Coupled Systems Mechanics, *Vol. 9, No. 5 (2020) 455-471*
DOI: https://doi.org/10.12989/csm.2020.9.5.455

Natural frequency analysis of tractor tire with different ground contacts and inflation pressures

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(Received March 3, 2020, Revised April 12, 2020, Accepted April 14, 2020)

Abstract. This paper presents the results of the study of vertically natural frequency of tractor tires are effected by changing different ground contacts and inflation pressures using the Free Decay Method. The results show that the natural frequencies of the tire are not affected while the vertical acceleration increased strongly due to the increase of inflation pressure when the tire performs free decay vibration on rigid ground. In addition, the number of natural frequency peaks of the tire also increases with increasing tire inflation pressure. On the other hand, the natural frequencies of the tractor tire increases strongly while the vertical acceleration decreases slightly with the increase of tire inflation pressure as the tire performs free decay vibration on soft soil. Further, the natural frequencies of tire–soil system are always higher than that of tire only, and it changed with changing the soil depth. Results also show the natural frequency of tire and tire–soil system is in the range of 3.0 to 10.0 Hz that lie within the most critical natural frequency range of the human body. These findings have to be mentioned and used as design parameters of the tractor suspension system.

Keywords: tractor tire; inflation pressure; natural frequency; decay method; FFT

1. Introduction

Most of the agricultural tractors does not have shock absorbers in the axles, having the tires the responsibility to absorb the impacts and vibrations (Daniel *et al.* 2017).

Tires are the suspension elements on most agricultural tractors that provide a connection between tractor and road as it drives over that rough ground surfaces (Lines and Young 1989). It has a great influence on enhancing the quality of tractor riding (Karakus *et al.* 2017). Dynamic parameters of a tractor tire are the radial stiffness and damping coefficient depending on the inflation pressure, tire size and tire load (Tian *et al.* 2011, Cuong *et al.* 2013). These dynamic parameters strongly affect tractor vibration (Zheng *et al.* 2019).

Natural frequencies are one of crucial dynamic parameters of tires (Xu *et al.* 2014). It has been researched and reported in many related studies. They concluded that the natural frequencies increase with the increase of tire inflation pressure, vertical load and tire size (Negrus *et al.* 1997, Jia *et al.* 2005, Kim *et al.* 2007, Guan *et al.* 2011) but all studies have treated for passenger car tires

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http://www.techno-press.org/?journal=csm&subpage=8 ISSN: 2234-2184 (Print), 2234-2192 (Online)

with high inflation pressure and small tire.

The study of dynamic parameters of tractor tire has been conducted by many researchers with treatments of tire contacted on the rigid or soft ground using different methods. Lines and Young (1989) used the rolling tractor tire test to measure the tire stiffness and damping and concluded that both tire stiffness and damping has an almost linear relationship with tire inflation pressure.

Tian *et al.* (2011) and Cuong *et al.* (2013) used free vibration logarithm decay method to measure the tractor tire dynamic parameters. They found that tire stiffness increases while tire damping decreases with the increase in tire pressure.

While Taylor *et al.* (2000) used five methods as load deflection, non-rolling vertical free vibration, non-rolling equilibrium load-deflection, rolling vertical free vibration, and rolling equilibrium load-deflection to measure and compare tire stiffness. The result showed that the tire stiffness increased while damping decreased relatively with increasing tire inflation pressure.

The natural frequencies of domestic tractors' vibrating systems are confirmed that lower of 10 Hz. Xu *et al.* (2014) concluded that the natural frequencies of the tractor in vertical, pitch and roll directions are concentrated in 3-4 Hz, 2.8-3.8 Hz and 2.9-3.9 Hz ranges, respectively. Kumar *et al.* (2001) indicated that the dominant frequencies of the tractor are 1-7 Hz, lie within the most critical natural frequency range of the human body is 2-6 Hz (Prasad *et al.* 1995, Matsumoto and Griffin 2001). Similar results are showed by Deltenre and Detain (1990), Sherwin *et al.* (2004), Pieters (2007) and Ferhadbegović (2009).

In the field of modeling of tire, soil, and tire-soil system, the tire was treated as visco-elastic material by a simple model as linear or nonlinear vertical parallel model with spring and damper (Lines and Murphy 1992, Cuong *et al.* 2013). The soil has been treated as damping material depending on soil type, moisture content, soil depth and temperature (Cautes and Nastac 2002, Cuong *et al.* 2014, Bawadi *et al.* 2016, Cuong *et al.* 2018), and modeled as a linear or non-linear parallel equivalent spring and damper (Bolton and Wilson 1990, Celebi *et al.* 2006, Prathap *et al.* 2010).

The tire-soil system was modeled through vertical elastic tire-soil mode (Bekker 1956, Bekker 1969). Rubinstein and Galili (1994) used the radial spring model to represent the soil-wheel interaction. Piotr (2006) modeled the pneumatic tired wheel-soil system with elastic model and elastic-damping model. Emam *et al.* (2011) modeled tire-soil model as a spring-mass-damper system. Cuong *et al.* (2018) modeled the damping of tire-soil system is two damper in parallel mode. Yong *et al.* (1980) detected the tire and soil deformation energies are affected by the relative tire-soil stiffness and concluded that a pneumatic tire with a specific inflation pressure can behave as a rigid wheel when loaded on a soft soil; on the contrary, the tire is a flexible wheel when the soil is sufficiently stiff to cause measurable deformation of the tire, and the tire deformations are small when the supporting soil is softer than the tire.

The studies of tractor tire dynamic parameters have done by many researchers. However, the needs of the analysis of the natural frequency of tire with different contact as rigid ground or soft soil and tire inflation pressure, and the comparison of both rigid and soft-soil ground have to continuously study to deeply characterize tractor tire dynamics.

2. Materials and methods

2.1 Scope and experiment set up

Three kinds of test tire (7.50.20 R1, 6.00-12 R1 and 5.00-16 R1) were selected and referring to

Table 1 Factors and levels of tire and soil

Tire code	Test code	Tire load, (kg)	Soil MC*, (%)	Soil depth, (mm)	Distribution of tire inflation pressure, (kPa)				
7.50-20 R1	T_1	264	-	-	60	90	120	150	180
6.00-12 R1	T_2	246	-	-	60	90	120	150	180
5.00-16 R1	T_3	200	-	-	120	150	180	210	240
7.50-20 R1	TS_4	264	48.8	12	60	90	120	150	180
7.50-20 R1	TS_5	264	48.8	16	60	90	120	150	180
5.00-16 R1	TS_6	200	48.8	08	120	150	180	210	240
5.00-16 R1	TS_7	200	48.8	12	120	150	180	210	240

*MC is moisture content

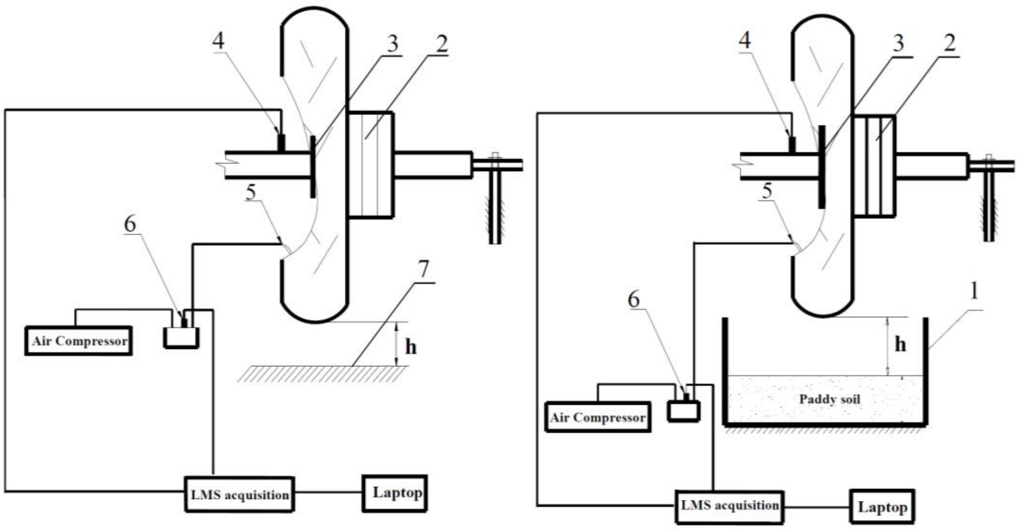


Fig. 1 Sketch of the measurement system. (a) Sketch for measurement of vertical acceleration of tractor tire dropping on the rigid ground; (b) Sketch for measurement of vertical acceleration of tractor tire dropping on soft soil: 1. Steel bin, 2. Load, 3. Plate to link tire rim, 4. Acceleration sensor, 5. Tire valve, 6. Air pressure sensor, 7. Rigid ground

Chinese standard GB 2979 (GB/T2979-2008, 2008) to determine the tire loads. During the experiments, the vertical accelerations of test tires were measured when the test tire is moving free decaying vibration with changing three tractor tires, five tire inflation pressure levels, two soil depths. Distributing factors and levels of the experiments are given in Table 1.

An air compressor and an air pressure sensor (NS-F/No. 21121268) were used to set up tire inflation pressure. A single-direction accelerometer (CA-YD 185TNC) was attached at a wheel axle to measure the vertical vibration amplitude of the test tire. An LMS Test Xpress data acquisition (sampled rate of 200 Hz) was used to measure acceleration signals and recorded by a laptop computer. The test rigs are shown in Fig. 1.

2.2 Soil characteristics

The soil texture was sandy clay loam soil (sand 56% silt 28% and clay 16%; soil texture was

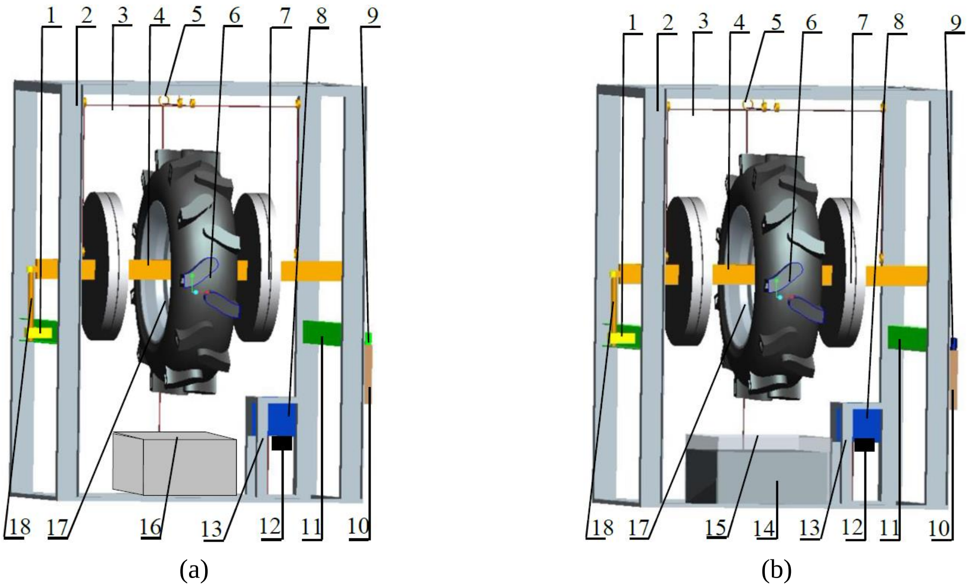


Fig. 2 The test rig (a) For measuring the acceleration of test tires dropping on rigid ground; (b) For measuring the acceleration of test tire dropping on soft soil

1. Linear bearing, 2. Support frame, 3. Steel wire rope, 4. Beam, 5. Hanging ring, 6. Test tire, 7. Load, 8. Electro-permanent lift magnet, 9. Displacement sensor, 10. Fixed bracket of displacement sensor, 11. Beam of linear bearing, 12. Carrying plate, 13. Fixed bracket of electro-permanent lift magnet, 14. Paddy soil, 15. Steel bin, 16. Rigid ground, 17. Plate to link tire rim, 18. Guiding bar.

determined by the hydrometer method (Bouyoucos 1927)). The gravimetric method (Black, 1965) was used to determine soil moisture content (48.8%) and dry bulk density (1.25g/cm^3), the soil penetration resistance (32kPa) was directly measured by a digital soil compaction meter (TJSD–750, manufactured by Zhejiang Top Cloud-Agri Technology Co. Ltd, China).

2.3 Test procedure

The test rig is shown in Fig. 2. It consists of a support frame, two linear bearings, steel wire rope, a beam, hanging rings, a test tire, loads, an electro-permanent lift magnet, a displacement sensor, a fixed bracket of displacement sensor, left and right beam of linear bearing, a carrying plate, a fixed bracket of electro-permanent lift magnet, paddy soil, a steel bin (1400×900×300 mm in Length×Width×Height), a plate to link tire rim and two guiding bars.

The support frame includes upper and lower rectangular frames that are attached to the uprights by bolts, the test tire was fixed on the beam through plate to link tire rim. The loads were fixed on the beam via constant corresponding weights.

The couple of linear bearing - guiding bar was used in order to ensure that the test tire moves only in vertical direction during the tests. The steel wire rope was used to connect the beam and the carrying plate through the hanging rings which are attached to the frame, the carrying plate was adsorbed by magnetic force of the electro-permanent lift magnet.

A chain block was used to lift the test tire up to a certain height then the steel wire rope system and the electro-permanent lift magnet adsorbed carrying plate to keep the test tire at the height of

200 mm.

The tested tire is suddenly dropped on ground contact by controlling the electro-permanent lift magnet in unabsorbed mode to make carrying plate free, the test tire drop on rigid ground (Fig. 2(a)) and drop on soft soil ground (Fig. 2(b)), and slid up-down by the guiding bar - linear bearing system to perform a free decaying vibration. The free vibration of the tested tire was measured by an accelerometer connecting with an LMS Test-Xpress data acquisition system and a computer.

2.4 Software and data analysis

Fourier analysis is performed using LMS Test. Xpress FFT Analyzer to determine the natural frequencies from the frequency spectrum. The data were presented in the charts using Microsoft Excel 2010.

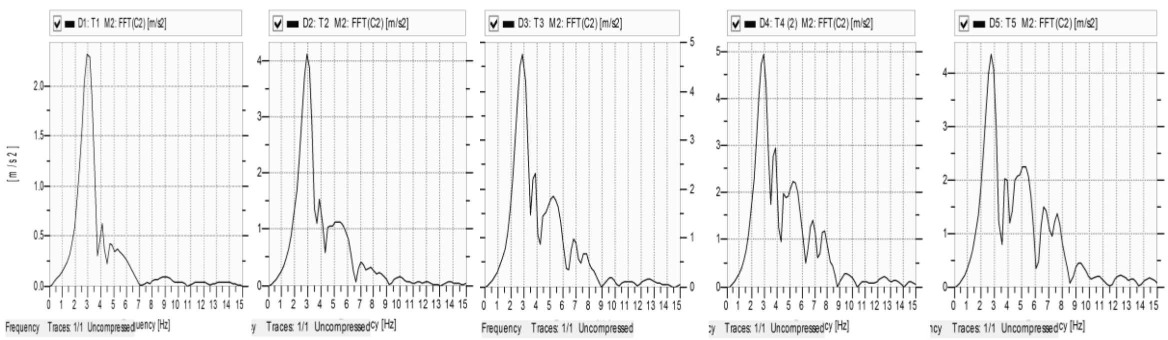
3. Results and discussion

3.1 Variation of the vertically natural frequency of tire with different inflation pressure

Figs. 3 and 4 show the spectrum of acceleration signals and variation of vertically natural frequency and acceleration of the T_1 test.

The vertically natural frequency (NF) of tractor tire no much change when changing tire inflation pressure. The first, second and third natural frequency change from 2.95 to 2.99 Hz, from 3.82 to 4.11 Hz and from 5.20 to 5.32 Hz when the tire inflation pressure increased from 60 to 180 kPa, increment of 30 kPa, respectively (Figs. 3 and 4). It is illustrated that the first, second and third natural frequency is closed to 3.0, 4.0, 5.2 Hz, respectively. The natural frequencies are in a low frequency of 3-9 Hz (Fig. 4).

The vertical acceleration (AC) strongly increase from 2.35 to 4.92 m/s^2, from 0.73 to 2.93 m/s^2 and from 0.35 to 2.27 m/s^2 at the first, second and third natural frequency, respectively by changing tire inflation pressure from 60 to 180 kPa, the increment of 30 kPa (Figs. 3 and 4). The number of frequency peak increase with the increase in tire inflation pressure, it increased from 3 to 6 peaks when the tire inflation pressure increased from 60 to 180 kPa but the vertical acceleration decreased



(a) (b) (c) (d) (e)

Fig. 3 The spectrum of vertical acceleration in frequency domain of tire T_1: Figs. 3(a), (b), (c), (d), (e) show acceleration spectrum of tire inflation pressure of 60, 90, 120, 150 and 180 kPa, respectively

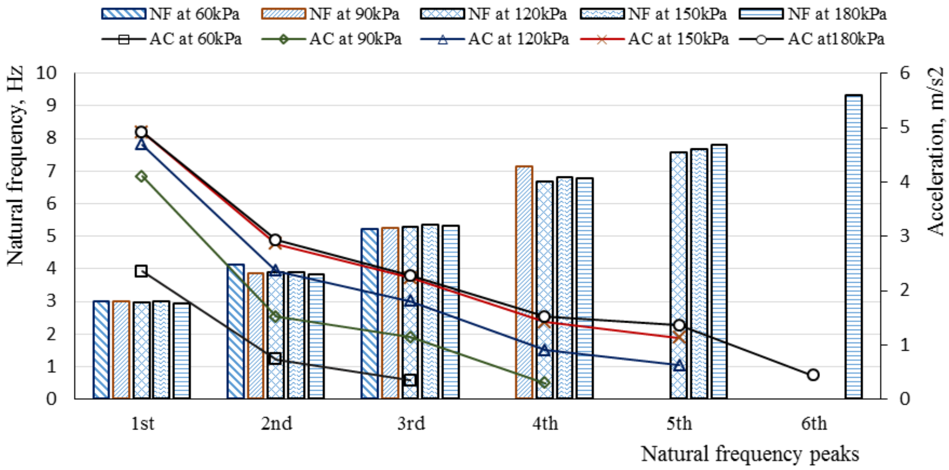
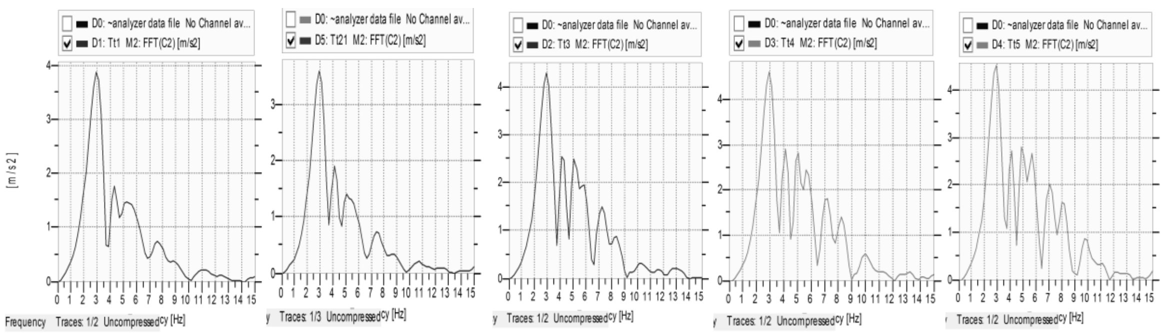


Fig. 4 Variation of vertically natural frequency and acceleration values of T_1 test tire



(a) (b) (c) (d) (e)

Fig. 5 The spectrum of vertical acceleration in frequency domain of tire T_2: Figs. 5(a), (b), (c), (d), (e) show acceleration spectrum of tire inflation pressure of 60, 90, 120, 150 and 180 kPa, respectively

in each next frequency peak of the tire (Fig. 4) by damping component of tractor tire. As a study of Tian *et al.* (2011) and Cuong *et al.* (2013) indicated the vertical tire stiffness increased with the increase of tire inflation pressure, these are causing the number of tire axle oscillation increased.

These results showed that the change of tire inflation pressure has little effect to the natural frequencies of tractor tire with low inflation pressure but it strongly effected to the vertical acceleration of tire at any peak of the frequencies.

For T_2 test, the first, second and third vertically natural frequency are closed to 3.00 Hz, 4.10 Hz and 5.00Hz, respectively when tire inflation pressure increase from 60 to 180 kPa, with increment of 30 kPa. The natural frequencies are ina low frequency of 3-9 Hz (Fig. 6). While the vertical acceleration of tire axle strongly increases from 3.82 to 4.80 m/s^2, from 1.74 to 2.78 m/s^2 and from 1.47 to 2.80 m/s^2 at the first, second and third natural frequency, respectively by changing tire inflation pressure from 60 to 180 kPa, an increment of 30 kPa (Fig. 6).

The number of frequency peaks also increases with the increase in tire inflation pressure, it increased from 4 to 6 peaks (Fig. 5) but the vertical acceleration also decreased in each next frequency peak of the tire. The results above are also indicating that the vertically natural frequency

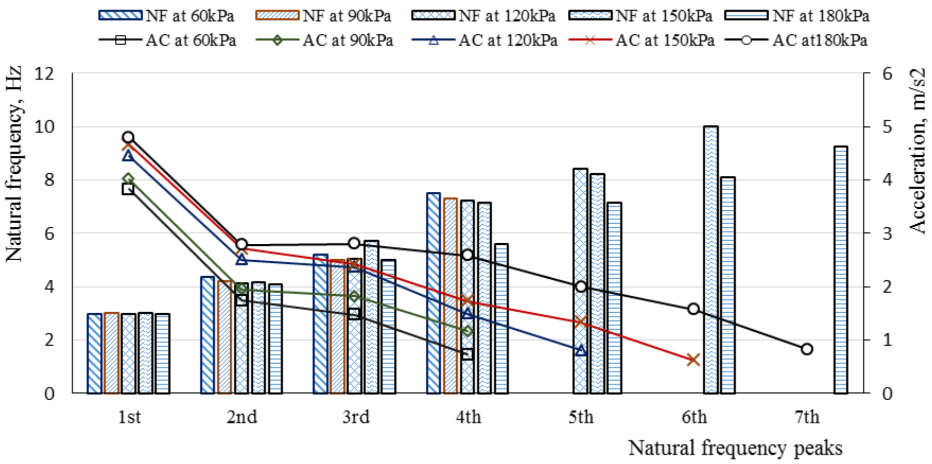
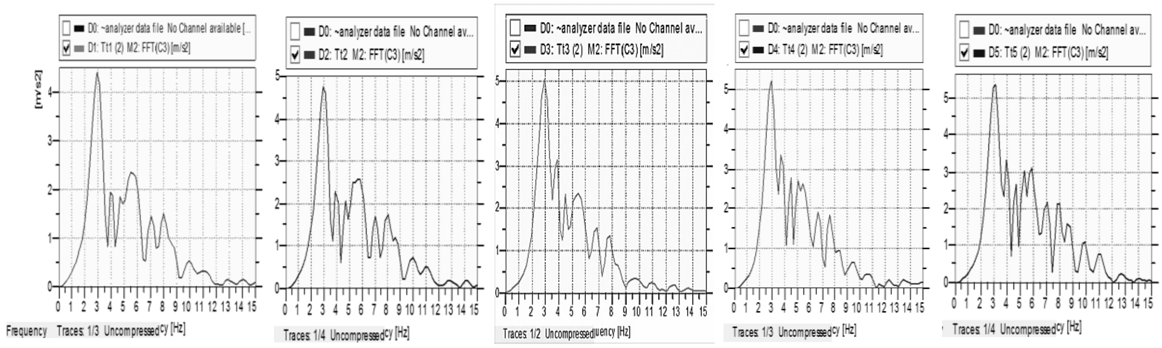


Fig. 6 Variation of vertically natural frequency and acceleration values of T_2 test tire



(a) (b) (c) (d) (e)

Fig. 7 The spectrum of vertical acceleration in frequency domain of tire T_3: Figs. 7(a), (b), (c), (d), (e) show acceleration spectrum of tire inflation pressure of 120, 150, 180, 210 and 240 kPa, respectively

of the tractor tire is little change while the vertical acceleration strongly changed by changing tire inflation pressure.

For T_3 test, the variation trends of the vertically natural frequency, the vertical acceleration and the number of frequency peak and are the same as for T_1 and T_2 test. (Figs. 7 and 8). The first, second and third vertically natural frequency is closed to 3.00 Hz, 3.90 Hz and 4.80 Hz, respectively when tire inflation pressure changes from 120 to 240 kPa, with an increment of 30 kPa. The natural frequencies are in a low frequency of 3-10 Hz (Fig. 8).

Fig. 8 shows the vertical acceleration of tire axle strongly increase from 4.47 to 5.42 m/s^2, from 1.96 to 3.36 m/s^2 and from 1.81 to 2.76 m/s^2 at the first, second and third natural frequency, respectively by changing tire inflation pressure from 120 to 240 kPa, an increment of 30 kPa. The number of frequency peak is higher than of T_1 and T_2 test because the tire inflation pressure is higher, the tire inflation pressure are distributed referring to the Chinese standard (GB/T2979-2008, 2008). This shows the vibration of the front tire is higher than of rear tire as by confirmed by a study of Cuong *et al.* (2013), it also increases with the increase in tire inflation pressure (6 to 9 peaks), the vertical acceleration also decreased in each next frequency peak of the tire (Fig. 7).

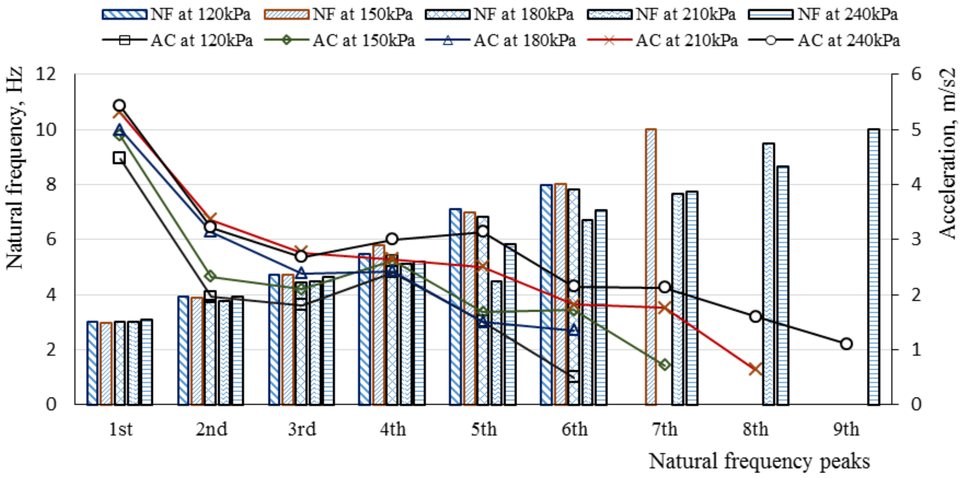
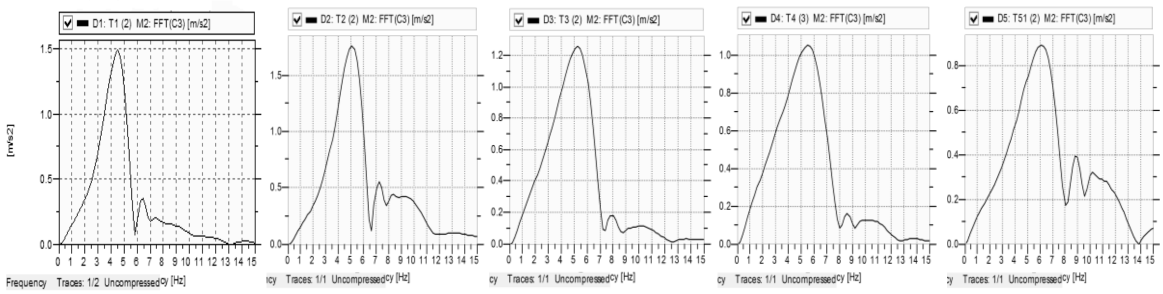


Fig. 8 Variation of vertically natural frequency and acceleration values of T_3 test tire



(a) (b) (c) (d) (e)

Fig. 9 The spectra of vertical acceleration in frequency domain of TS_4 test when tire inflation pressure increased: Figs. 9(a), (b), (c), (d) & (e) for tire inflation pressure change from 60 to 180 kPa, with increment of 30 kPa, respectively

The results indicated that the vertically natural frequency of tractor tire is no much change while the vertical acceleration strongly increases when inflation pressure increased. These findings confirmed that the tractor with low inflation pressure, the tire inflation pressure has no effect on the natural frequency of tire, which was noticed as the design of tractor suspension systems.

3.2 Variation of the natural frequencies of tire-soil system with different tire inflation pressure

For TS_4 test, the first natural frequency linearly increased from 4.48, 5.05, 5.45, 5.72 to 6.10Hz when increasing inflation pressure from 60 to 180 kPa, with increment of 30 kPa (Figs. 9 and 10), the vertically natural frequency strongly increased with increment approximately of 0.4 Hz.

On the other hand, the vertical acceleration of tire decreased from 1.48 to 0.96 m/s^2 finding at the first frequency peak when tire inflation pressure from 60 to 180 kPa, with an increment of 30 kPa, respectively. These show that the tractor working on soft soil field can reduce vibration by the interaction of tire–soil system as the conclusion by Cuong *et al.* (2013) and Cuong *et al.* (2018).

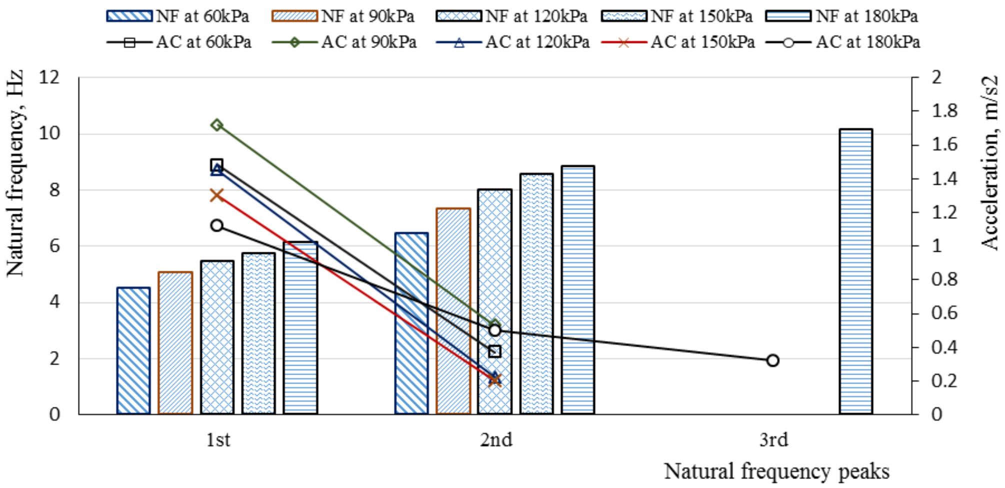
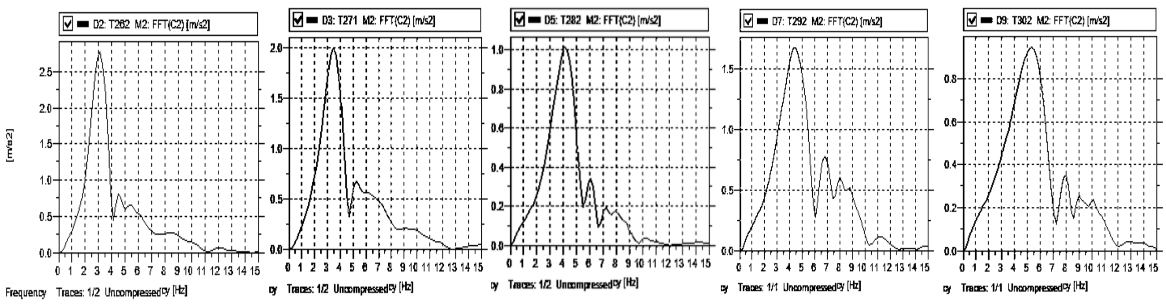


Fig. 10 Variation of vertically natural frequency and acceleration values of TS_4 test tire



(a) (b) (c) (d) (e)

Fig. 11 The spectra of vertical acceleration in frequency domain of tire TS_5 when tire inflation pressure increased: Figs. 11(a), (b), (c), (d) and Fig. 9(e) for tire inflation pressure change from 60 to 180 kPa, increment of 30 kPa, respectively

The practical complexity when tractor used to work on soft plastic soils (Nguyen and Inaba 2011).

The number of frequency peaks slightly increased with increasing tire inflation pressure (Fig. 9) but it has reduced by comparing in the case of tire dropped on rigid ground.

For TS_5 tire, the vertically natural frequency strongly increased from 3.08, 3.40, 4.03, 4.41 to 5.32 Hz when increasing inflation pressure from 60 to 180 kPa, an increment of 30 kPa (Fig. 11 and 12), the natural frequency strongly increased with increment approximately of 0.5 Hz.

The vertical acceleration of tire decreased from 2.74 to 0.95 m/s^2 finding at the first frequency peak when tire inflation pressure from 60 to 180 kPa, with an increment of 30 kPa, respectively (Fig. 11).

The number of frequency peaks increased with increasing tire inflation pressure (Fig. 10) but it has reduced by comparing in the case of tire dropped on rigid ground.

For TS_6 test, the vertically natural frequency linearly increased from 3.72, 3.94, 4.20, 4.36 to 4.49 Hz when increasing inflation pressure from 120 to 240 kPa, with an increment of 30 kPa (Fig. 13 and 14), the natural frequency slightly increased with increment approximate of 0.15 Hz showing

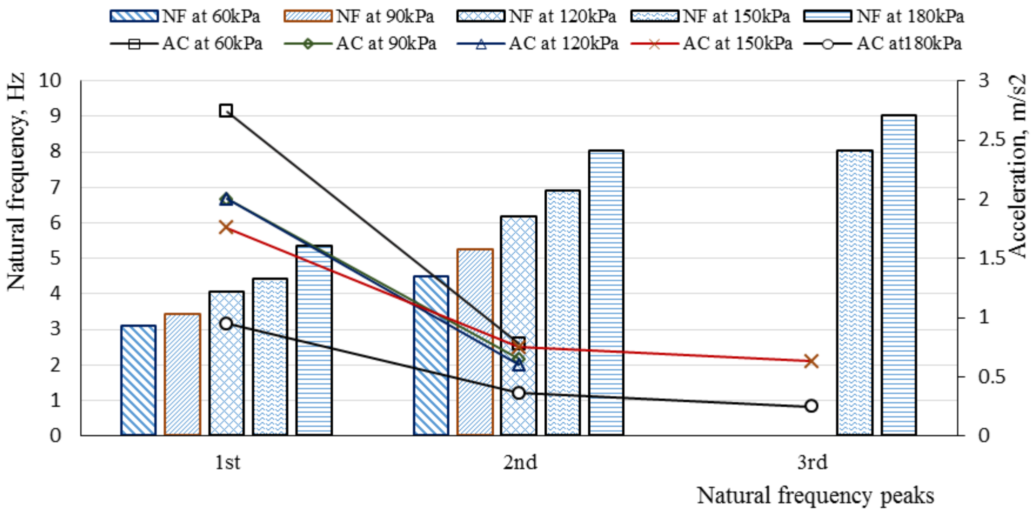
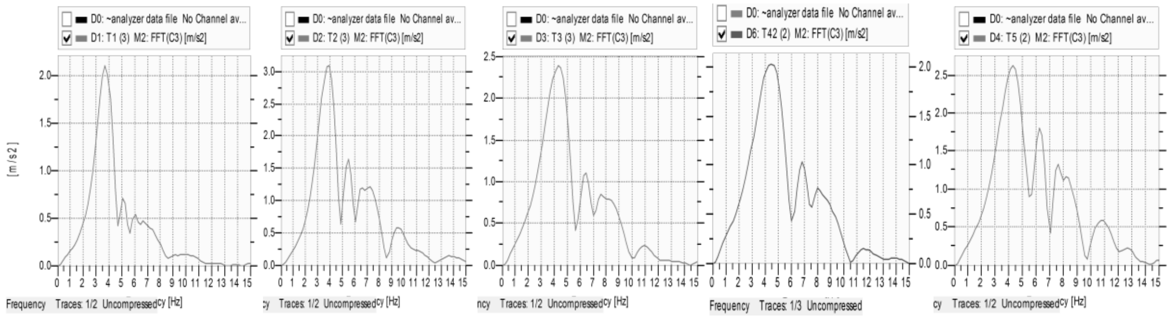


Fig. 12 Variation of vertically natural frequency and acceleration values of TS_5 test tire



(a) (b) (c) (d) (e)

Fig. 13 The spectra of vertical acceleration in frequency domain of tire TS_6 when tire inflation pressure increased: Figs. 13(a), (b), (c), (d) and Fig. 10(e) for tire inflation pressure change from 120 to 240 kPa, with increment of 30 kPa, respectively

no much change in natural frequency of tire in small soil depth when changing tire inflation pressure but it is always higher than of case of the tire only. So it can states that tractor tire with small size, the tire inflation pressure slightly affected to natural frequency in tire-soil system while it strongly affected in case of a large one in the same soil depth.

The vertical acceleration of tire-soil system discontinuously decreases with the crease in tire inflation pressure (Fig. 14).

For TS_7 test, the vertically natural frequency increased from 3.04, 3.42, 4.00, 4.33 to 4.57 Hz when increasing inflation pressure from 120 to 240 kPa, with an increment of 30 kPa (Fig. 15 and 16), the natural frequency strongly increased with increment approximately of 0.4 Hz, the increment of frequency is same in TS_4 test.

The same trend of TS_6 test was observed in the vertical acceleration of tire-soil system; it also discontinuously decreases with the crease in tire inflation pressure (Fig. 16).

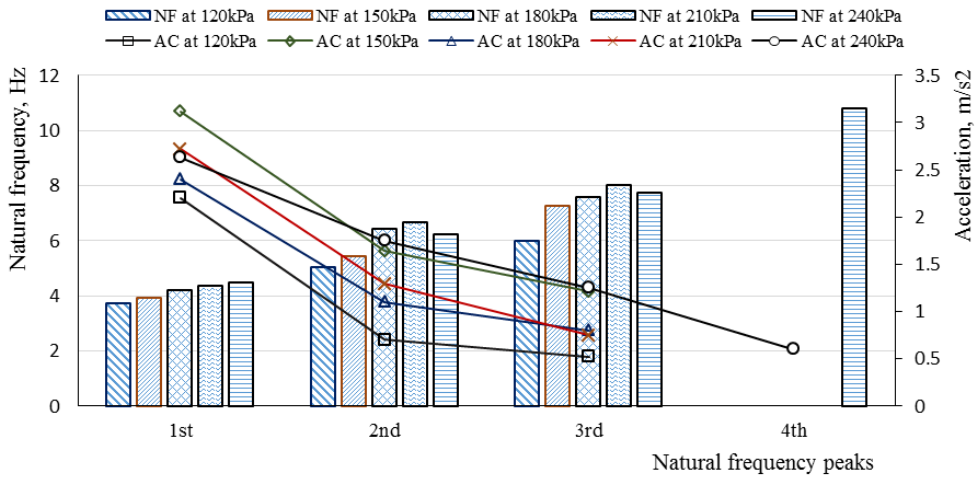
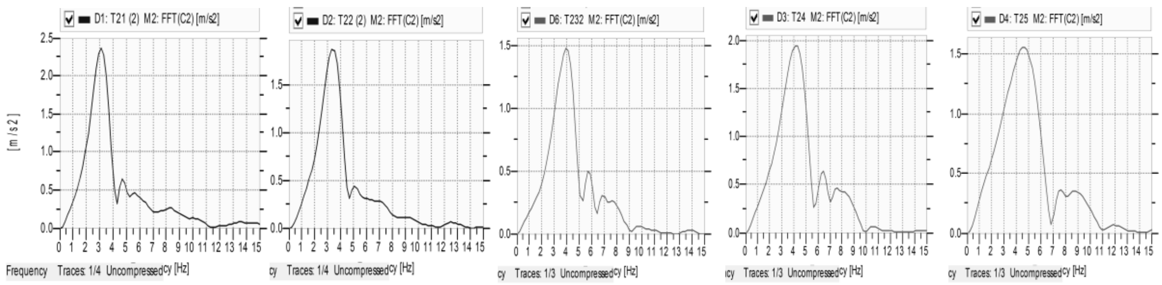


Fig. 14 Variation of vertically natural frequency and acceleration values of TS_6 test tire



(a) (b) (c) (d) (e)

Fig. 15 The spectra of vertical acceleration in frequency domain of TS_7 test when tire inflation pressure increased: Fig. 15(a), (b), (c), (d) and Fig. 11(e) for tire inflation pressure change from 120 to 240 kPa, with increment of 30 kPa, respectively

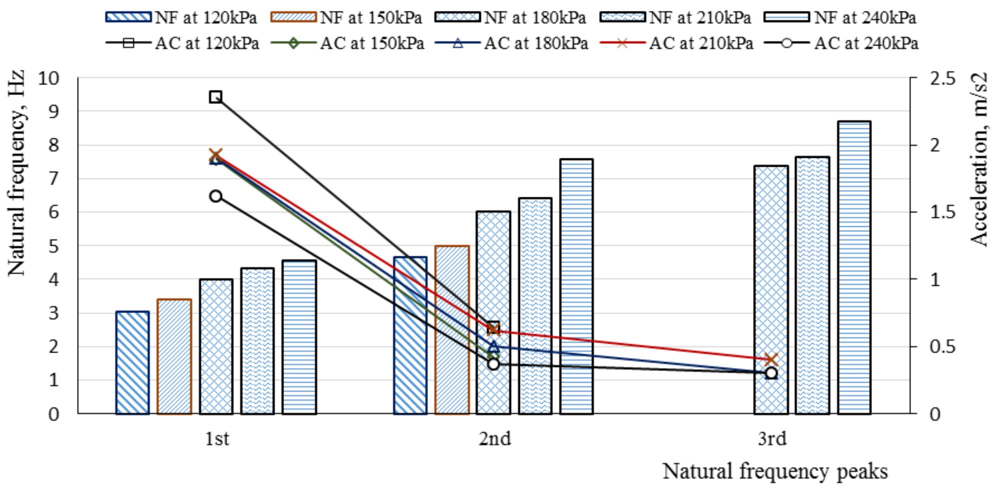


Fig. 16 Variation of vertically natural frequency and acceleration values of TS_7 test tire

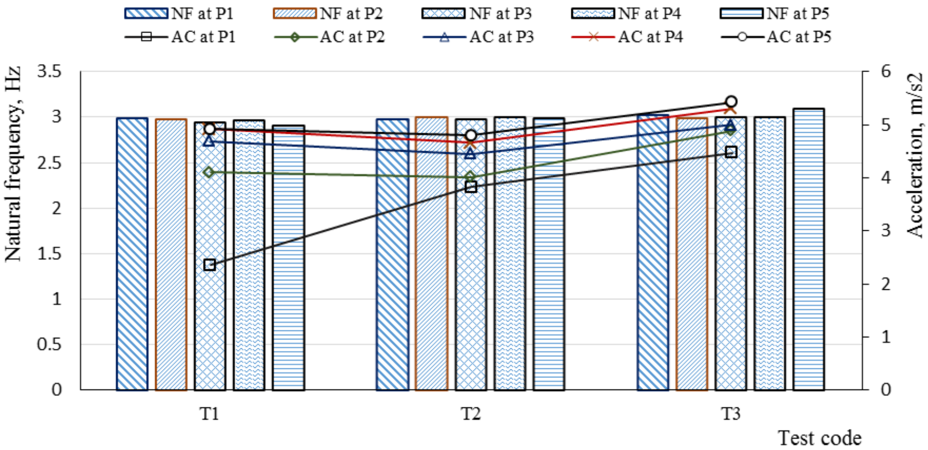


Fig. 17 Comparision of natural frequencies (NF) and acceleration (AC) between T_1, T_2 and T_3 test with different tire inflation pressure. P_1, P_2, P_3, P_4 and P_5 is tire inflation pressure of 60, 90, 120, 150 and 180 kPa contributed for T_1 and T_2, and is 120, 150, 180, 210, 240 kPa contributed for T_3 test, respectively. All values considering at the first natural frequency

3.3 Comparation of the natural frequencies of tire and tire-soil system with different tire, inflation pressure and soil depth

The tire inflation pressure and tire load are distributed referring Chinese standard (GB/T2979-2008). Comparing the natural frequencies of three T_1, T_2, T_3 tests with different tire inflation pressure, tire size, tire load, it shows that the variation trends of vertically natural frequencies and acceleration in three test codes are similar (Fig. 17). The first, second and third natural frequency of all three tires is closed to 3.0, 4.0 and 5.0 Hz. The vertical acceleration in T_3 is always higher than of T_1 and T_2 test, and there are little differences in the vertical acceleration in T_1 and T_2 test, it showed that the inflation pressure strongly effected tire vertical acceleration.

The first, second and third vertically natural frequency are closed to 3.00 Hz, 4.00 Hz and 5.00 Hz, respectively when tire inflation pressure changed, it is showing that tractor tires with low inflation pressure conducted natural frequencies are in low frequency of 3-10 Hz and no much effected by tire inflation pressure. The natural frequency values are in low frequency as founding by Maurizio *et al.* (2017), they found that the vertically natural frequency of the tires is in the range from 2.20 to 3.40 Hz. While Nikolay *et al.* (2017) found that the tire vertical vibration natural frequency of tractor is 6.40 Hz. Caprara *et al.* (2000) determined the natural frequency of three tractor tires are in the range of 8.9 to 10.9 Hz. Geice *et al.* (2014) found the frequency of axle rear of the tractor tire is in the range 2-4 Hz. Goerıng *et al.* (2006) found the natural frequencies of a tractor are in the range of 3-5 Hz, this frequency range is also the resonance frequencies of tire. Xu *et al.* (2014) concluded that the natural frequencies of the tractor in vertical, pitch and roll directions are concentrated in 3-4 Hz, 2.8-3.8 Hz and 2.9-3.9 Hz ranges, respectively. Some conclusions showed that natural frequency increased with increasing tire inflation pressure (Negrus *et al.* 1997, Jia *et al.* 2005, Kim *et al.* 2007, Karakus *et al.* 2017), there were different by the contribution of the tire in high inflation pressure and performed in car or truck tire, and effect by hysteresis manner of the tire (Elsalam *et al.* 2017), the tires due to complex mechanics of the rubber-textile composite, the complex tire contour, and the large deformations (Jia *et al.* 2005).

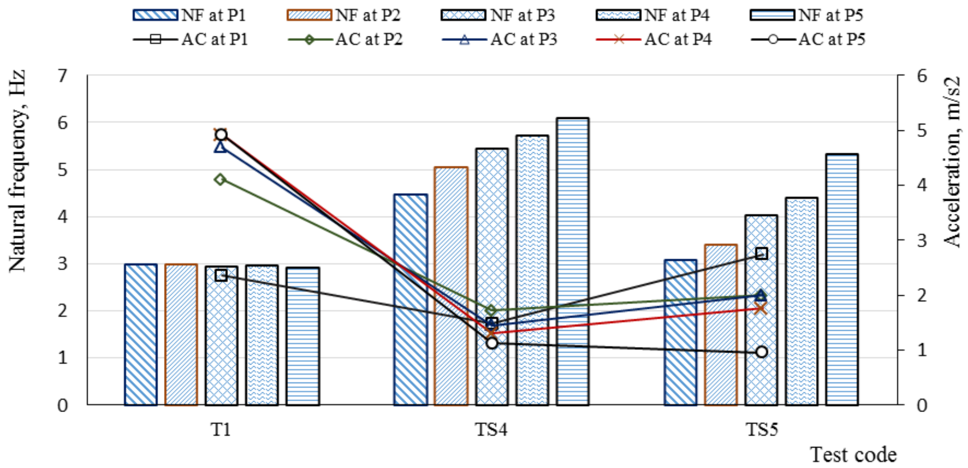


Fig. 18 Comparision of natural frequencies (NF) and acceleration (AC) between T_1, TS_4 and TS_5 test with different tire inflation pressure. P_1, P_2, P_3, P_4 and P_5 is tire inflation pressure of 60, 90, 120, 150 and 180 kPa, respectively. All values considering the first natural frequency

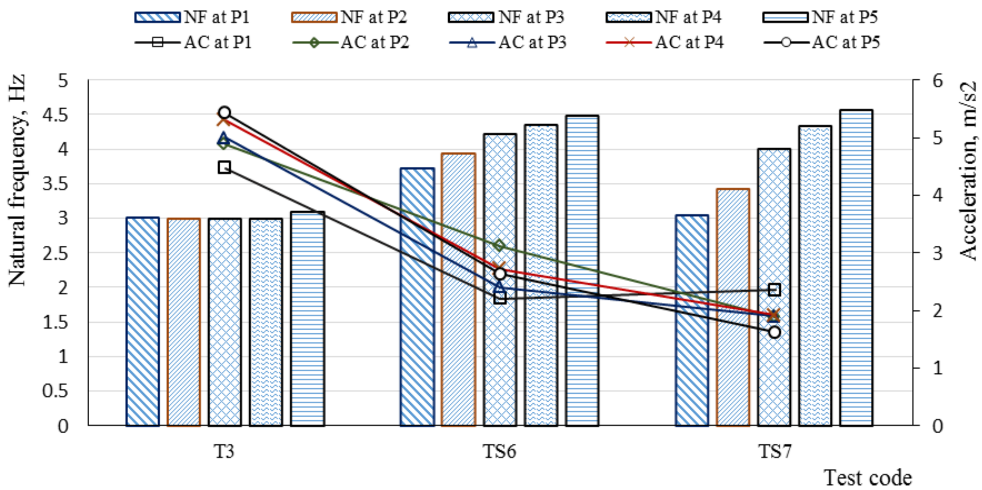


Fig. 19 Comparision of natural frequencies (NF) and acceleration (AC) between T_3, TS_6 and TS_7 test with different tire inflation pressure. P_1, P_2, P_3, P_4 and P_5 are tire inflation pressure of 120, 150, 180, 210, 240 kPa, respectively. All values considering the first natural frequency

It can be concluded that with a tractor has no suspension system, and tire is unique elastic contact between tractor and road so that the natural frequency of tire is important by it can cause the resonance phenomenon of the tractor. These have to regard in the design tractor suspension system. It evident that the change of tire inflation pressure and tire size to control vibration frequency of tractor traveling on soft soil ground has no invalid.

By comparing the vertically natural frequency of T_1, TS_4 and TS_5 test (Fig. 18), it is indicating the natural frequencies of T_1 test is lower than of TS_4 and TS_5 test. In addition, the vertically natural frequency of TS_5 test is lower than of TS_4 test. It showed that the tire vertical frequency of tire

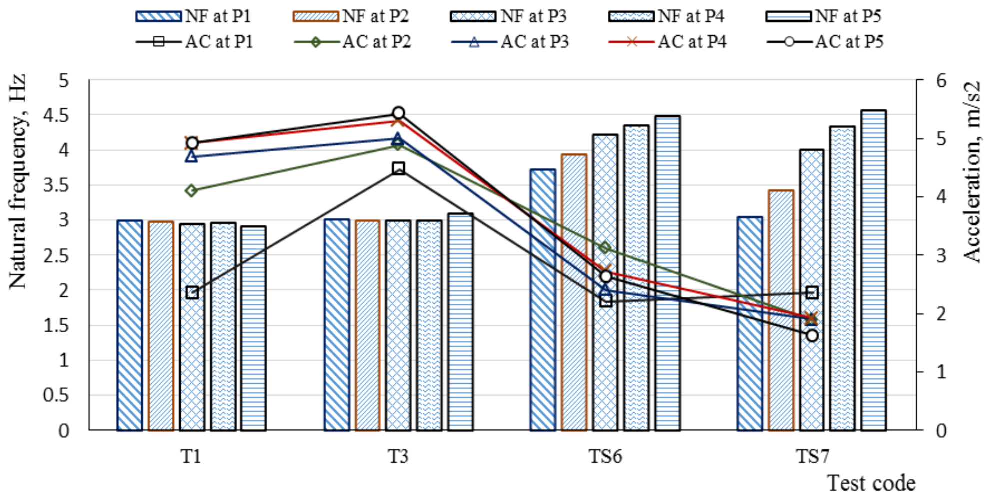


Fig. 20 Comparision of natural frequencies (NF) and acceleration (AC) between T_1, T_3, TS_4 and TS_7 test with different tire inflation pressure. P_1, P_2, P_3, P_4 and P_5 are tire inflation pressure of 60, 90, 120, 150 and 180 kPa contributed for T_1 and TS_4, and 120, 150, 180, 210, 240 kPa contributed for T_3 and TS_7 test, respectively. All values considering the first natural frequency

dropped on rigid ground increased up to 200% comparing to tire dropped on soft soil ground and the vertical frequency of tire changed with changing the field condition as soil depth.

On the contrary, the vertical acceleration of T_1 test is higher than of TS_4 and TS_5 test, it is showing that the absorbing capacity the vibration of tire-soil system as a conclusion by Cuong *et al.* (2013) and Cuong *et al.* (2014).

Another comparison of the natural frequency of T_3, $TS_{6,}$ and TS_7 (Fig. 19), the same trend of the vertically natural frequencies and acceleration. There is deviation in vertically natural frequency with the increment of 0.15 Hz in TS_6 test comparing to TS_7 test is 0.4 Hz. It indicates that the practical complexity of suspended characteristics of the tractor tire-soil system (Nguyen and Inaba 2011). The deviation of vertical acceleration of tire was found between T_3, TS_6 and TS_7 test, these deviations reduce when the soil depth increase.

Comparing TS_4 and TS_7 test with the same soil depth (Fig. 20), the natural frequencies of TS_4 test are always higher than of TS_7 test, the natural frequencies of TS_4 increased from 4.48 to 6.10 Hz when increasing inflation pressure from 60 to 180 kPa, while the natural frequencies of TS_7 test increased from 3.04 to 4.57 Hz when increasing inflation pressure from 120 to 240 kPa, both of two is same the increment of 0.4 HZ. It shows that the natural frequency of rear tire is higher than of front tire, although the inflation pressure of front tire is higher, these must be regarded in tractor design process.

The above results show the vertically natural frequency of tire no effected by tire inflation pressure while it strongly effected tire-soil systems. The vertically natural frequency of tire–soil system was always higher than of tire only. The results also show the vertical frequencies of tractor tire are in the range 3-10 Hz lying within the most critical natural frequency range of the human body (Kumar *et al.* 2001, Matsumoto and Griffin 2001). These findings confirmed that tractor tire with low inflation pressure needs to regard the natural frequency of tire or tire-soil and treat them as practical complexity which was noticed on the design of tractor suspension systems.

4. Conclusions

The study investigated the vertically natural frequency of tractor tire by changing different ground contacts and inflation pressures and resulted in the following findings:

- The vertically natural frequency of the tractor tire was not significantly affected by its inflation pressure which was in the range of 60 to 240 kPa and the tire size. On the other hand, it was significantly affected by the interaction of tire-soil systems and inflation pressure.
- The first, second and third vertically natural frequencies of tractor tire are close of 3.0 Hz, 4.0 Hz and 5.0 Hz for all three kinds of tire when the tire performs free decay vibration on rigid ground while it is strongly affected by changing tire inflation pressure, it counts in the range of 3.10-9.02Hz when the tire performs free decay vibration on soft soil ground. The natural frequency of tire-soil system also always changed with changing soil depth and tire size.
- On the other hand, the vertical acceleration of tractor tire increase with an increase in inflation pressure but it is a slightly and discontinuous decrease in tire-soil systems.
- The vertically natural frequency of tire–soil system was always higher than of tire only (up to 200%) and it is in the range 3-10 Hz. The natural frequency of rear tire is higher than of front tire because the inflation pressure distributed in front tire is higher.

The vertical damped natural frequency of tractor tire is an important vibrational parameter that can be causing damage to the health of tractor driver, so it has to take into account tractor suspended system design process. The results of this study have to be regarded in study of vibration of tractor working in different conditions and it was noticed on the design of tractor suspension systems.

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