relaxation Time (sec), E_i is Modulus of Elasticity, and η_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 3 and 4, respectively [7,11]. The compressive testing and tensile testing was performed on the cylindrical shape and dumbbell shape specimens, which were prepared from NPT's tread and spoke respectively. In addition, steel the belt layers were modeled using linear elastic material with modulus of elasticity (E) of 200 GPa and Poisson's ratio of 0.3.

Table 3 Hyperelastic constants of NPT components.

Constant	Component	
	Spoke	Shear Band
λ_1	0.112983	1.15673
λ_2	-11.0664	1.06228
α_1	3.1488	5.37146
α_2	-1.75206	-2.31827

Table 4 Viscoelastic constants of NPT components.

i^{th}	τ_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 ANALYSIS OF OBSTACLE TRAVERSING

The FEM of NPT was combined with road surface model for obstacle traversing analysis of NPT. The tread and shear band was assigned to be in contact with the road surface with friction coefficient of 0.8. The Coulomb's friction model was used to evaluate the friction force which occurred between the tire and road surfaces. The cleat surface was attached to road surface for the purpose of obstacle traversing simulation. Three size of rectangular shape cleat surface was selected in this research to study the effects of obstacle geometry to dynamic behaviors of NPT. The schematic diagram of installation and placement of NPT FEM onto the road and cleat surface along with its boundary conditions is shown in Fig.6. The cleat surfaces are varied in height, which the schematic diagram of each cleat dimension is shown in Fig.7 and are summarized in Table 5.

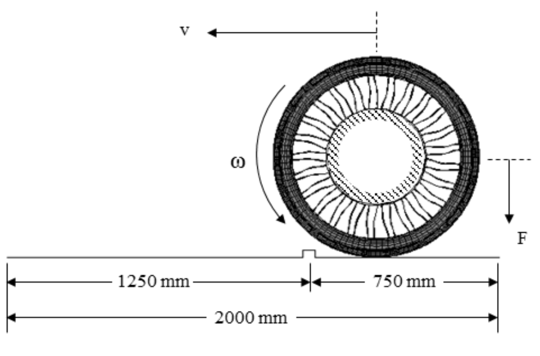

Fig.6 Boundary conditions of NPT combined with road and cleat surfaces.

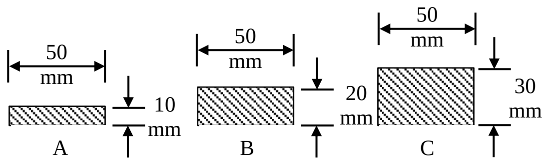

Fig.7 Detail of cleats dimension with different height (A) 10 mm (B) 20 mm (C) 30 mm

Table 5 Details of cleat dimensions.

Cleat	Length	Width	Height
A	500	50	10
B	500	50	20
C	500	50	30

The hub of NPT was modeled as rigid surface, which was assigned to be perfectly glued contact with the inner ring of spoke. The vertical load of 5 kN was assigned to the center of rigid hub, which was also applied to move forward at the speed (v) of 10 km/hr with corresponding angular velocity (ω) of 3055.6 rad/sec.

The dynamic transient analysis was performed using finite element software MSC.Marc, The analysis was divided into 2 main stage, which was 1) loading stage, and 2) rolling stage. At $0 < t < 1$ sec., the NPT was assigned to be loaded with force gradually increase from zero to maximum force of 5 kN while the tire was assigned to be stationary. At $1 < t < 1.4$ sec., after the NPT was fully loaded, the tire was assigned to be rotated and moved forward while the maximum force was still applied. The force and displacement history were collected after the analysis was complete at t = 1.4 sec to study the tire-road interaction and dynamic behaviors of NPT. The stress and deformation of NPT FEM at t = 1 sec., which is when the vertical force is fully applied, is shown in Fig. 8. It should be note that the analysis at this stage was corresponding to vertical stiffness testing of tire at maximum force 5 kN, which the vertical stiffness was founded to be 648.7078 N/mm.

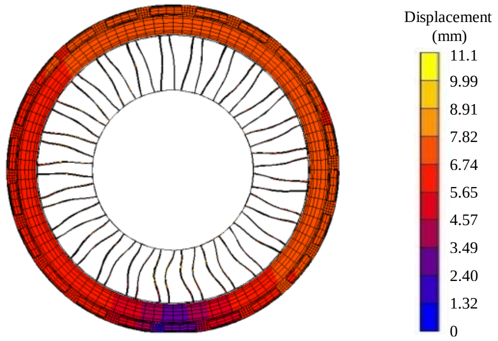

Fig.8 Displacement and deformation result at t = 1 sec and F = 5 kN.

In addition, the spokes at the upper portion of

NPT was observed to be in tension, while the spokes at lower portion was observed to be in bending mode. The tire-road interaction and deformation at various time t are shown in Fig.9.

The impact force and vertical displacement history at hub center were collected, which the vertical displacement was normalized to exclude initial displacement due to deformation at t = 1 sec where the load was fully applied. The normalized vertical displacement of tire center and impact force at various time are shown in Figs. 10, 11 respectively. The average vertical displacement of tire center and average impact force along with their maximum values can be concluded as shown in Fig. 12 and Fig. 13, respectively. The summarization of average normalized displacement at tire center and average impact force can be concluded as shown in Table 6.

a)

b)

c)

d)

e)

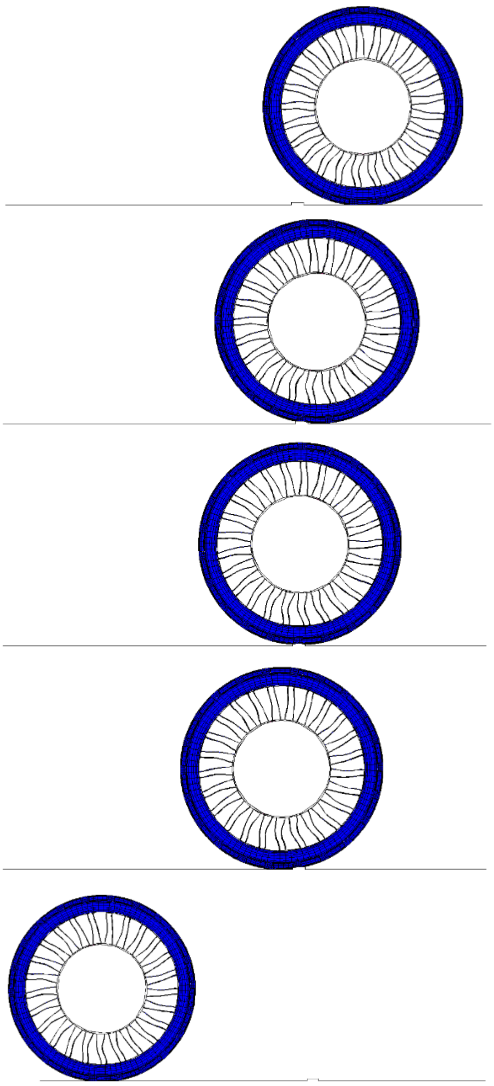

Fig.9 Deformation and tire-road interaction of NPT at a) t = 1 sec, b) t = 1.72 sec, c) t = 1.88 sec, d) t = 1.14 sec, and e) t = 1.40 sec.

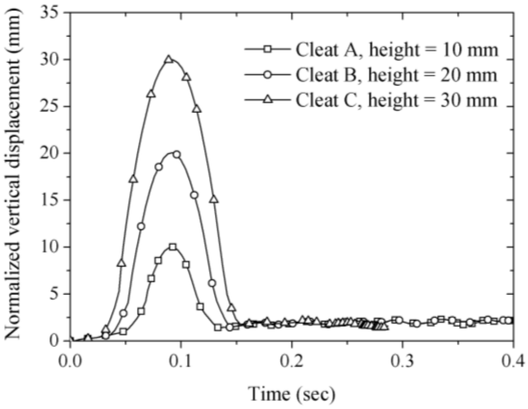

Fig.10 Vertical displacement at various time.

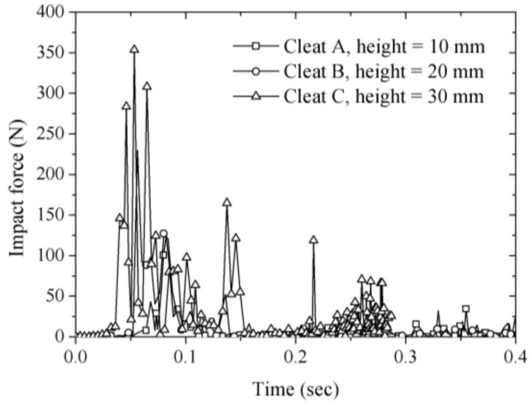

Fig.11 Impact force at various time.

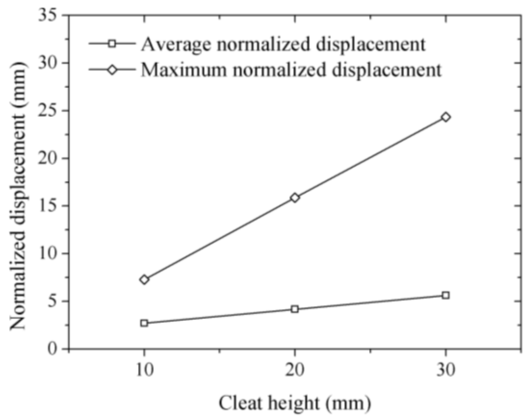

Fig.12 Vertical displacement at various cleat heights.

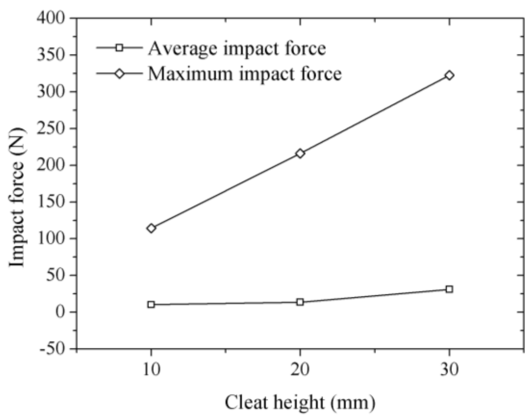

Fig.13 Impact force at various cleat heights.

Table 6 Summarization of average normalized displacement and average impact force.

Cleat	Height	Average normalized displacement (mm)	Average impact force (N)
A	10	2.706719	10.26311
B	20	4.184955	13.68296
C	30	5.617848	30.87236

The NPT model with highest cleat (height = 30 mm) was shown to yield greatest value of both average vertical displacement of tire center and average impact force. However the oscillatory response after the NPT rolled down a cleat was scant when compared with pneumatic tire [12-15]. Considering the observed underdamp characteristic of the oscillatory, the NPT has potential to be optimized the ride comfort properties for the vehicles.

5. CONCLUSION

The FEM of NPT was developed to study dynamic characteristics and evaluate the ride comfort property of the NPT. The FEM of NPT, which composed of Tread, shear band and Spokes, was modeled 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 validated Ogden hyperelastic material model and generalized Maxwell viscoelastic material model were used to model nonlinear elastic and inelastic behaviors of NPT components. The FEM of NPT was then assigned to traverse across cleats with different heights to study the effect of obstacle on tire-road interaction and dynamic response of NPT. The impact force history and deformation behavior of NPT at any given time was analyzed. The results were compared to discuss the validity of the model to capture important dynamic characteristic. The FEM of NPT with highest cleat (height = 30 mm) was shown to yield greatest value of both average vertical displacement of tire center and average impact force at 5.617848 mm and 30.87236 N respectively. The underdamped oscillatory behavior was observed from vertical displacement and impact force, which shown that NPT has potential to be optimized regarding ride comfort properties. The analysis results shown that the devloped hyperviscoelastic dynamic FEM of NPT can be used in designing of NPT to have dynamic characteristic such as ride quality for challenging the commonly used pneumatic tire.

6. ACKNOWLEDGMENTS

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