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Original Research Article

Experimental Study on Development of Smart Algorithm Based on Tire Deflection to Detect the Drops in Tire Pressure

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Abstract

This study aims to experimentally investigate accordance between tire pressure and vertical deflection of tire in order to use in TPMS (Tire Pressure Monitoring System). For this aim, the resonance frequency of vertical deflection of tire is determined by using test results. Thus, the road tests have been conducted on dry flat road for measuring the tire deflection. These tests are run at constant vehicle speeds 30 and 100km/h for tire pressures 15, 20, 25, 30, 35psi. Therefore, the vertical deflection changes have been measured under same road conditions with different vehicle speeds. The frequency responses of the measured vertical deflections are obtained by implementing sampled root mean square (SRMS) method to vertical deflection signals. The resonance frequency of the vertical deflection is taken from the frequency responses. The results show that the accordance between tire pressure and vertical deflection of tire is achieved irrespective of the changes in vehicle speed. Consequently, the algorithm to detect the drops in tire pressure is developed by using the time and frequency domain results.

Key words: Tire pressure, tire deflection, resonance frequency, vehicle speed, algorithm.

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1. Introduction

In the vehicles, acceleration, braking and handling performances greatly depend on the tire-road contact patch. Because the braking and driving forces are not transferred onto road, when the contact greatly decreases. This causes inconsistent braking maneuver, long acceleration process and unstable handling as well as tire wear. When it is considered that only vehicle component which is in contact with road is pneumatic tire, the pneumatic tire parameters determining the changes in tire-road contact have direct effect on vehicle dynamics.

One of the most important tire parameters is tire inflation pressure, since the pressure distribution inside tire determines the area of tire-road contact patch. In other words, if the tire pressure decreases relative to nominal pressure, the pressure distribution is centered on shoulder and the contact area decreases in middle of tire. Under-inflated tires build up heat faster and cannot carry their required load. This causes excessive flexing in the tire resulting in tread separation and blowout [1]. Also, if the tire pressure greatly increases relative to nominal pressure, the pressure distribution is concentrated on the middle of tire contact patch and the contact area decreases in shoulder of tire [1,2]. Therefore, proper tire maintenance is an important safety function and the maintaining sufficient air pressure is required if tires are to provide all of the handling, traction and durability of which they are capable [3]. The vehicles which have low tire pressure significantly affects the traffic security, and they can be the cause of fatal accidents [4]. Pohl et al. [5] stated that a puncture of the tires in motion can lead serious accidents and imperil human life. For this reason, active braking and steering systems are designed to compensate the vehicle stability during sudden decreases in tire pressure [6,7]. Moreover, it leads the fuel consumption and exhaust emissions to increase. Persson et al. [8] have reported that vehicle consumes more fuel and tire wears in shorter time due to reductions in tire pressure. However, the control of tire pressure is often neglected by drivers.

For this reason, the U.S. Transportation Recall Enhancement, Accountability, and Documentation Act (TREAD) have made mandatory to use a low pressure warning system in vehicles [9]. Thus, TPMS has become obligatory for every new vehicle in the United States since 2007. Moreover, Europe is in trend to accept similar regulations as a way to decrease exhaust emissions and enhance safety. Also, China intends to accept similar regulations [10].

A TPMS is a system which warns the driver when the tire pressure reduces relative to nominal tire pressure. For TPMS, tire blowouts are the primary safety use case. The other is the fact that tires can leak as much as one psi per month through natural leakage and as much as 85 percent of all tire pressure losses are through slow leaks without suffering any road damage at all [1, 11].

TPMS systems are classified in two different categories. These are based on direct and indirect methods. Direct TPMS directly uses a pressure signals which sent by pressure sensor coupled to the wheels. The pressure signals are sent to the vehicle by means of radio frequency technology. Therefore, the reductions in tire pressure are determined by using these pressure signals. A direct TPMS can also give information to the driver about pressure deviations [9]. However, this method needs extra hardware, so it is very expensive. Also, it has disadvantage due to centrifugal force of rotated tire. Because, the force applied by centrifugal force onto the sensor causes wrong information to be given about tire pressure by the direct TPMS. For this, the acceleration sensor is used. This makes the direct TPMS more expensive and complex.

For this reason, the other alternative method is used. It is called as indirect tire pressure monitoring system. This system employs existing wheel speed sensors and software algorithms. The indirect systems have low cost, since it needs no extra hardware. An indirect TPMS estimates reductions in tire pressure by using estimation algorithm and thus they need no tire pressure sensors. At present, they generally use wheel speed signals measured by ABS sensors. In this system, it is considered that the static and dynamic loads of vehicles cause the tire diameter to decrease because of reductions in tire pressure. This induces the tire to rotate at more different speeds and frequencies. For this reason, the changes in resonance frequency of wheel speed are estimated or measured [12,13].

However, several deficiencies are available for indirect TPMS using speed signals of four wheels. At first, the system may not predict the real tire pressures at different vehicle speeds [14]. Also, it works, only if the vehicle is driven. Moreover, an alert signal is not sent by TPMS, when tire pressures of the same axle or same side reduce at same rate. Also, this is valid, when pressures of all tires are equally low. For this reason, TPMSs, which work even when the vehicle is in stationary and determine the changes in tire pressure of individual wheel, are needed. Therefore, nowadays, some studies have focused on TPMSs based on the changes in vertical tire stiffness. When tire pressure decreases, the vertical stiffness of the tire drops, and the amount of sinking increases. Hence, the vertical deflection of the tire increases, then the wheel rolling speed becomes correspondingly lower [15]. The measurement of tire stiffness is very difficult with a sensor, thus vertical tire stiffness is obtained by the other tire parameters measured directly with sensors. For this aim, the changes in vertical stiffness are obtained through the vertical deflection of tire[16]. For this, the fact that the vertical deflection increases when tire is under-inflated is used. Here, the wheel radius analysis is performed and this analysis is based on vibration analysis and especially estimation properties of the resonance frequency [9].

As a result, a number of studies performed for indirect TPMS show that the only wheel speed information is not enough to estimate tire pressure under all driving conditions due to given deficiencies. Instead, another dynamic parameter of tire must be used for indirect TPMS. The most important parameters are longitudinal tire force and vertical deflection of tire [15]. In this study, vertical tire deflection is used for estimating the changes in tire pressure. Because this parameter determines the variations in vertical stiffness of tire through deformation and deflection of tire which represent the changes in tire pressure in best way [9,15]. The most effective way is to occur resonance frequencies of vertical tire deflection for applying to TPMS.

However, the resonance frequencies of vertical tire deflection are not investigated to determine drops in tire pressure with TPMS. Also, the impact of vehicle speed has not been searched on the resonance frequency of vertical tire deflection. Whereas NHTSA has reported that the decreases in tire inflation pressure lead the friction coefficient to drop 5% and 9%, respectively as the vehicle speed increases. For this reason, this study has focused on the accordance between tire pressure and the resonance frequencies of the vertical tire deflection by considering the changes in vehicle speed. Also, it aims to develop the algorithm to detect the drops in tire pressure based on tire deflection.

2. Tire Model

The main source of TPMSs investigated in this study is the changes occurring in resonance frequency of vertical tire deflection. For this, the vertical vibration analysis of tire is carried out. In this analysis, tire is modeled as a spring in vertical direction as shown in Fig.1. However, tire damping is neglected in this model.

In Fig.1, tire is divided into belt side and rim side. Rim side is rigid, but belt side can deform in vertical direction relative to rim side as shown in Fig.1. In this model, only inertial element of the tire is mass of lower part of the belt side in the contact region. Thus, the vertical deflection of tire is represented by Δz during the vertical displacement of the mass. The parameters of the model are given in Table 1.

In this study, the variation of tire radius is described with respect to vertical tire deflection as follows [2]:

$$\delta R_e = (1-\eta)\Delta z \tag{1}$$

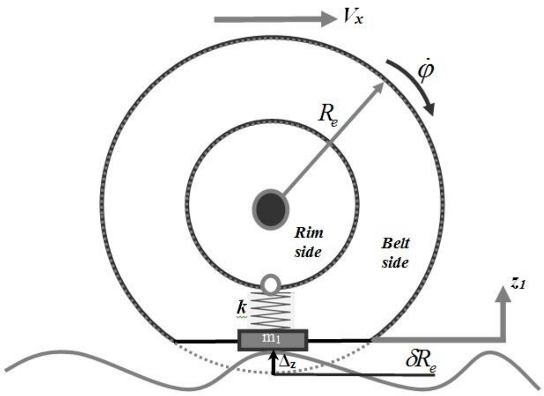

Figure 1. The vertical dynamic model of deflated tire

Table 1. The parameters related to the vertical dynamic model of deflated tire

V_x	Vehicle speed
$\dot{\varphi}$	Wheel speed
R_e	Tire radius
δR_e	Variation of tire rolling radius
m_1	Mass of lower part of the belt side
z_1	Vertical displacement of the mass
Δ_z	Variation of tire deflection
k	Tire stiffness

where η is experimental constant. It takes 0.4 and 0.1 values for cross ply and radial ply, respectively [2]. Also, the variation of vertical tire deflection given in Eq. 1 is described as follows [18]:

$$\Delta z = \frac{m_1 g}{\Delta k} \tag{2}$$

where Δk is the decrease in vertical spring stiffness of tire. This parameter reflects the changes in tire pressure to the tire deflection. Thus, the tire spring stiffness decreases by Δk as tire pressure decreases [8]. This shows that the tire deflection increases as tire pressure drops. In this study, the tire carcass of test vehicle has radial ply. Thus, η is 0.1 and the variation of tire radius is defined for radial ply as follows:

$$\delta R_e = 0.9\Delta z \tag{3}$$

Eq. 3 clearly means that the tire deflection has same variation as the tire radius. Therefore, wheel speed is obtained during the drops in tire pressure in two different ways. The first one is defined by using the variation of tire radius as follows [8]:

$$\dot{\phi} = \frac{V_x}{R_e - \delta \mathrm{R_e}} \tag{4}$$

The second one is described with respect to tire deflection by substituting the Eq.3 into Eqs.4a and 4b as follows:

$$\dot{\phi} = \frac{V_x}{R_e - 0.9\Delta_z} \tag{5}$$

Therefore, following description is taken into consideration to determine the effects of changes in vehicle speed on the tire deflection by rearranging Eq.5 relative to Δz.

$$\Delta_z = \frac{1}{0.9}(R_e - \frac{V_x}{\dot{\phi}}) \tag{6}$$

As shown in Eq.6, the vertical tire deflection depends on the ratio of vehicle speed to wheel speed. According to Eq.6, the vertical tire deflection increases, when the vehicle speed decreases with respect to wheel speed and it decreases as the vehicle speed increases. Hence, a change in the vehicle speed leads the tire deflection to decrease or increase. After determining the effects of vehicle speed on tire deflection, the resonance frequency of vertical tire deflection is obtained. For this, the vertical vibration of tire belt side mass m_1 is considered as shown in Fig.1. Therefore, the dynamic equation describing free vibration of vertical motion of m_1 is used as follows:

$$m_1\ddot{z}_1 + (k - \Delta k)z_1 = 0 \tag{7}$$

$$m_1\ddot{z}_1 = \Delta k z_1 - k z_1 \tag{8}$$

The right two terms of the Eq.8 are vertical spring force tire and the decreases in the vertical force due to tire deflation, respectively. The decrease in the vertical tire force is determined with the decrease in vertical spring stiffness of tire as follows:

$$\Delta k = \frac{m_1 g}{\Delta z} \tag{9}$$

The vertical displacement and acceleration of belt side mass are described for obtaining resonance frequency as follows:

$$z_1 = a\sin\omega t \tag{10a}$$

$$\ddot{z}_1 = -\omega^2 a\sin\omega t \tag{10b}$$

When Eqs.10a and 10b are substituted into Eq.7, the following description is obtained.

$$-m_1\omega^2 a\sin\omega t = -(k-\Delta k)a\sin\omega t \qquad (11a)$$

$$m_1\omega^2 = k-\Delta k \qquad (11b)$$

Therefore, the resonance frequency of vertical tire deflection is described as follows:

$$\omega = \sqrt{\frac{1}{m_1}(k-\Delta k)} \qquad (12)$$

Eq.12 shows that the resonance frequency of vertical tire deflection reduces as the tire spring stiffness decreases due to tire deflation. In other words, the resonance frequency decreases, when the tire pressure drops.

In this study, the effects of vehicle speed on the resonance frequency are taken into consideration. For this, the Eq.6 is substituted into Eq.9, then the obtained equation is substituted into Eq.12 and the resonance frequency is described in terms of vehicle speed as follows:

$$\omega_r = \sqrt{\frac{k}{m_1} - \frac{0.9g}{R_e - \frac{V_x}{\dot{\varphi}}}} \qquad (13)$$

Eq. 13 clearly shows that the resonance frequency increases when the vehicle speed is decreased according to wheel speed. However, the increases in vehicle speed reduce the resonance frequency. This shows the resonance frequency of vertical tire deflection includes the effects of vehicle speed.

As a result, the variations in vertical tire deflection give the information about the changes in tire pressure through vertical frequency of tire deflection. For this, the changes in tire stiffness are taken as a reference. Also, the effects of changes in vehicle speed on tire deflection are considered. Thus, in this study, the frequency responses of the tire deflection are investigated and the accordance between the tire pressure and the resonance frequency is experimentally searched. Also, the effects of changes in vehicle speed on the resonance frequency are discussed.

3. Experimental material and method

In experimental study, the vertical tire deflection has been measured by means of non-contact laser height sensor as shown in Fig.2. The height sensor is available in vehicles with semi-active or active suspensions [9].

A B C

Figure 2. a) Test vehicle **b)** Mounting components of laser sensor **c)** Position of the sensor on wheel

For this reason, the tire deflection can be easily measured in this vehicle. The height sensor has 100-350 mm measurement range and 0.1mm resolution. This sensor has been mounted to the wheel lug nuts via adjustable mounting collets as shown in Figs.2b and 2c. In this way, it is located exactly in the wheel centre, and it can rotate with respect to the wheel about the wheel's y-axis. To restraint this rotation, the sensor has been connected to the vehicle body with a rod in order to assure that the sensor measures in the vehicle body (vertical) z-direction.

The test vehicle used for driving tests is

Toyota Auris as shown in Fig. 2a. Technical specifications of test vehicle and tire are given in Table 2.

Table 2. The test vehicle specifications

Total vehicle weight	1412 kg
Front axle weight	898 kg
Rear axle weight	514 kg
The weight acting on front tire	449 kg
Tire dimension	255/55/R16
Tire tread depth	7mm
Tire nominal inflation pressure	35 psi
Tire maximum pressure	45 psi
Effective rolling radius with nominal tire pressure	0,315 m
Carcass type	Radial
Speed rating	V (240 km/h)
Load index	81 (462 kg)
Traction	AA

After mounting this sensor onto the test vehicle, it is connected to data acquisition unit. The unit is switched according to the reference variable. In this study, the reference variable is vehicle speed. Thus, the measurements are initiated and stopped within the same time period by keeping the vehicle speed at constant level.

4. Experimental Results and Discussion

4.1. Time domain results

In this section, the resonance frequencies of vertical tire deflection oscillations are assessed by using the frequency response for time domain results of the measured tire deflection. Time result of some of measured vertical deflections is given for 15psi and 35 psi in Fig.3.

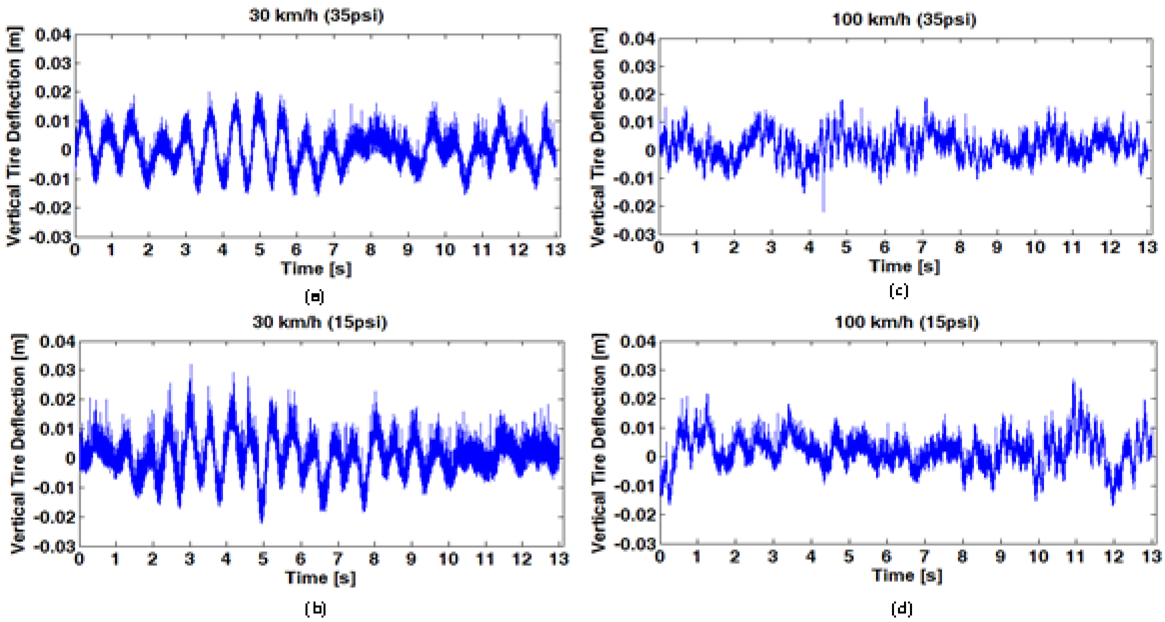

Fig.3. Time results of vertical tire deflection

In Fig.3, the time domain results of lowest tire pressure and nominal tire pressure are given. Therefore, the tire deflection increases at low vehicle speed as tire pressure decreases as shown in Figs. 3a and 3b. Also, the deflection decreases as the vehicle speed increases as shown in Figs. 3a and 3c. The same trend is seen in Figs.3b and 3d. This shows that the accordance between experimental and theoretical results is obtained according to Eqs.2 and 6. Therefore, the accuracy of experimental results is proved in time domain.

4.2. Frequency response results

In this study, the frequency responses of vertical tire deflection are investigated to determine whether the nominal tire pressure has highest and lowest peaks and resonance frequency or not. In this way, it is occurred whether the vertical tire deflection information is used in TPMS or not. The frequency responses are obtained by using Fourier Fast Transform (FFT) of measured tire deflection. FFT method is described as follows:

$$X(j\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}dt \quad (14)$$

where $X(j\omega)$ is frequency response and $x(t)$ is measured tire deflection in time domain. Here, the square root of the square of the average of sampled tire deflection signals is used to occur effective resonance frequencies in frequency responses. This method is called as a sampled root mean square (SRMS). SRMS is described as follows:

$$SRMS = \sqrt{(\frac{1}{n}\sum_{j=1}^{w}(A_j)^2} \quad (15)$$

where A is vertical tire deflection, n is the number of data samples and w is the window with five samples of A. From the calculated SRMS values, firstly a single average RMS envelope value of every five data of tire deflection is obtained, then the data sequence composing from the RMS envelope values is got. The frequency response of this data sequence is calculated by using FFT method. Therefore, the frequency response of the vertical tire deflection values including effective information related to resonance frequency is acquired. Here, the frequency responses of measured and only filtered measured datas are compared with tire deflection data processed by using SRMS to determine effectiveness of SRMS method. The filtered vertical tire deflection is obtained by using low pass filter; because we need peaks and resonance frequencies information associated with low frequency. The results are shown in Fig.4.

As shown in Fig 4, FFT of measured tire deflection without filtering has no clear peak. Thus, it does not give clear information about the resonance frequency. The filtered FFT gives information related to peak and resonance frequency. However; it causes a number of peaks to occur. This may lead wrong information to be given about resonance frequency at specially 15 psi tire pressure. Nevertheless, FFT obtained with SRMS has a clear peak and thus it has resonance frequency at all tire pressures. This clearly shows that the most appropriate method to determine resonance frequency is frequency responses of tire deflection achieved by SRMS.

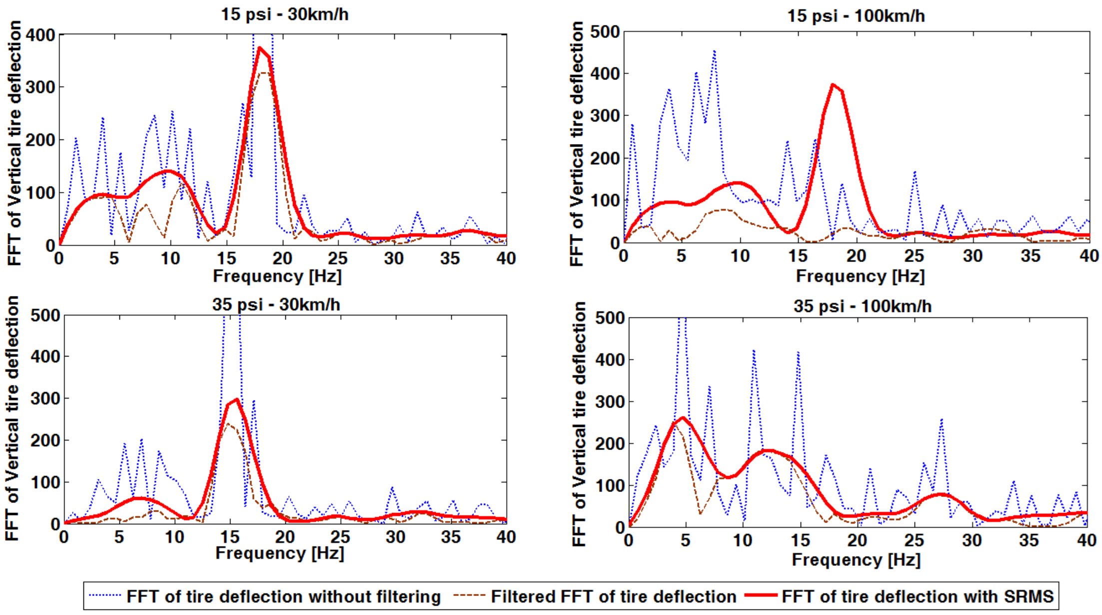

Fig. 4. The comparison of FFT processing methods

The frequency responses of vertical tire deflection are shown in Figs. 5 and 6 for the tire pressures 15, 20, 25, 30, 35psi at vehicle speeds 30 and 100 km/h, respectively. Also, the frequency and amplitude values of peaks are given in the square as shown in Figs. 5 and 6. In Figs. 5 and 6, it is considerable point that the frequency responses of 35 psi are related to nominal tire pressure. It is remarkable that the tire pressures which are lower than nominal tire pressure are considered as shown in Figs.5 and 6. In this way, the frequency responses of nominal tire pressure are compared with those of lower tire pressures. As shown in Figs. 5 and 6, the frequency responses have peaks at 2-5Hz, 5-10Hz, 10-19Hz, 19-29Hz, 29-34Hz and 34-40Hz frequency ranges.

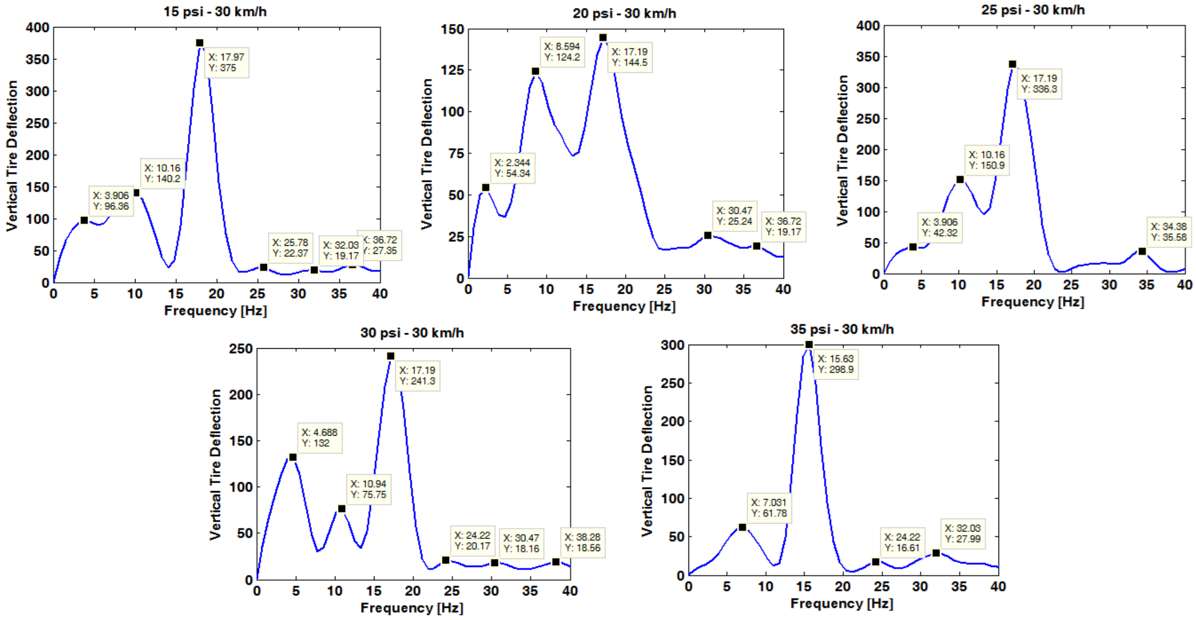

Fig.5. Frequency responses of vertical tire deflection for 30 km/h

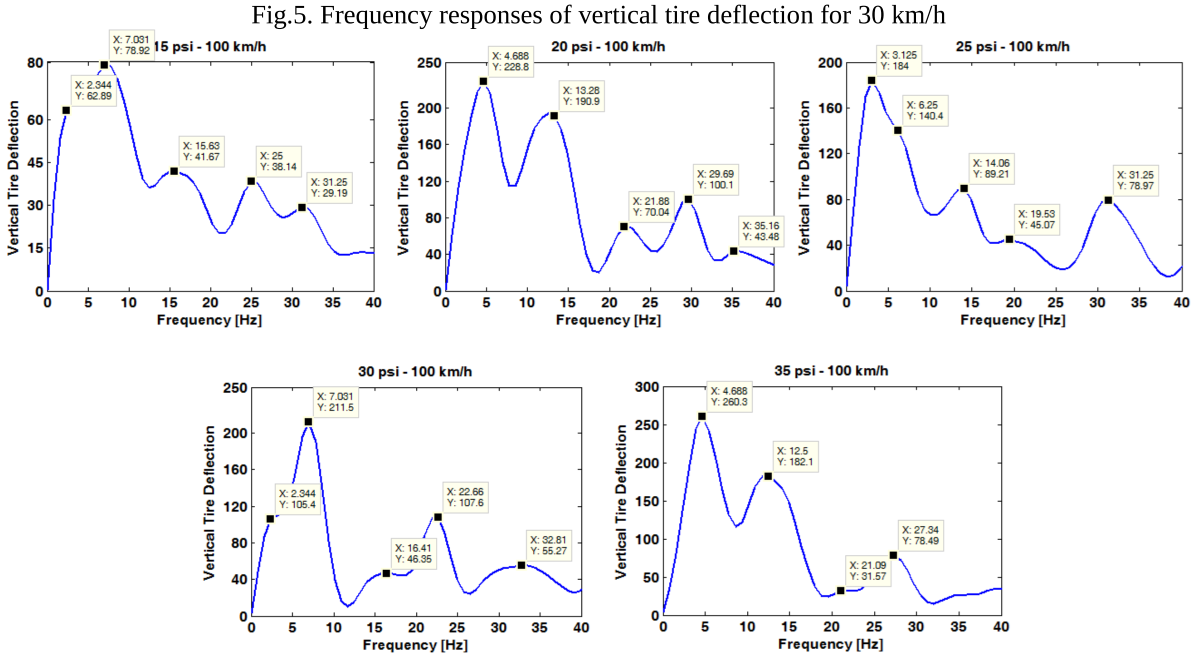

Fig.6. Frequency responses of vertical tire deflection for 100 km/h

The third of these ranges, which is 10-19Hz, is associated with tire deflection oscillations resulting from axle oscillations. The other peaks result from rotational speed oscillations of wheel [1,2]. Thus, the tire deflection is separately excited by the axle and wheel rotational speed oscillations. There is no combined excitation on tire deflection variations.

As shown in Fig.5, when the tire deflection is excited by the axle oscillations at 30km/h, 20psi provides the oscillation which has the lowest peak. Also, 15 and 25psi’s cause the highest peaks. However, if the vehicle speed increases to 100km/h, 15psi provides the lowest tire deflection oscillations, while 20 psi causes the highest oscillations at 100 km/h as shown in Fig.6.

When the frequency responses are analyzed for wheel speed oscillations at lower frequency than that of axle oscillations at 30 km/h as shown in Fig.5, 30psi and 25psi lead the highest peaks at 2-5Hz and 5-10Hz frequency ranges, respectively. Also, 30 psi and 35 psi have the lowest peaks at 2-5Hz and 5-10Hz. When the vehicle speed is increased to 100 km/h, 15 psi and 20 psi have the lowest and the highest peaks respectively at 2-5Hz as shown in Fig. 6. Also, 15 psi and 30 psi have the lowest and the highest peaks respectively at 5-10Hz. When the Fig 5 is investigated for wheel speed oscillations which have higher frequencies than those of axle oscillations at 30 and 100km/h, the vertical deflection has too low peaks to distinguish the tire pressures. However, the peaks emerge at these frequencies, as the vehicle speed is increased. The level of these peaks is greatly reduced by 15 psi. Also, the nominal tire pressure damps peaks at 19-29Hz and 34-40Hz frequency ranges.

As a result, nominal tire pressure has neither lowest nor highest peaks, when the tire deflection is excited by the axle or wheel speed oscillations at 30km/h and 100km/h as shown in Figs.5 and 6. Therefore, the level of tire deflection oscillations does not change in certain array with tire pressures. The level of peaks only indicates the effects of tire pressure on the tire deflection. This clearly shows that the level information of peaks is not suitable to TPMS. For this reason, the accordance among resonance frequencies of the oscillations is considered according to the tire pressures to use in TPMS. For this, the resonance frequencies are taken from Figs. 5 and 6 and Table 3 is established.

Table 3 enables the resonance frequency accordance to determine for different tire pressures at same vehicle speed. Therefore, at vehicle speed of 30 km/h, the nominal tire pressure has the lowest resonance frequency at 5-10 Hz and 10-19 Hz ranges. Also, the nominal tire pressure has the lowest resonance frequency at 10-19 Hz and 29-34 Hz ranges at vehicle speed of 100 km/h. In this way, the resonance frequencies of tire deflection resulting from axle and wheel speed oscillations are suitable to determine drops in tire pressure at same vehicle speed.

Table 3. The resonance frequencies for tire pressures at same vehicle speed

		Tire pressures (30 km/h)				
Excitation source	**Frequency range**	**15 psi**	**20 psi**	**25 psi**	**30 psi**	**35 psi (Nominal tire pressure)**
Wheel speed oscillations	2 – 5 Hz	3,906 Hz	2,344 Hz	3,906 Hz	4,688 Hz	Damped
Wheel speed oscillations	5 – 10 Hz	10,160 Hz	8,594 Hz	10,160 Hz	10,940 Hz	***7,031 Hz***
Axle oscillations	10 – 19 Hz	17,970 Hz	17,19 Hz	17,190 Hz	17,190 Hz	***15,630 Hz***
Wheel speed oscillations	19 – 29 Hz	25,780 Hz	Damped	Damped	24,220 Hz	24,220 Hz
Wheel speed oscillations	29 – 34 Hz	32,030 Hz	30,470 Hz	34,380 Hz	30,470 Hz	32,030 Hz
Wheel speed oscillations	34 – 40 Hz	36,720 Hz	36,720 Hz	Damped	38,280 Hz	Damped
		Tire pressures (100 km/h)				
Wheel speed oscillations	2 – 5 Hz	2,344 Hz	4,688 Hz	3,125 Hz	2,344 Hz	4,688 Hz
Wheel speed oscillations	5 – 10 Hz	7,031 Hz	Damped	6,250 Hz	7,031 Hz	Damped
Axle oscillations	10 – 19 Hz	15,630 Hz	13,280 Hz	14,060 Hz	16,410 Hz	***12,500 Hz***
Wheel speed oscillations	19 – 29 Hz	25,00 Hz	21,880 Hz	19,530 Hz	22,660 Hz	21,090 Hz
Wheel speed oscillations	29 – 34 Hz	31,250 Hz	29,690 Hz	31,250 Hz	32,810 Hz	***27,340 Hz***
Wheel speed oscillations	34 – 40 Hz	Damped	35,160 Hz	Damped	Damped	Damped

In spite of this, the resonance frequencies of tire deflection resulting from wheel speed oscillations are different from each other at different vehicle speeds. Nevertheless, the resonance frequencies of tire deflection resulting from axle oscillations at 30km/h are same as those of 100km/h. Thus, the resonance frequencies resulting from axle oscillations can determine the drops in tire pressure irrespective of the changes in vehicle speed. Here, it is important how the vehicle speed varies these resonance frequencies. For this reason, Table 4 is obtained from Figs. 5 and 6 to determine the resonance frequency variations at different vehicle speeds.

Table 4 shows that the resonance frequency of axle oscillations decreases at all tire pressures when the vehicle speed increases. This validates the frequency response results when Eq.13 is considered. Also, it is remarkable that the resonance frequency of nominal tire pressure decreases only when the vehicle speed increases as shown in Table 4. However, the increases occurring in the resonance frequency at same vehicle speed mean the drops in tire pressure. Here, the changes in vehicle speed must be considered to determine the drops in tire pressure. In other side, the other resonance frequencies have no certain array to determine the drops in tire pressure when the vehicle speed varies.

Table 4. The resonance frequencies for vehicle speeds

Excitation source	**Vehicle speed**	**Frequency range**	**15 psi**	**20 psi**	**25 psi**	**30 psi**	**35 psi (Nominal tire pressure)**
Wheel speed oscillations	**30 km/h** **100 km/h**	2 – 5 Hz	3,906 Hz 2,344 Hz	2,344 Hz 4,688 Hz	3,906 Hz 3,125 Hz	4,688 Hz 2,344 Hz	Damped 4,688 Hz
Wheel speed oscillations	**30 km/h** **100 km/h**	5 – 10 Hz	10,160 Hz 7,031 Hz	8,594 Hz Damped	10,160 Hz 6,250 Hz	10,940 Hz 7,031 Hz	7,031 Hz Damped
Axle oscillations	**30 km/h** **100 km/h**	10 – 19 Hz	***17,970 Hz*** ***15,630 Hz***	***17,19 Hz*** ***13,280 Hz***	***17,190 Hz*** ***14,060 Hz***	***17,190 Hz*** ***16,410 Hz***	***15,630 Hz*** ***12,500 Hz***
Wheel speed oscillations	**30 km/h** **100 km/h**	19 – 29 Hz	25,780 Hz 25,00 Hz	Damped 21,880 Hz	Damped 19,530 Hz	24,220 Hz 22,660 Hz	24,220 Hz 21,090 Hz
Wheel speed oscillations	**30 km/h** **100 km/h**	29 – 34 Hz	32,030 Hz 31,250 Hz	30,470 Hz 29,690 Hz	34,380 Hz 31,250 Hz	30,470 Hz 32,810 Hz	32,030 Hz 27,340 Hz
Wheel speed oscillations	**30 km/h** **100 km/h**	34 – 40 Hz	36,720 Hz Damped	36,720 Hz 35,160 Hz	Damped Damped	38,280 Hz Damped	Damped Damped

4.3. Tire pressure detection algorithm

In this section, the tire pressure detection algorithm is developed based on tire deflection. For this, both time and frequency domain results are used in the algorithm. Therefore, the measured tire deflection information is used to determine the drops in tire pressure when the vehicle is in stationary. The resonance frequency of measured tire deflection is used to occur the drops in tire pressure when the vehicle is in motion. The block diagram is established to explain the processing of algorithm for vehicle speed 30 km/h as shown in Fig.7.

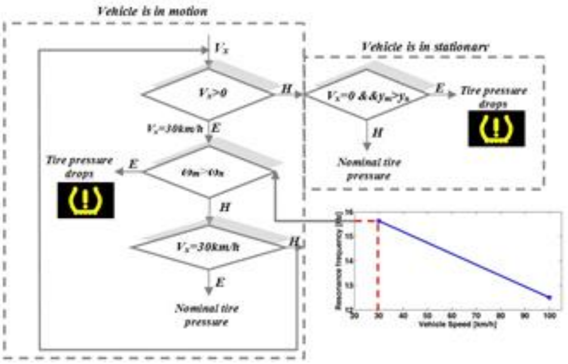

Fig. 7. Block diagram of tire pressure detection algorithm for 30 km/h

As shown in Fig.7, the inputs of this algorithm are the measured vehicle speed and resonance frequency. In this way, the top block identifies whether the vehicle is in motion or not. If the vehicle speed is zero, the measured tire deflection is compared with that of nominal tire pressure. For this, the rule is designed as follows:

- If $V_x=0$ && $y_m>y_n$, the tire pressure drops, otherwise inflation pressure is nominal inside tire

where y_m is measured tire deflection and y_n is tire deflection at nominal tire pressure. In this rule, the term $V_x=0$ describes to the stopping vehicle. When it is occurred that the vehicle is driven at certain vehicle speed, the resonance frequency is measured and it is compared with that nominal tire pressure at same vehicle speed. The resonance frequency of nominal tire pressure is taken from vehicle speed vs resonance frequency graph as shown in Fig.7. Therefore, the rule is developed at same vehicle speed as follows:

- If $V_x>0$ and $\omega_m>\omega_n$, the vehicle speed is checked and tire pressure drops when the vehicle speed is same. Nevertheless, the inflation pressure is nominal inside tire, if the vehicle speed is different. Because, the resonance frequency decreases only if the vehicle speed increases.

where ω_m is resonance frequency of measured tire deflection and ω_n is resonance frequency of nominal tire pressure. In this rule, the rules $V_x>0$ describes to the moving vehicle.

5. Conclusion

In this study, the effects of tire pressure on the vertical tire deflection have been experimentally examined. For this, firstly, the tire model is established and the effects of tire deflection and vehicle speed on the resonance frequency of tire deflection are theoretically described by using the model. Then, the road tests have been conducted in constant vehicle speeds 30 and 100km/h. Each test has been repeated for tire pressures 15, 20, 25, 30 and 35psi. The test results are validated by means of measured tire deflection signals in time domain. Thus, the frequency responses of time domain results are obtained to occur the drops in tire pressure. Here, it is aimed to determine whether the peak level and resonance frequencies of tire deflection are appropriate or not. For this, the tire deflection datas including effective information related to resonance frequency are revealed by using the sampled root mean square (SRMS) method.

The frequency response results indicate that the level of the tire deflection peaks is not suitable to determine the drops in tire pressure. Instead, the resonance frequency of the tire deflection resulting from axle oscillations must be used. Because this frequency of nominal tire pressure remains at the lowest level and it decreases in certain array as the tire pressure drops.

Therefore, this study clearly occurs that the drops in tire pressure should be detected by using the resonance frequency arising from axle oscillations. For this, the resonance peaks of tire deflection resulting from wheel speed oscillations must be removed by filtering the frequency response of effective rolling radius signals.

Consequently, the algorithm rules are developed by using these results. The algorithm is able to determine the drops in tire pressure whether vehicle is in stationary or motion. In this algorithm, it is considerable point that the vehicle speed is constantly checked. In this way, the drops in tire pressure are detected independently of the changes in vehicle speed. Also, the algorithm determines the drops in tire pressure regardless of the pattern of movement of the vehicle. This compensates the deficiency in TPMS using wheel speed signals of ABS.

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