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<td>load, velocity, vibration, solid tire, towing tractor</td>
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Experimental Study the Effect of Load and Velocity on Vibration of Solid Tire

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

\textsuperscript{1}Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom, 73170, Thailand

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

* Corresponding author, Email address: chakrit.suv@mahidol.ac.th

Abstract

This research aimed to analyze the vibration characteristics of solid tires which affected to the baggage towing tractor driving in the airport apron of Suvarnabhumi International Airport, Thailand. The drum testing method had been performed to measure the vibration of KOMACHI solid tires (size 6.00-9 inch) by means of the contact force during solid tire rolling on a drum. The characteristic curves of solid tire were proposed to be advance for estimation of the vibration effects on KOMACHI solid tires. The peak-to-peak of contact force which happened by the compression load on the rolling tire was a severe effect on the tractor suspension. The limitation of the compression load on the KOMACHI solid tire was 400 kg.

Keywords: Load, towing tractor, velocity, vibration, solid tire
1. Introduction

The baggage towing tractor is widely used to tow the baggage carts in the airport apron. The pneumatic tires have a short life when they have been used with the tractors of the Thai Airways International Public Company Limited. The solid tire was carried to use with the tractor instead. The long life and heavy weight supporting are the main expectation for using solid tires. Unfortunately, the vibration happens on the tractor riding which affects to the rapid damage of tractor suspension.

The tire vibration is an important study for the tire development. Nguyen and Inaba (2011) studied the effects of tire inflation pressure and tractor velocity on vibrations. The vibration which was transmitted by the pneumatic tire through the rear axle was measured using a tri-axial accelerometer. Cuong, Zhu, and Zhu (2013) also studied effects of tire inflation pressure and speed on vibration of a tractor. The root mean square (RMS) of acceleration always increases following tractor speeds at a constant inflation pressure. The tire inflation pressure reduction could reduce the tractor vibration. The pneumatic rolling tire had been affected by the dynamic tire stiffness which was classified into vertical, sidewall, and enveloping stiffness. The sidewall stiffness had the greatest effect on the vibration of tire (Kang, 2009). The vertical stiffness of the pneumatic agricultural tire could be determined by rolling the testing tire along the hard surface. The oscillation of the test frame which connected the axle of tire and pivot point was measured by the potentiometer to calculate the tire stiffness (Taylor, Bashford, & Schrock, 2000). The carcass stiffness of the agricultural tire could estimate well using the pressure mapping method (Misiewicz, Richards, Blackburn, & Godwin, 2016). The pneumatic agricultural tires (smooth and treaded tire) were determined the carcass stiffness on hard surfaces using the footprint area method, the tire load or deflection...
method, the pressure mapping method, and the manufacturer’s specification method. The vibration behavior of pneumatic tires could measure on an instrumented drum wheel (IDW) at a laboratory. Schwartz (2001) presented a new methodology which made the correlation of high-speed tire vibrations with the measuring behaviors on IDW comprising of the longitudinal force vibration (LFV), the radial force vibration (RFV), and the radial run out (RRO). The LFV had strong speed dependence while RFV and RRO did not. The effects of tire vibration are not only the tire inflation pressure and vehicle speed, but also are the road surfaces. Kindt, Sus, and Desmet (2009) analyzed the rolling tire vibration due to the road impact excitations using Laser Dropper Vibrometry. The radial tire was set to rotate against another radial tire. The excitation amplitude dependency which built by mounting a cleat on the driven tire was restricted to the tire sidewall stiffness. The contact forces happened on the tire tread comprising of the vertical, longitudinal and transverse contact force. Lundberg, Kari, and Arteaga (2017) measured the three force components which were generated in the rolling contact between a tire tread block and substrate. The internal drum test had been used for the force measurements and the high signal was obtained from the vertical contact force.

The effects of pneumatic tire vibration which depended on the tire inflation pressure, vehicle velocity and road surface roughness could be determined by the drum testing method at a laboratory. The drum testing had been proper to determine the vibration effects of the solid tire which were the dynamic response. Unfortunately, the solid tire vibration lacked for vibration studies in the previous reviews. In order to know the effects of vibration on the usage conditions of solid tires, the objectives of this research are as follows to: (a) estimate the effect of load and velocity on the vibration of solid tire, and (b) determine the correlation of solid tire vibration with load and velocity.
2. Methodology

The baggage towing tractor of the Thai Airways International Public Company Limited which is used in Suvarnabhumi International Airport is shown in Fig. 1. The solid tire was used with the tractor which had the minimum weight about 1,350.00 kg. This tractor was the smallest model. The main tractor weight is at the front engine; therefore, solid tires were installed at the front wheel while the rear wheel still be the pneumatic tires. In the daily usage to tow the baggage carts, the baggage towing tractor is driven with the speeds from 10 km/h to 50 km/h. The failure or blowout phenomena which used the solid tire under severe conditions such as overloading, high speed, or high temperature work place were out of interesting.

2.1 Solid tire characteristic

The solid tires were manufactured by V. S. Industry Tyres Co., Ltd in Thailand which made of natural rubber. The three different compound rubber layers were the construction of solid tires. The solid tires, KOMACHI, are selected to use with the tractor and are shown in Fig. 2. There were used three KOMACHI solid tires for the drum testing. The specification of solid tire is described in Table 1. The width and rim size (6.00-9 inch) were 6.0 and 9.0 inch, respectively. The E-collar profile width of 4.0 inch for the wheel diameter of 9.0 inch was proper to fit with these solid tires (4.00E-9).

2.2 The drum testing conditions

The drum testing used the IDW, KAYTON model: DTM-350PC, of Research and Development Centre for Thai Rubber Industry (RDCTRI) in Thailand. The drum had a diameter of 1.70 m and a smooth surface. The precisions of the drum testing speed were
0 to 2 km/h. The testing was performed by rotating the drum with the speed of 10, 20, 30, 40 and 50 km/h at each compression load. The compression load to solid tire had been restricted in the horizontal direction by pressing a solid tire on the drum using the hydraulic system to control the tire mounting arm. The compression loads were specified at 400, 500 and 600 kg, respectively. The minimum load of the towing tractor which pressed on the size 6.00-9 inch KOMACHI solid tire was 400 kg.

Figure 3 shows the experimental setup of drum testing of the solid tire using the IDW. The load cell was installed at the tire mounting arm and would be measured the contact force which happened between the drum and tire rotation in the horizontal direction or normal to the contact area. The contact force which was signal by the load cell would be collected by the data acquisition of the drum testing machine with the sampling rate of 1.64 Hz. The error of the contact force measurement was less than 0.5 N. The solid tire would be rotated to warm on the drum about 30 mins before drum testing at each compression load and speed. There was used one solid tire for one compression load condition. The testing time was 900 sec for the certain condition of steady state. The measuring time was started after the testing time of 300 sec; therefore the recording time was 600 sec for each drum testing condition which ensure the rolling solid tire responding in the steady state range of time. The environmental temperature was controlled at 38 °C for each drum testing. The tire temperature during the drum testing was perpetually investigated to control not over 40 °C for protection of the tire damage.
3. Results and Discussion

3.1 Drum testing results

The contact forces of the drum testing at the compression load of 400 kg under the rolling speed from 20 to 50 km/h are shown in Fig. 4. The time domain analysis was employed to investigate the variation of contact forces and vibrations of the solid tire rolling at the different speed. The contact force of solid tire was obtained in the sinusoidal or harmonic vibration form. The frequency of contact force which was investigated by the number of amplitude in the range of recording time was increased according to the rolling speed of solid tire. The maximum excursion of contact force signal was referred to the peak-to-peak which was a useful quantity for the maximum vibration consideration (Thomson & Dahleh, 2017). The peak-to-peak of contact force at each tire rolling speed was inversely proportional to the frequency. There were reduced gradually by the speed increasing.

The contact force signal was carried to determine the vibration frequency using the Fast Fourier Transform (FFT) which was described in Chapra and Canale (2001). The frequency domain by performing FFT to the contact force signal in the time domain helped to determine the vibration frequency of solid tire rolling distinctly. It was clear to understand that the contact force frequency was increased by the speed of rolled solid tire while the frequency was decreased by the increase of rolling speed of tire (Kozhevnikov, 2012). Figure 5 shows the vibration frequency of the contact force signal when the solid tire is loaded at 400 kg on drum, and rolled on drum at 10, 20, 30, 40 and 50 km/h, respectively. The peak FFT amplitude happened at the frequency of 0.0993 Hz when the solid tire was rolled at the speed of 10 km/h. It was the vibration frequency of contact force signal. The frequency of contact force was increased following the rolling speed of
solid tires. In the same direction of pneumatic tire testing (Jiang et al., 2019), this frequency was lower than the frequency of the tire rotation. The FFT amplitude was 0.1633, 0.1740, 0.2251 and 0.2440 kN at the rolling tire speed of 20, 30, 40 and 50 km/h, respectively.

The peak-to-peak and FFT of contact force signal had the similar graph trend as the constant compression load of 400 kg when the drum testing had been increased the compression load at 500 kg and 600 kg under the same range of rolling speed (Fig. 6-9). The peak of contact force signal in frequency domain was distinctly significant vibrational specification of solid tires. Table 2 concludes the testing results of the peak-to-peak of contact force. The peak-to-peak of contact force along the recording time was average to obtain in Table 2. Table 3 concludes the frequency which obtains by the FFT method.

3.2 Evaluations

Figure 10 shows the relation of the frequency and rolling speed at the different compression load on solid tire. The increase of tire frequency was depended on the increased of tire velocity according to the physical phenomena. The relation between the frequency of contact force and the rolling speed at the different compression load on solid tire is written following the linear equation (Chapra & Canale, 2001).

\[ f = \alpha V + \beta \]  

(1)

where \( V \) is the rolling speed of solid tire, \( \alpha \) and \( \beta \) is constant as shown in Table A of appendix.

The compression load or tractor weight increase had effect to reduce the frequency of the solid tire at each constant speed. Although the increase of compression load on
pneumatic tire implied the natural frequency increased because of the increase of contact area (Kozhevnikov, 2012). In the case of rolling solid tire, the experiment results shown that the vibration frequency was deceased by the increase of compression load. This phenomenon happened because of the hardness of solid tire affected to reduce the contact area of rolling solid tire. The relation between frequency and compression load is obtained by the linear regression method (Chapra & Canale, 2001) and can be written by a following equation.

\[
\frac{f}{f_0} = 1 - \left(\frac{L_c}{D}\right)^{-\frac{1}{P}}
\]  

(2)

where \( f_0 \) is the initial frequency at the tire speed, \( L_c \) is the compression load or supported weight of solid tire, \( D \) and \( P \) is constant as shown in Table A of appendix.

Substitution of Eq. (1) as the initial frequency into Eq. (2), the frequency of contact force will depend on the compression load and solid tire velocity which is written as follows:

\[
f = (\alpha V + \beta) \left(1 - \left(\frac{L_c}{D}\right)^{-\frac{1}{P}}\right)
\]  

(3)

Equation 3 is novel and useful to determine the frequency of this KOMACHI solid tire when supported and rolled at variable values.

Figure 11 shows the relation of the peak-to-peak of contact force and the solid tire rolling speed at each compression load. The peak-to-peak of contact force was reduced when the rolling speed of solid tire was increased. This phenomenon was caused by the decrease of contact area between the tire tread and drum surface when the solid tire was increased the rotational speed. The relation between peak-to-peak of contact force and
rolling speed of solid tire is the linear form (Chapra & Canale, 2001) and written by a
following equation.

\[ \Delta F_s = \alpha V + \mu \]  

(4)

where \( \Delta F_s \) is the peak-to-peak of contact force, \( V \) is the rolling speed of solid tire, \( \delta \) and \( \mu \) are constant which depended on the compression loads. The constants in Eq. (4) were
separated by compression load which was equal or less than 400 kg, and more than 400
kg. Table A in appendix is described these constants.

The peak-to-peak of contact force increased rapidly by the compression load of 400
kg to 500 kg. Consequently, the weight of baggage towing tractor should not more than
1.6 tons for protection of the maximum value of peak-to-peak of the contact force which
happened to the tractor suspension.

Particularly, the characteristic equations which comprise of the frequency and peak-
to-peak of contact force for the baggage towing tractor tires are useful for analysis and
development of solid tires in the future work.

4. Conclusions

The solid tire size 6.00-9 inch was carried to determine the vibration
characteristic. The drum testing was performed to measure the contact force which
happened on the rolled solid tire. The compression load or the tractor weight on a wheel
was varied for the drum testing. This weight accorded the smallest size of tractor. The
range of tractor speed covered the maximum speed of tractor was specified to test. The
contact force signal was obtained from the drum testing. The FFT was employed to
determine the frequency of the contact force signal. Within the limits of the experimental
conditions, the main testing results are as follows:
(a) The frequency of contact force signal or the tractor vibration from the solid tire was proportional to the tractor speed. Otherwise, they were inversely proportional to the compression load or weight of tractor.

(b) The peak-to-peak magnitude of the contact force which acted from the smooth surface ground was inversely proportional to the tractor speed. Moreover, they were increased by the tractor weight at the constant driving speed.

(c) The maximum weight of tractor should less than 1.6 tons for the solid tire size 600-9 because the peak-to-peak of contact force would be increased rapidly when the tractor weight more than 1.6 tons.

(d) The solid tire size 6.00-9 inch is not appropriate to use with the baggage towing tractor because the severe vibration which happens on rolling solid tire has been transferred to the hub of wheel and suspension. Moreover, it varies by the driving speed of tractor that makes the tractor suspension supporting variable forces.

(e) The peak-to-peak of contact force represented the severe vibration. The reduction of solid tire weight is recommended to reduce the severe vibration on tractor suspension.

Acknowledgments

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References


Figure 1 The baggage towing tractor of the Thai Airways International Public Company Limited.

Figure 2 The testing solid tire.

Figure 3 The drum testing of solid tire.

Figure 4 The contact force of solid tire at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h by the compression load of 400 kg.

Figure 5 The vibration frequency of contact force signal at the rolling tire speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h by the compression load of 400 kg.

Figure 6 The contact force of solid tire at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h by the compression load of 500 kg.

Figure 7 The vibration frequency of contact force signal at the rolling tire speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h by the compression load of 500 kg.

Figure 8 The contact force of solid tire at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h by the compression load of 600 kg.

Figure 9 The vibration frequency of contact force signal at the rolling tire speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h by the compression load of 600 kg.
Figure 10 Frequency vs. rolling speed of solid tire at the compression load of 400, 500 and 600 kg.

Figure 11 The peak-to-peak of contact force vs. rolling speed of solid tire at the compression load of 400, 500 and 600 kg.
Table 1 Solid tire size and specification.

Table 2 The peak-to-peak of contact force.

Table 3 The vibration frequency of contact force signal.

Table A The constant values in Eq. 1-4 for KOMACHI solid tire series II size 600-9 inch.
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Figure 11 The peak-to-peak of contact force vs. rolling speed of solid tire at the compression load of 400, 500 and 600 kg.
<table>
<thead>
<tr>
<th>Size (inch)</th>
<th>Rim size (inch)</th>
<th>Tire dimension (mm)</th>
<th>Weight (kg)</th>
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<tr>
<td>600-9</td>
<td>4.00E-9</td>
<td>145</td>
<td>523</td>
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**Table 1 Solid tire size and specification.**

<table>
<thead>
<tr>
<th>Compression load (kg)</th>
<th>The average peak-to-peak of contact force (N) at the different rolling tire speed</th>
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<tr>
<td></td>
<td>10 km/h</td>
</tr>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
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</table>

**Table 2 The peak-to-peak of contact force.**

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<tr>
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<th>The frequency of contact force (Hz) at the different rolling tire speed</th>
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<tr>
<td></td>
<td>10 km/h</td>
</tr>
<tr>
<td>400</td>
<td>0.0993</td>
</tr>
<tr>
<td>500</td>
<td>0.0960</td>
</tr>
<tr>
<td>600</td>
<td>0.0930</td>
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</table>

**Table 3 The vibration frequency of contact force signal.**
<table>
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<tr>
<th>Eq.</th>
<th>$L_c$ (kg)</th>
<th>$\alpha \times 10^{-3}$</th>
<th>$\beta \times 10^{-3}$</th>
<th>$D$</th>
<th>$P$</th>
<th>$\delta$</th>
<th>$\mu$</th>
<th>$R^2$</th>
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<tr>
<td>(1)</td>
<td>400</td>
<td>0.35</td>
<td>75.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>0.31</td>
<td>77.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>0.30</td>
<td>74.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.93</td>
</tr>
<tr>
<td>(2)</td>
<td>400-600</td>
<td>-</td>
<td>-</td>
<td>883.7</td>
<td>0.17</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>400-600</td>
<td>0.30</td>
<td>75.0</td>
<td>883.7</td>
<td>0.17</td>
<td>-</td>
<td>-</td>
<td>0.92</td>
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<tr>
<td>(4)</td>
<td>$\leq 400$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-4.99</td>
<td>753.4</td>
<td>-</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>$&gt;400$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-6.35</td>
<td>1,034</td>
<td>-</td>
<td>0.94</td>
</tr>
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</table>

Eq. is the number of equation, $L_c$ is the compressive load, $\alpha$, $\beta$, $D$, $\delta$ and $\mu$ are the constant, and $R^2$ is the coefficient of determination.

**Table A The constant values in Eq. 1-4 for KOMACHI solid tire series II size**

600-9.