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Original Article

Effects of load and velocity on vibrations of a solid tire: Experimental study

Juthanee Phromjan[1, 2] and Chakrit Suvanjumrat[1, 2*]

[1] *Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Salaya Campus, Phutthamonthon, Nakhon Pathom, 73170 Thailand*

[2] *Laboratory of Computer Mechanics for Design (LCMD), Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Salaya Campus, Phutthamonthon, Nakhon Pathom, 73170 Thailand*

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Abstract

This research aimed to analyse the vibration characteristics of solid tires for a baggage towing tractor, when driving in the airport apron of Suvarnabhumi International Airport, Thailand. Drum testing had been performed to measure the vibrations of KOMACHI solid tires (size 6.00-9 inch), monitoring the contact force during solid tire rolling on a drum. The characteristic curves of solid tire were proposed to be used for estimating the vibration effects on KOMACHI solid tires. The peak-to-peak distance in contact force of the rolling tire under a compression load had a severe effect on the tractor suspension. The KOMACHI solid tire was rated for 400 kg compressive load.

Keywords: load, towing tractor, velocity, vibrations, solid tire

1. Introduction

Baggage towing tractors are widely used to tow the baggage carts in the airport aprons. Pneumatic tires have a short life span when used on the tractors of the Thai Airways International Public Company Limited, so instead of them solid tires are used. The main requirements for the tires are long life span and load carrying capacity. Unfortunately, tire vibrations on the tractor can quickly induce damage to the tractor suspension.

The tire vibrations are an important aspect in the tire development. Nguyen and Inaba (2011) studied the effects of tire inflation pressure and tractor velocity on vibrations. The vibrations transmitted by the pneumatic tire to the rear axle were measured using a tri-axial accelerometer. Cuong, Zhu, and Zhu (2013) also studied effects of tire inflation pressure and driving speed on vibrations of a tractor. The root mean square (RMS) of acceleration always increased with tractor speed at a constant inflation pressure. Reducing tire inflation pressure could reduce the tractor vibrations. The pneumatic rolling tire is affected by the dynamic tire stiffness, classified into vertical, sidewall, and enveloping stiffnesses. 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 tire along a hard surface. The oscillations of the test frame connected to the axle of tire and a pivot point were measured using a potentiometer to calculate the tire stiffness (Taylor, Bashford, & Schrock, 2000). The carcass stiffness of the agricultural tire can be estimated well using the pressure mapping method (Misiewicz, Richards, Blackburn, & Godwin, 2016). The pneumatic agricultural tires (smooth and treaded tire) were measured for their 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 be measured on an instrumented drum wheel (IDW) in a laboratory. Schwartz (2001) presented a new methodology, which made the correlation of high-speed tire vibrations with the measurements from IDW, comprising

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

longitudinal force vibration (LFV), radial force vibration (RFV), and radial run out (RRO). The LFV had strong speed dependence while RFV and RRO did not. The tire vibrations are not only affected by tire inflation pressure and vehicle speed, but also by the road surfaces. Kindt, Sus, and Desmet (2009) analyzed the rolling tire vibrations due to road impact excitations using Laser Dropper Vibrometry. The radial tire was set to rotate against another radial tire. The excitation amplitude dependency induced by mounting a cleat on the driven tire was restricted to the tire sidewall stiffness. The contact forces on the tire tread were decomposed to vertical, longitudinal and transverse contact forces. Lundberg, Kari, and Arteaga (2017) measured the three force components generated by rolling contact between a tire tread block and a 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 on pneumatic tire vibration of tire inflation pressure, vehicle velocity and road surface roughness could be determined by the drum testing method in a laboratory (Phromjan & Suvanjumrat, 2018). Drum testing is appropriate for determining the vibration effects in a solid tire from dynamic response. Unfortunately, solid tires have been missed by vibration studies in previous reviews. In order to know the effects of vibration on the usage conditions of solid tires, the objectives of this research were as follows: (a) estimate the effects of load and velocity on the vibrations of solid tire, and (b) determine the correlation of solid tire vibrations with load and velocity.

2. Methodology

The baggage towing tractor of the Thai Airways International Public Company Limited that is used in Suvarnabhumi International Airport is shown in Figure 1. Solid tires are used on the tractor whose minimum weight is about 1,350.00 kg; this one is the smallest model of a tractor. The main tractor weight is in the front from the engine; therefore, solid tires were installed on the front wheels while the rear wheels still have pneumatic tires. In the daily usage to tow the baggage carts, the baggage towing tractor is driven at speeds from 10 km/h to 50 km/h. Tire failure or blowout of a solid tire can happen under severe conditions, such as overloading, high speed, or high temperature.

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

2.1 Solid tire characteristic

The solid tires were manufactured by V. S. Industry Tyres Co., Ltd in Thailand and were made of natural rubber. Three compound rubber layers were used in the construction of solid tires. The solid tires, KOMACHI, selected for use with the tractor are shown in Figure 2. Three KOMACHI solid tires were subjected to drum testing. The specifications of solid tires are described in Table 1. The width and rim size (6.00-9 inch) were 6.0 and 9.0 inches, respectively. The E-collar profile width of 4.0 inch for the wheel diameter of 9.0 inch was a proper match with these solid tires (4.00E-9).

Figure 2. The testing of a solid tire

Table 1. Solid tire size and specification

Size (inch)	Rim size (inch)	Tire dimension (mm)		Weight (kg)
		Section width	O.D.	
6.00-9	4.00E-9	145	523	27

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 precision of the drum testing speed was from 0 to 2 km/h. The testing was performed by rotating the drum at speeds of 10, 20, 30, 40 and 50 km/h at each compression load. The compression load for the 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 to measure the contact force between the drum and tire in the horizontal direction or normal to the contact area. The contact force signal from the load cell was logged by the data acquisition of the drum testing machine with a sampling rate of 1.64 Hz. The error of the contact force measurement was less than 0.5 N. The solid tire was rotated against the drum for about 30 mins for warm-up before drum testing at each compression load and speed. One solid tire was used for each compression load condition.

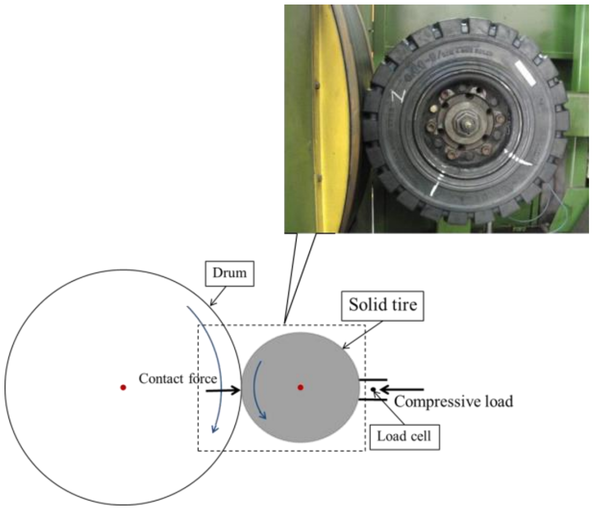

Figure 3. The drum testing of a solid tire

The testing time was 900 sec to make certain that steady state was reached. The measuring was started after the testing time of 300 sec; so the recorded time was 600 sec for each drum testing condition, ensuring rolling solid tire responses in the steady state. The environmental temperature was controlled at 38 °C for each drum testing run. The tire temperature during the drum testing was continuously monitored to not exceed 40 °C for protection against damage.

3. Results and Discussion

3.1 Drum testing results

The drum testing results at 400 kg compression load and rolling speeds from 20 to 50 km/h are shown in Figure 4. Time domain analysis was employed to investigate the variation of contact forces and vibrations of the solid tire rolling at these speeds. The contact force of solid tire had sinusoidal or harmonic vibrations. The frequency was investigated by counting the number of peaks in the range of recording, and it increased with the rolling speed. The peak-to-peak distance in recorded contact force is a useful quantity in maximum vibration studies (Thomson & Dahleh, 2017). The peak-to-peak contact force at was inversely proportional to the frequency, across the rolling speeds, gradually decreasing as the speed increased.

The contact force signal was used to determine the vibration frequency, by using the Fast Fourier Transform (FFT) as described in Chapra and Canale (2001). In frequency domain after FFT applied to the contact force signal, the vibration frequency of solid tire was distinct. Clearly the contact force frequency increased with speed of rolling while the amplitude decreased with speed (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 at the frequency of 0.0993 Hz was observed for rolling speed of 10 km/h. It was the vibration frequency of contact force signal. The frequency of contact force increased with speed, and similar to pneumatic tire testing (Jiang *et al*., 2019), this frequency was lower than the frequency of the tire rotation. The FFT amplitudes were 0.1633, 0.1740, 0.2251 and 0.2440 kN at the speeds of 20, 30, 40 and 50 km/h, respectively.

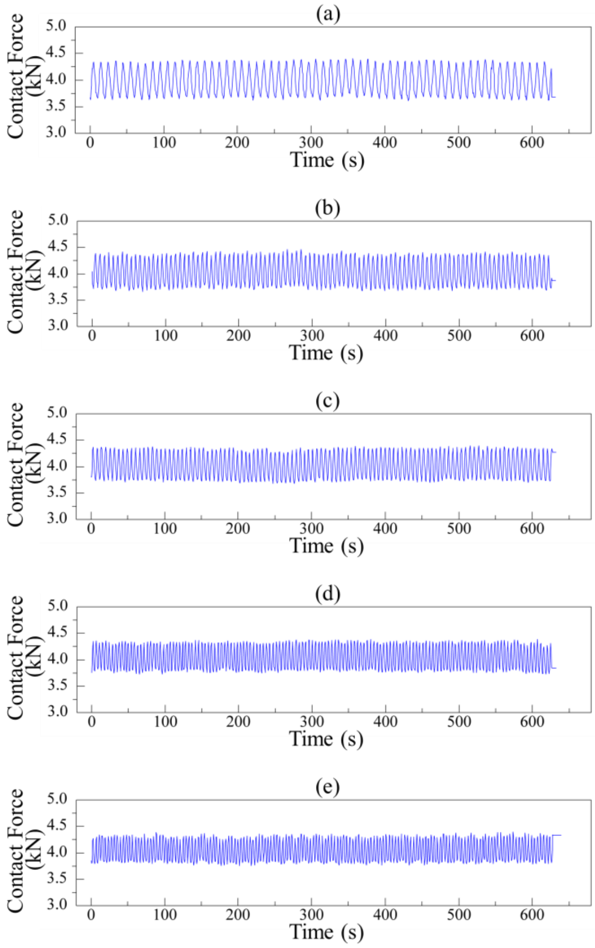

Figure 4. The contact force of solid tire at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h at 400 kg compression load

The peak-to-peak and FFT of contact force signal had similar trends at constant compression load of 400 kg as in drum testing at compression loads of 500 kg and 600 kg at the same range of rolling speeds (Figure 6-9). The peak in frequency domain was distinct enabling vibrational specification of the solid tires. Table 2 summarizes the testing results of the peak-to-peak contact force. The peak-to-peak force along the recording time was averaged for Table 2. Table 3 summarizes the frequencies obtained after FFT.

3.2 Evaluations

Figure 10 shows the relation of the frequency and rolling speed for various compression loads on the solid tire. The frequency increased with velocity. The relation between the frequency of contact force and the rolling speed at different compression loads on the solid tire followed a linear equation (Chapra & Canale, 2001).

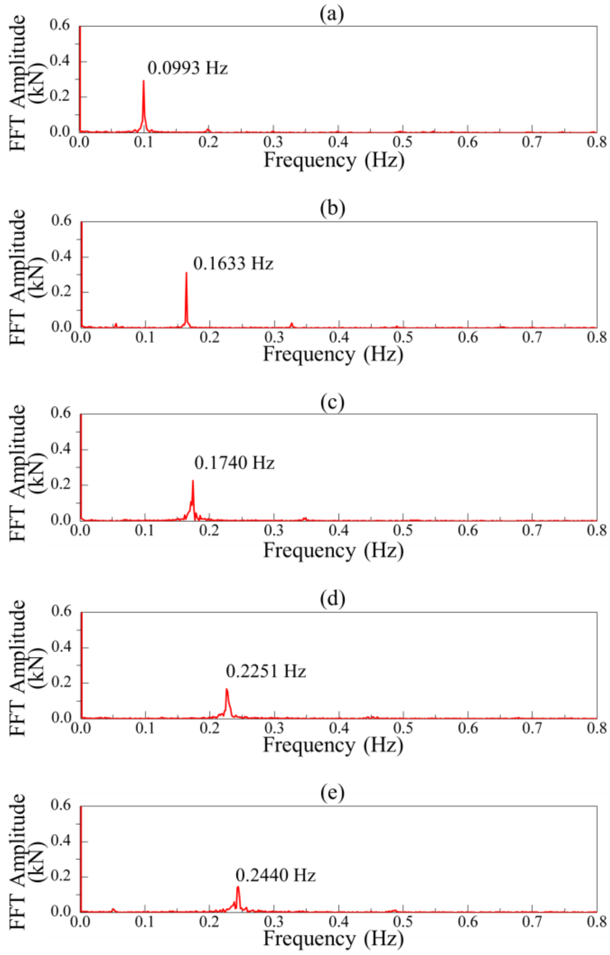

Figure 5. The vibration frequency of contact force signal at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h at 400 kg compression load

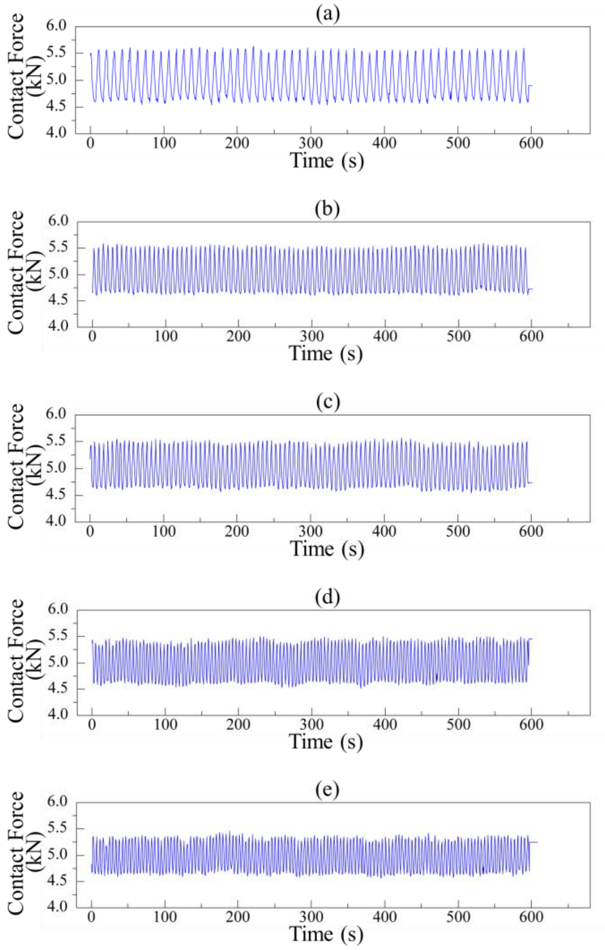

Figure 6. The contact force of solid tire at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h at 500 kg compression load

Table 2. The peak-to-peak contact force

Compression load (kg)	The average peak-to-peak of contact force (N) at the different rolling tire speed				
	10 km/h	20 km/h	30 km/h	40 km/h	50 km/h
400	699.5	654.5	610.2	552.7	501.1
500	979.3	874.0	856.5	807.5	690.4
600	939.9	903.5	906.9	812.7	673.6

Table 3. The vibration frequency of contact force signal

Compression load (kg)	The frequency of contact force (Hz) at various rolling speeds				
	10 km/h	20 km/h	30 km/h	40 km/h	50 km/h
400	0.0993	0.1633	0.1740	0.2251	0.2440
500	0.0960	0.1571	0.1657	0.2139	0.2243
600	0.0930	0.1505	0.1571	0.2065	0.2148

$$f = \alpha V + \beta \tag{1}$$

where V is the rolling speed of solid tire, and α and β are constants shown in Table A of the appendix.

The compression load (tractor weight) reduced the frequency of the solid tire at each constant speed. An increase in compression load on a pneumatic tire implies a natural frequency increase, because of the increased contact area (Kozhevnikov, 2012). In the case of a rolling solid tire, the experimental results show that the vibration frequency decreased with compression load. This happened because of the hardness of solid tire reduced 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 as follows.

$$\frac{f}{f_0} = 1 - \left(\frac{L_c}{D}\right)^{-\frac{1}{P}} \tag{2}$$

where f_0 is the initial frequency at the tire speed, L_c is the compression load or supported weight of solid tire, and D and P are constants shown in Table A of appendix.

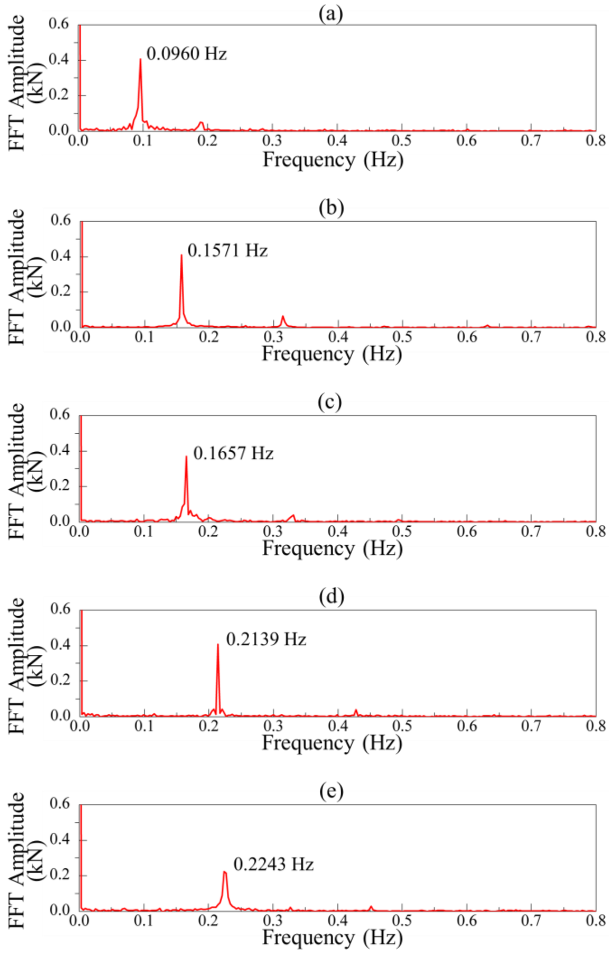

Figure 7. The vibration frequency of contact force signal at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h at 500 kg compression load

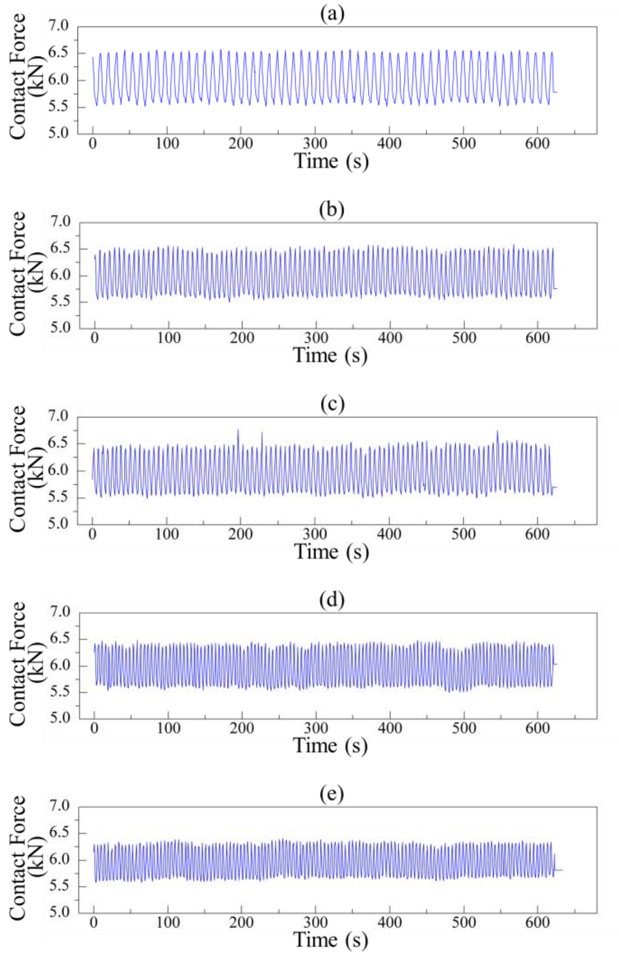

Figure 8. The contact force of solid tire at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h at 600 kg compression load.

On substituting Equation (1) as the initial frequency into Equation (2), the frequency of contact force will depend on the compression load and solid tire velocity as follows:

$$f = (\alpha V + \beta)\left(1 - \left(\frac{L_c}{D}\right)^{-\frac{1}{P}}\right) \tag{3}$$

Equation 3 is novel and useful for determining the frequency of this KOMACHI solid tire when supported and rolled at various loads or speeds.

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

$$\Delta F_s = \alpha V + \mu \tag{4}$$

where ΔF_s is the peak-to-peak of contact force, V is the rolling speed of solid tire, and δ and μ are constants dependent on the compression load. The constants in Eq. (4) were separated by compression load to cases less than 400 kg, and those with more than 400 kg. Table A in the appendix describes these constants.

The peak-to-peak contact force increased rapidly when compression load changed from 400 kg to 500 kg. Consequently, the weight of baggage towing tractor should not be more than 1.6 tons to avoid the maximum peak-to-peak contact force variation, and to avoid damage to the tractor suspension.

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

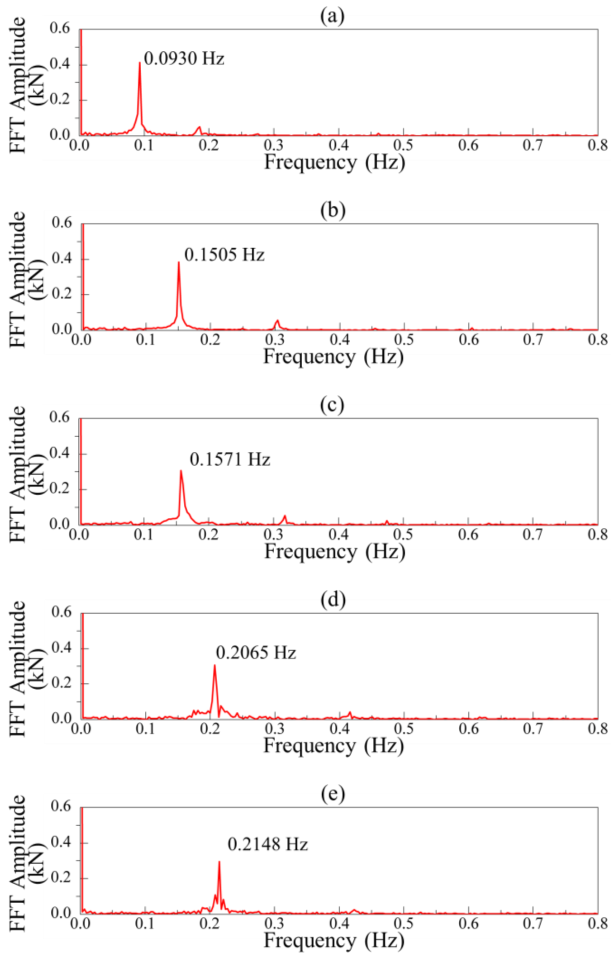

Figure 9. The vibration frequency of contact force signal at the rolling speed of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 km/h at 600 kg compression load

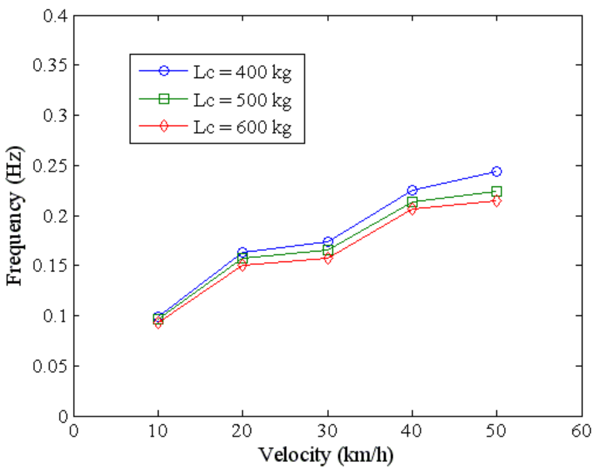

Figure 10. Frequency vs. rolling speed of solid tire at the compression loads of 400, 500 and 600 kg

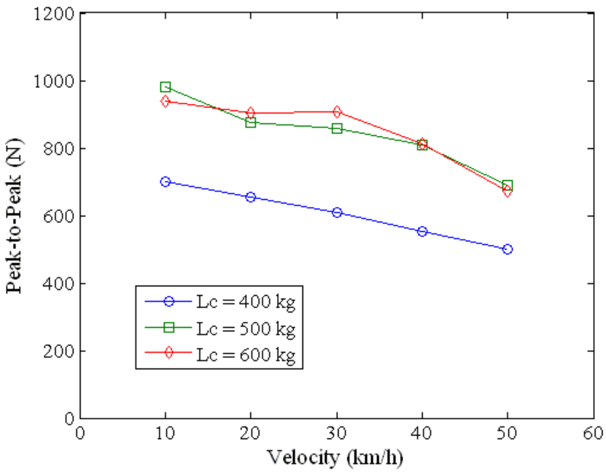

Figure 11. The peak-to-peak contact force vs. rolling speed of solid tire at the compression loads of 400, 500 and 600 kg

4. Conclusions

Solid tires of size 6.00-9 inch were subjected to determinations of the vibration characteristics. Drum testing was performed to measure the contact forces with the rolled solid tire. The compression load or the tractor weight on a wheel was varied in drum testing, starting from that for the smallest size tractor. The range of tractor speeds specified for testing covered the speeds used in practice. Contact force signals were recorded from drum testing and FFT was employed to determine the frequency of vibrations in contact force. Within the limits of the experimental conditions, the main results are as follows:

(a) The frequency of contact force or tractor vibrations from the solid tire was proportional to the tractor speed, and inversely proportional to the compression load or weight of tractor.

(b) The peak-to-peak magnitude of the contact force against a smooth surface was inversely proportional to the tractor speed, increasing with tractor weight and with the constant driving speed.

(c) The maximum weight of tractor should less than 1.6 tons for the solid tire size 6.00-9 because the peak-to-peak contact force increased rapidly for tractor weights more than 1.6 tons.

(d) The solid tire size 6.00-9 inch is not appropriate for use on the baggage towing tractor because of severe vibrations of the rolling solid tire, transmitted to the hub of the wheel and to the suspension. Moreover, the vibrations vary by driving speed so the tractor suspension will experience variable forces.

(e) The peak-to-peak contact force indicated severe vibrations. Reducing weight of the solid tire is recommended, in order to reduce the severe vibrations in tractor suspension.

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Appendix

Table A. The constant values in Equations 1-4 for KOMACHI solid tire series II size 6.00-9

Equation	L_c (kg)	$\alpha \times 10^{-3}$	$\beta \times 10^{-3}$	D	P	δ	μ	R^2
(1)	400	0.35	75.7	-		-	-	0.95
	500	0.31	77.4	-		-	-	0.93
	600	0.30	74.5	-		-	-	0.93
(2)	400-600	-	-	883.7	0.17	-	-	-
(3)	400-600	0.30	75.0	883.7	0.17	-	-	0.92
(4)	≤ 400	-	-	-		-4.99	753.4	0.99
	>400	-	-	-		-6.35	1,034	0.94

Equation is the number of equation, L_c is the compressive load, α, β, D, δ and μ are constants, and R^2 is the coefficient of determination.