The Contact Patch Analysis of Solid Tire on Drum Testing by Finite Element Method

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Abstract
The drum testing method is an effective method to study the tire-rotating characteristic. The rolling resistance and contact force are carried out for tire performance development. The tire was tested by the cylindrical drum indoor laboratory. Thus, the contact patch of rolling solid tire on the drum surface should provide the same results as the tire testing on a flat surface. This research uses a finite element method to develop the drum testing of solid tire model and to investigate the contact patch. The compressed contact patches of solid tire on drum were compared with the validated contact patches of solid tire on the flat surface. The different results showed the effect of the drum curvature. Consequently, the diameter of the drum wheel was optimized for solid tire testing. It is interesting to note that the suitable ratio between drum diameter and solid tire diameter was 1.81.

Keywords: Solid Tire, Contact Patch, Drum Testing, Finite Element Method

1. Introduction
The solid tire is important in the support of the heavy load and plays a key role in the industry. The purpose of this investigation is to develop solid tire performance. This study uses the performance of the tire testing to provide the physical behavior of tire. Evidence suggests that the drum testing is among the most important method for testing a rolling tire in the laboratory [1]. To mimic the flat road, a large diameter drum was selected to provide the contact patch characteristic between tire and drum. The diameter of the steel drum was 1.7 m. and was presumed the suitable drum diameter for study contact force response of rolling solid and pneumatic tires [2]. It could indicate the peak-to-peak of the contact force between solid tire and drum. It was also found that it was higher than the contact force of a pneumatic tire. Moreover, the drum testing machine was performed to study the noise and vibration behavior of a rolling mechanical system by using tire to represent the flexible ring model. The Laser Doppler Vibrometer (LDV) was installed with drum testing machine to measure the vibration velocity of rolling tire [3]. Previous research findings into the drum testing method have been consistent to investigate the air-related tire noise generation mechanisms (e.g. Eisenblatter et al.,
Researchers attempted to evaluate the impact of the drum testing on the small tire with the ratio between drum and tire diameter of 41.67. The experimental results from the drum testing were compared well with an existing theoretical model. Nowadays, the computer-aided design (CAD) and computer-aided engineering (CAE) have been employed popularly to develop the tire performance. Prior to the work of Palanivelu et al., (2015), the role of the explicit finite element analysis was largely used to simulate a tire rolling for the development of tire noise generation mechanisms model. The finite element tire model with OMA technique was compared with the experiment. The results indicate that the established procedure can be used to study the dynamic behavior of tire and road interaction. Wei and Olatunsun (2014) [6] studied and validated the effect of different height obstacle on pneumatic tire behavior traversing by the finite element method (2.44 m. drum diameter). Besides, the transient dynamic responses of a pneumatic tire rolling over road obstacles were investigated. Using this approach, researchers have been able to simulate the speed and height of obstacle, which shows a significant influence on reaction force between tire and road. Using the resonant amplitude of vertical force, we were able to increase the speed of the tire and the tire deformation when the tire impacted the higher obstacle. Moreover, the drum testing method was created to develop the accurate simulation of a pneumatic tire rolling over cleat by 3-D finite element method [7]. Besides, the drum was modeled with a rigid element. The tire rolling speed gave a remarkable influence while the change of the tire inflation pressure only produced a remarkable variation in vertical dynamic force. Unfortunately, the large drum, which was used to represent the flat road, has to use a lot of resources for finite element analysis. The diameter of the steel drum is one of the most common characteristics, which might affect the rolling solid tire was studied by 3D finite element analysis. The 3D finite element analysis was developed in this research. Also, the diameter of the drum wheel was optimized to reduce the computing time for simulation the rolling solid tire.

2. Solid Tire Testing on Flat Surface

The solid tire sizes of 6.00-9.00 inch KOMACHI series II was used in this study. As can be seen in Figure 1 the KOMACHI series II consists of three main rubber layers and they were assembled comprising internal, middle and tread layer. To obtain the rigid the internal layer, the four steel rings were inserted. The tire stiffness tester (EKTRON TEK model: PL-2003) was the testing equipment and used to study the solid tire stiffness and the solid tire contact patch. The testing was performed by mounting the solid tire with the mounting arms and raising the measurement table to press the mounted tire (see Figure 2). Using the deformation and looking at the compression force of solid tire, it was possible to identify press the mounted tire. Meanwhile, the contact patch of the solid tire also occurred on a pressure measurement film, which was placed between a solid tire and measurement table. This was the pigment of color on the film which illustrated the contact patch characteristics comprising footprint area, contact area and contact pressure. Figure 3 describes the contact patch characteristics of the KOMACHI solid tire. The red contour was a contact area (CA) while the footprint area (FA) was calculated by multiplying width (a) and height (b) of the red contour. Subsequently, this contour has been transformed into the contact pressure and contoured by the image processing method.

3. Finite Element Analysis

Analysis of a large strain was based on a hybrid formulation, which is effective for the analysis of rubberlike material [8]. The finite element analysis (FEA) of the solid tire testing was governed by the strain energy density per unit volume, \( \dot{U} \), and is written by the following equation (1).

\[
d_0 \dot{U} = \int_0^s d \dot{\epsilon} \phi
\]  

(1)
Figure 1. The KOMACHI series II solid tire (a) overall dimension and (b) the inside structure.

Figure 2. The tire stiffness tester, EKTRON TEK model: PL-2003.

Figure 3. The contact patch result by (a) a pressure measurement film and (b) image processing translation.

where $d_0 \delta U$ and $d_0 \delta S$ are incremental potential energy and Piola-Kirchhoff stress which was computed only from the displace field. The integral form of a total Lagrangian formulation is shown in equation (2).

$$ \int_{V_0} \delta S \delta \varepsilon dV_0 = R $$

The general form of a principle of virtual work, which was written in the total Lagrangian formulation, is given by equation (3).

$$ \delta \left( \int_{V_0} \delta UdV_0 \right) = R $$
where $U$ is the incremental potential which can be modified to include the effect of interpolated pressure by adding to the term of the displacement based on the total element pressure.

### 3.1 Solid tire model

The rubber layers of KOMACHI solid tires were modeled using different material formulas for rubber compounds. The internal layer (M058) was the hardest, the middle (M047) and the tread layer were softer. The material property of each rubber layer was carried out using tensile testing, which is based on the ASTM D412 standard. To obtain a material model from the tensile testing results, the linear regression method was employed in order to fit with the stress-strain curves. The Ogden hyperelastic constitutive model (see Equation 4) which is a strain-energy density function. It is found that it is the most suitable material model to represent the solid tire deformation in all rubber layers [9]. The constant values of the Ogden constitutive model are presented in Table 1.

\[
U = \sum \frac{H_i}{\alpha_i} \left( \lambda_{1i}^{\alpha_i} + \lambda_{2i}^{\alpha_i} + \lambda_{3i}^{\alpha_i} - 3 \right) + 4.5K(J^{1/3} - 1)^2
\]

and $\lambda_i = J^{1/3}\lambda_1$, $J = \lambda_1\lambda_2\lambda_3$

where $\lambda_i$ is the deviatoric principle stretches, $J$ is the Jacobean determinant, $K$ is the initial bulk modulus, and $\mu_i, \alpha_i$ are constants.

| Rubber layer | $\mu_1$ | $\mu_2$ | $\alpha_1$ | $\alpha_2$ | $K$    |
|--------------|---------|---------|-----------|-----------|-------|
| M067         | 1.075   | 154.616 | 2.927     | 1.14e-7   | 7,866.61 |
| M047         | 0.362   | 510.855 | 3.233     | 0.0056    | 10,078  |
| M058         | 3,615.31| 2,915.36| 0.0028    | 0.0024    | 42,449  |

The 3-D solid tire model was created using miscellaneous methods: the 3D scanner and Computer-Aided Design (CAD) in response to the geometry of KOMACHI series II solid tire, which has 6.00-9.00 inch in size. Each component of the solid tire was divided by hexahedral elements. The rubber layer elements are presented by different colors, as shown in Figure 4(a). The internal, middle, tread layer and steel wires were assembled by 16,623, 8,448, 14,366 and 7,040 hexahedral elements, respectively. In Figure 4(b) there are finite element pouts that are connected by conjunct nodes regardless of the connection between the outer tread and the inner tread layer. Both of them were defined in the glue contact condition.

3.2 Compression testing of solid tire on flat surface

The purpose of the experiment was to set up the finite element model of the solid tire to compress on a rigid flat plate according to the physical tire stiffness testing. The multi-point constraint (MPC) was defined on nodes at the inner surface to link an axis of solid tire model and to model the steel wheel, which was installed by the solid tire. The fixed boundary is assigned at a wheel fixed point to mimic the solid tire that mounts on the mounting arm of the stiffness tester (see Figure 5a). The contact boundary condition between the solid tire model and the rigid flat plate was specified with the static friction coefficient of 0.8. Thus, the rigid flat plate was assigned to lift in a vertical direction to press the solid tire model with three different loads, 400, 800 and 1,200 (kgs), respectively.

3.3 Compression testing of solid tire on drum

To compress a solid tire model on the drum, the cylindrical steel drum was created using the curvature rigid element. The diameter of the rigid drum was adjusted to study the effect on the contact patch. It was varied in a range of 0.2 to 2.45 m., which was the feasible curvature of the drum surface.
The solid tire model was fixed at the wheel fixed point in the same method as the solid tire model and was compressed on a flat surface. The vertical load was assigned on a rigid drum to move and press the solid tire model at 400 kgs. The finite element model of the solid tire, which was compressed by the steel drum, was used to study the impact of curvature surface on a contact patch, as shown in Figure 5 b.

Figure 4. The finite element model of (a) solid tire components and (b) contact boundary conditions.

Figure 5. The finite element model of solid tire compressing by: (a) flat surface and (b) drum surface.

4. Results and Discussions

4.1. Validation
To assess the accuracy simulation, the contact patches of the experiment were carried out to validate the finite element model. There was comprised the contact patched by the vertical load of 400, 800 and 1,200 kgs. The contact coefficient of the solid tire model, which is the ratio of the contact area to footprint area (CA/FA), was used to be a benchmark. Figure 6 provides a contact patch obtained by the experiment and simulation. The results revealed that the contact patch of the solid tire model showed an agreement with the pressure measurement film. From the data, it shows a similar contact coefficient at 0.4. It can thus be suggested that the finite element model of the solid tire could simulate the contact patch on the curvature surface and obtain the accuracy results.

4.2. The effect of drum curvature
The mechanical behaviours of solid tire FE model i.e. vertical deformation, contact patch and contact pressure were used to investigate the effect of drum curvature. The finite element model of the solid tire,
which was validated on a flat surface, was carried out to compress on rigid drums by the compression load of 400 kgs. The small radius of the drum surface was intense to the contact pressure on the solid tire. It is possible to hypothesise that the bigger the vertical deformation increased by the small road, the smaller the footprint area was. Figure 7 shows the results of the simulation, the vertical deformation and the contact pressure of the compression testing obtained by the drum surface. The colour contour represents the results from the intense value of the simulation. It was found that the contact patch distribution was better at the larger drum. Particularly, the footprint area as found to be increased to constant values after the size of the diameter of the drum was larger than 0.95 m. The contact coefficient at the constant footprint indicated a good agreement on a flat surface. The experiment found an error, which is less than 4.90%. The vertical deformation and the contact pressure are decayed in the exponential form. At the drum diameter of 0.95 m, the vertical deformation and contact pressure were constant. As can be seen in Figure 8, the graphs from the simulation results regarding the diameter of the drum was varied.
Figure 7. The finite element analysis result of: (a) vertical deformation and (b) contact pressure under compressing of solid tire by various drum diameter.

5. Conclusion

The main goal of the current study was to develop the drum testing of solid tire using the finite element method. The contact patch by different compressing surface, flatness and curvature, were investigated. Concerning the benchmark, the contact patches of solid tire modelled by the flat surface compression were validated. The second aim of this study was to investigate the effects of that the finite element model was error less than 3.87%. The current study was designed to determine the effect of curvature surface by testing the solid tire with drum. This study has found that generally the diameter of rigid of the drum was in a range of 0.2 to 2.45 m. Also, it was found out that the small drum causes the vertical deformation. In addition, the higher the contact pressure, the smaller the footprint area was. The results of the distribution of the contact patch was satisfied when the solid tire was compressed by the larger drum. In regards of the analysis of the finite element, the results indicated that the contact patch characteristic of the solid tire model was constant at the drum diameter ranged from 0.95 m to 2.45 m. The contact patch at those state showed a good agreement with the compressing solid tire of the flat surface. The research has also shown that the experiment of the optimum drum diameter of the solid tire suggested a ratio of the tire diameter 1.81. These findings have significant implications for the understanding of how to reduce cost of the drum testing machine and to reduce the time-consuming process of the tire testing simulation.
**Figure 8.** The vertical deformation and contact pressure of solid tire compressing on various drum.

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