Hamed, M., Tesfa, Belachew, Gu, Fengshou and Ball, Andrew

A study of the influence of vehicle tyre pressure on suspension system response using a full car model

A STUDY OF THE INFLUENCE OF VEHICLE TYRE PRESSURE ON SUSPENSION SYSTEM RESPONSE USING a FULL CAR MODEL

M. Hamed, B. Tesfa, F. Gu, and A. D. Ball
Centre for Efficiency and Performance Engineering, University of Huddersfield, Huddersfield, HD1 3DH, UK

ABSTRACT

The incorrect inflation pressure in tyre affects vehicle handling, passenger comfort and braking conditions, as well as reducing fuel efficiency and tyre life. To address this problem a numerical model has been developed. The model has been developed with 7-DOF for a full car system. State space approach has been adapted to analyze the system parameters using MATLAB programs. To validate the model, the experimental work has been conducted by driving a car on the road with bumps with healthy tyres condition. During the experiment the tyre pressure was controlled and the suspension vibration was measured. The model has been validated fairly using an experimental data in time domain. For detail analysis, the Short-Time Fourier Transform (STFT) method was used to obtain contents due to road excitation at the bumps. The results show, by reducing the tyre pressure by 35%, the total vibration energy transmitted to the car is increased by 27 %, 30.5 % and 28.2 % for reduction of tyre pressure of driver wheel, passenger wheel and front wheels respectively. In addition, the result shows that the mathematical modelling can have a potential for developing an on-line suspension condition monitoring tool in future.

Keywords — Condition monitoring, suspension modelling, vibration measurement, vehicle tyres inflation, short-time Fourier transform

INTRODUCTION

The suspension is linked with tyre which provides traction between the vehicle and the road while providing a flexible cushion that absorbs shock. Tyre is the most important parts of a car. It transmits all drive, brake and steering forces to the road through a very small contact patch. According to Eslaminasab et al [1] ride comfort is proportional to the absolute acceleration of the vehicle body; while road handling is depend on the relative displacement between vehicle body and the tires. On the other hand, vehicle stability is also linked to the tire-ground contact.

According to the Good Garage [2]. Ministry of Transport (M.O.T) data, between October 2010 and September 2011, approximately 24.2 million tests were carried out in UK. Figure 1 represents the percentage of failures by category for different car models. Lighting problems (19.79 %) were the major causes for a re-test followed by suspension faults (13.18 %), brakes faults (11.47 %) and tyres faults (8.75 %). In addition, data from the previous two years shows that fails due to faults with suspension have risen sharply with 300,000 additional cars failing their MOT for this reason in 2010/11 compared to 2008/09.

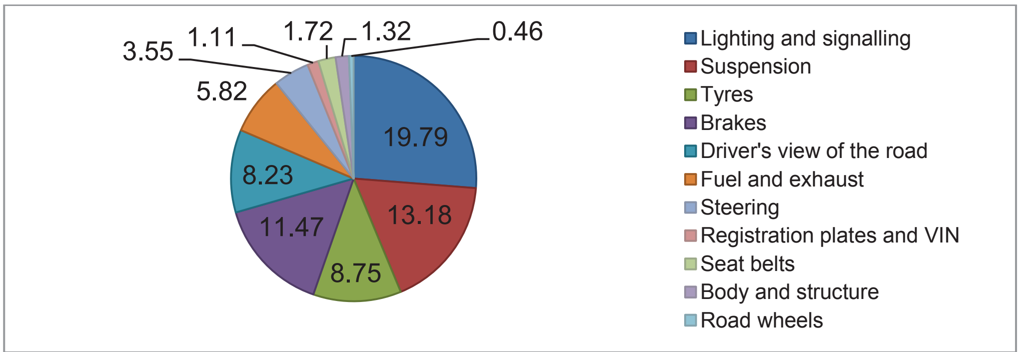

Figure 1 Percentage of failure by category for different cars [2]

As it is demonstrated in the pie chart (Figure 1), suspension and tiers faults are the 2nd and the 3rd frequent faults in MOT test respectively.

To find effective method to improve suspension systems and to diagnose problems at early phase, experimental investigation of tyres and suspension system is complex, expensive and time consuming.

These challenges have led to many researches in developing numerical models for tyre and suspension system. [1], [3]–[7]. A mathematical model for the quarter car with 2-DOF and a half car with 4-DOF have been investigated using MATLAB by Faheem [3]. It was concluded that, both models can be used to analyse the parameters of suspensions. Rao [4] has developed a mathematical model of a three degree of freedom for quarter car semi-active suspension system by using MATLAB/SIMULINK. The model was used for the testing of skyhook and other strategies of semi active suspension system. This research concluded that, the modified sky hook strategy is the optimum solution to obtain comfort ride for passengers. Rievaj et al [8], has presented the effect of tyre pressure on stopping distance. Three probable options been tested. This study concluded that, the vehicle´s handling and stability worsens when the tyres are under-inflated. In addition, the tyre pressure has impact on the vehicle driving characteristic. The influence of the variation in the tyre inflation pressure on the steady state and transient handling dynamics of an urban bus has been discussed by Al-Solihat et al [9], through analysis of a three-dimensional (3D) vehicle model. This study concluded that, a lower tyre inflation pressure yields higher yaw and roll rates, a higher acceleration of the sprung mass. This is mostly attributable to the reduced effective roll stiffness. An indirect tyre pressure monitoring system based on vibration and wheel radius analysis has been presented by Persson and Gustafsson [10]. These two approaches are combined for optimal performance concerning sensitivity to detect pressure losses up to 25 % and robustness to different driving conditions.

In the above investigation, most of the researchers focused on the individual effects of suspension and tyres on the stability of the car, passenger comfort and vehicle handling. However, tyres and suspension are interrelated systems. Therefore, the first objective of this study is to investigate the effects of the tyre pressure on the performance of the suspension using mathematical models which is validated by experimental data. In addition, most of the previous researches on suspension were focused on the assumption that, the signal of vibration is stationary. Due to vehicle starting, accelerating and breaking conditions, the generated vibration signals are non-stationary. The second objective of this study is to apply short-time Fourier transform (STFT) analysis to obtain more accurate information of the signal in time and frequency simultaneously.

SUSPENSION SYSTEM MODEL AND DYNAMICS

The system was modelled as a seven-degree-of-freedom (7-DOF) system. Numerical models are developed to study the heave, pitch, and roll motions of the vehicle for road inputs. Figure 2 shows full vehicle models. The following assumptions were made to simplify the model:

- Each tyre is modelled as a single linear spring
- Each of the suspension springs are linear
- Each of the suspension dampers are linear

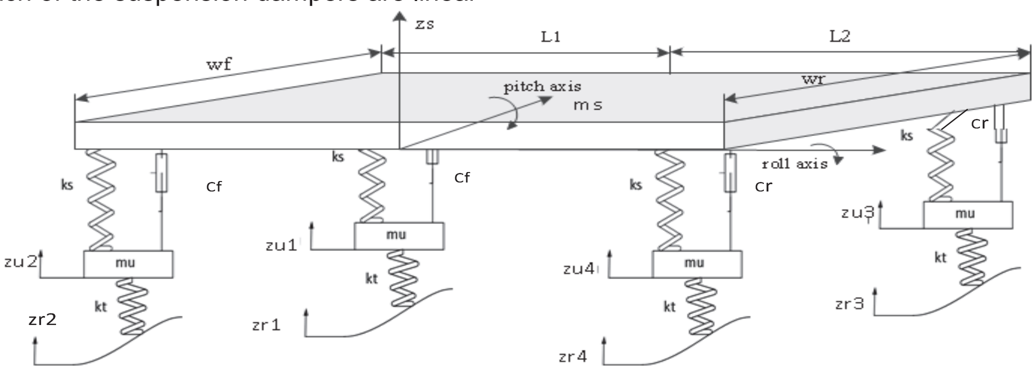

Figure 2 full vehicle models

By applying forces equilibrium, equation of motion for bouncing of sprung mass will be as following:

$$m_s\ddot{z}_s = k(z_{u1} - z_{s1}) + k_f(z_{u2} - z_{s2}) + k_r(z_{u3} - z_{s3}) + k_r(z_{u4} - z_{s4}) + c_f(\dot{z}_{u1} - \dot{z}_{s1}) + c_f(\dot{z}_{u2} - \dot{z}_{s2}) + c_r(\dot{z}_{u3} - \dot{z}_{s3}) + c_r(\dot{z}_{u4} - \dot{z}_{s4}) \quad (1)$$

For pitching moment of inertia of sprung mass

$$I_p\ddot{\theta} = k_f l_1(z_{u1} - z_{s1}) + k_f l_1(z_{u2} - z_{s2}) - k_r l_2(z_{u3} - z_{s3}) - k_r l_2(z_{u4} - z_{s4}) + c_f l_1(\dot{z}_{u1} - \dot{z}_{s1}) + c_f l_1(\dot{z}_{u2} - \dot{z}_{s2}) - c_r l_2(\dot{z}_{u3} - \dot{z}_{s3}) - c_r l_2(\dot{z}_{u4} - \dot{z}_{s4}) \quad (2)$$

For rolling motion of the sprung mass

$$I_r\ddot{\varphi} = k w_f(z_{u1} - z_{s1}) - k_f w_f(z_{u2} - z_{s2}) + k_r w_r(z_{u3} - z_{s3}) - k_r w_r(z_{u4} - z_{s4}) + c_f w_f(\dot{z}_{u1} - \dot{z}_{s1}) - c_f w_f(\dot{z}_{u2} - \dot{z}_{s2}) + c_r w_r(\dot{z}_{u3} - \dot{z}_{s3}) - c_r w_r(\dot{z}_{u4} - \dot{z}_{s4}) \quad (3)$$

For each wheel motion in vertical direction

$$m_f\ddot{z}_{u1} = -k_f(z_{u1} - z_{s1}) - c_f(\dot{z}_{u1} - \dot{z}_{s1}) + k_{tf}(z_{r1} - z_{u1}) \quad (4)$$

$$m_f\,\ddot{z}_{u2} = -k_f\,(z_{u2} - z_{s2}) - c_f\,(\dot{z}_{u2} - \dot{z}_{s2}) + k_{tf}\,(z_{r2} - z_{u2}) \quad (5)$$
$$m_r\,\ddot{z}_{u3} = -k_r\,(z_{u3} - z_{s3}) - c_r(\dot{z}_{u3} - \dot{z}_{s3}) + k_{tr}\,(z_{r3} - z_{u3}) \quad (6)$$
$$m_r\,\ddot{z}_{u4} = -k_r\,(z_{u4} - z_{s4}) - c_r(\dot{z}_{u4} - \dot{z}_{s4}) + k_{tr}\,(z_{r4} - z_{u4}) \quad (7)$$

The parameters of suspension system and the definition of equation variables were summarised in Table 1 which were adopted from [5].

Table 1 shows definition of equations variables and parameters of suspension

Variables	Definitions	Units
m_s=1136	Sprung mass (mass of the vehicle body)	kg
$m_f = 63$, m_r=60	Unsprang mass (mass of front and rear wheels)	kg
$I_r = 400,\ I_p = 2400$	Roll and pitch of moment of inertia	Kg m²
$l_1 = 1.15,\ l_2 = 1.65$	Distance from front and rear wheel to the car centre	m
$k_f = 36297, k_r = 19620$	Stiffness of front and rear springs for vehicle body	N/m
$k_{tf} = 182470\ , k_{tr} = 182470$	Stiffness of tyre	N/m
$c_f = 3924, c_r = 2943$	Damper coefficient for front and rear vehicle	Nm/sec
$w_f = 1.505\ ,\ w_r = 1.557$	Front and rear track width	m
θ, φ	Roll and pitch angle	rad
z_s	Displacement of the vehicle body	m
$z_{s1}, z_{s2}, z_{s3}, z_{s4}$	Vehicle body displacement at each wheel position	m
$z_{u1}, z_{u2}, z_{u3}, z_{u4}$	Displacement of each wheel	m

The system can be represented in state space matrix forms as

$$\dot{x} = A(x) + B(u) \quad (8).$$

$$y = C(x) + D(u) \quad (9)$$

Where equation (8) known as the input state equation and A is the 14×14 system matrix, equation (9) known as the output for state equation. To simulate the state space matrixes and to analysis the variables parameters of suspension system, MATLAB code has been developed.

THE EXPERIMENTAL SET UP AND TEST PROCEDURES

Experimental Facilities

In this study a 2003 Volkswagen Polo car, 4 cylinder engines, with a front wheel drive has been used. In order to collect the data, a measurement system was designed and installed in the car. The photo of the sensor set up and schematic of the measurement system are shown in Figure 3. This measurement system was comprised of, vibration sensors (IEPE accelerometer), data acquisition system and computer.

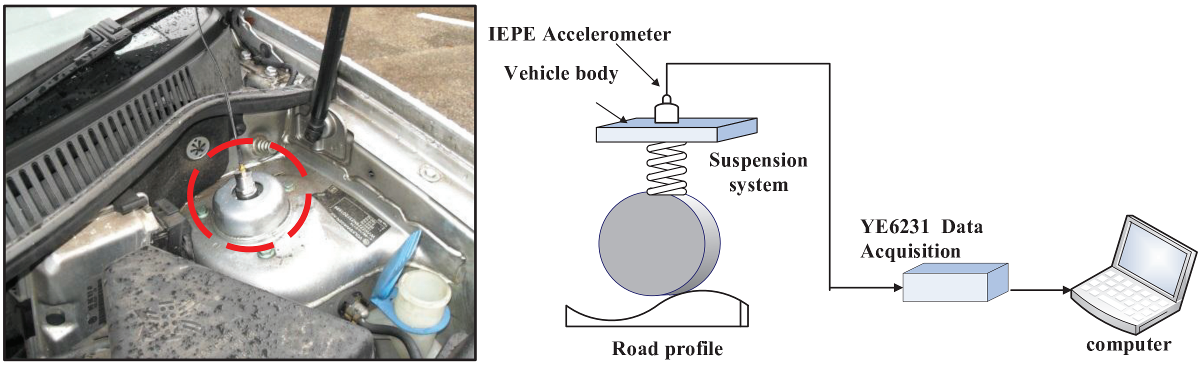

Figure 3 IEPE Accelerometer fixed on front left suspension and schematic of the measurement system

The tested car was equipped with one IEPE accelerometer for measuring acceleration signal of the suspension system. Table 2 presents the specification of the sensor which has been mounted on the upper mounting point of the front left shock absorber as shown in Figure 3.

Test Procedures

The aim of this test was to obtain the vibration (acceleration) of suspension system, in order to validate the suspension numerical model which is developed to evaluate the effects of tyre inflation on the performance of suspension. The test has been conducted for different tire pressure in four cases as described in Table 3.

Table 2 IEPE accelerometer data

Model	CA-YD-185TNC
Sensitivity	4.986 mV/ms-2
Frequency range	0.5 to 5000 Hz
Weight	35 g
Temperature	-40 to +120 ºC

Table 3 Experimental set up

Test	Wheels pressure conditions	
	Passenger wheel	Driver wheel
A	Standard pressure	Standard pressure
B	1.5 bar	Standard pressure
C	Standard pressure	1.5 bar
D	1.5 bar	1.5 bar

RESULTS AND DISCUSSION

In this study a numerical investigation has been carried out to investigate the effect of under-inflated tyres on suspension system. The model has been validated using an experimental investigation. For both numerical and experimental investigation a road profile with a bump which is located in the University of Huddersfield was used. The bump profile is about 5.80 m width (B), 0.45 m length of the obstacle (L) and 0.050 m height (H). The bump sketch diagram and the plot of road profile in time domain is shown in Figure 4.

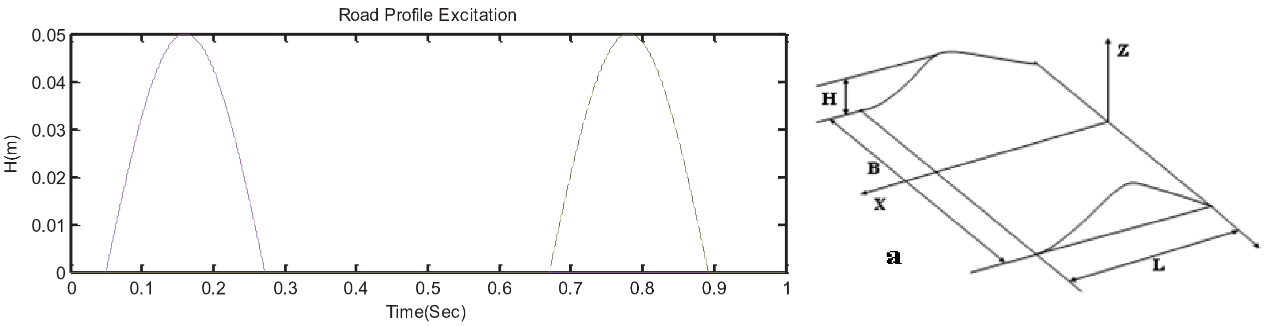

Figure 4 Road profile in time domain and the sketch diagram of the bump

The model was simulated at different cases as presented in Table 3. The experimental investigation was carried out for only healthy condition. The simulation was conducted in MATLAB by solving state space equation. Figure 5 depicts the acceleration of suspension of standard pressure case in time domain based on model simulation and experimental. It can be noted that the amplitude of vibration signal was high when front wheels and rear wheels passing over the bump.

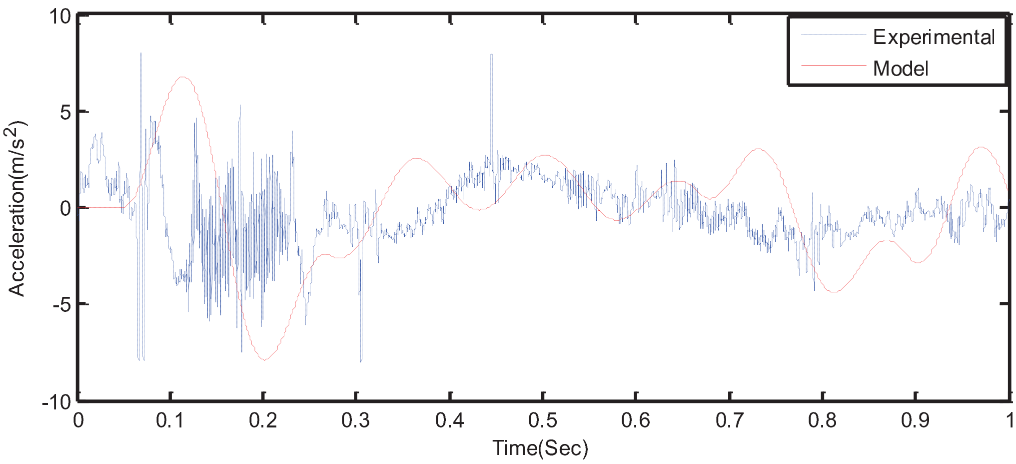

Figure 5 Vibration (acceleration) of suspension simulation and experimental

In addition, from this figure, it can be noted that, there are spikes in acceleration were recorded at places other than the bump during the experimental investigation. This can be attributed to road disturbances like potholes, cracks on the road and etc. From Figure 5 it can be also seen that the model is fairly predict the performance of the suspension system comparing with the experimental results.

Once the model was validated, it has been used to investigate the effects of tyre inflation on the suspension performance using STFT. Figure 6 shows the STFT plot in the low frequency range of the vibration signal for all conditions as presented in Table 3. In Figure 6, the energy distribution level in the signal was presented by different colour counters, where the red colour showed the highest energy content and followed by yellow, green and blue. It can be noted from this figure that, the amplitude of the signal has less value in the test where all tyres pressure are standard as a baseline than other tests where the amplitude of the highest frequency shows an increase with tests when the pressure was lowered in passenger wheel, driver wheel and both front wheel by 35%.

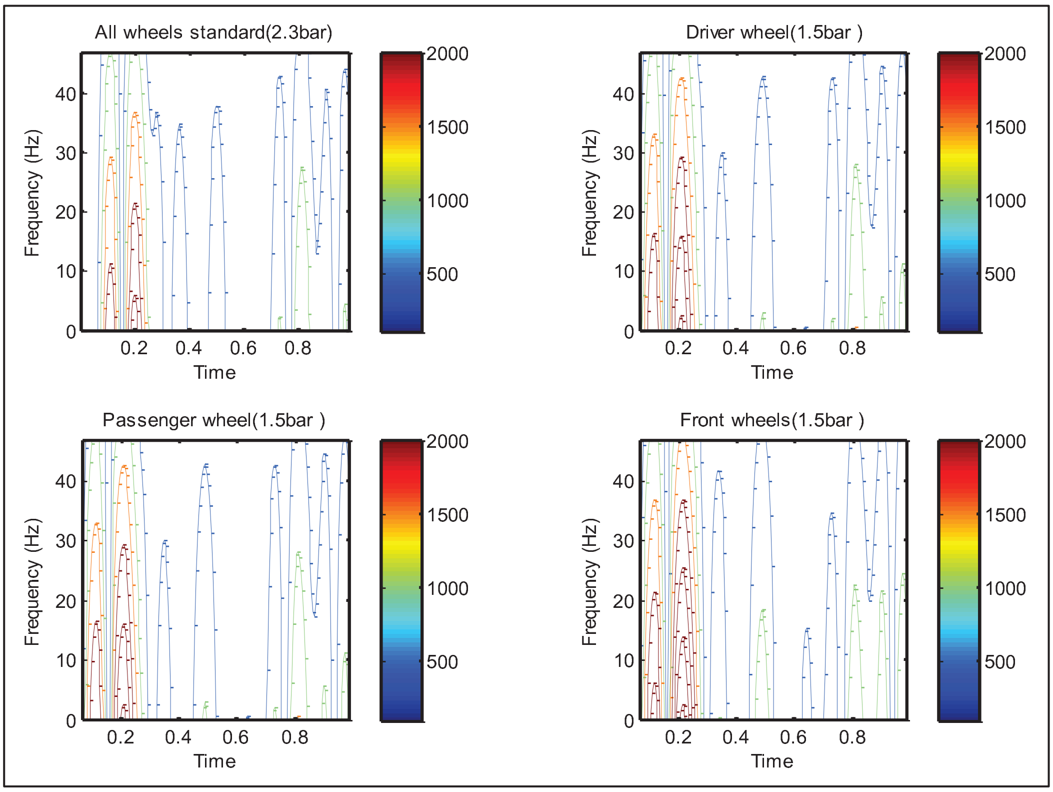

Figure 6 The STFT energy distributions for range of tire pressure conditions

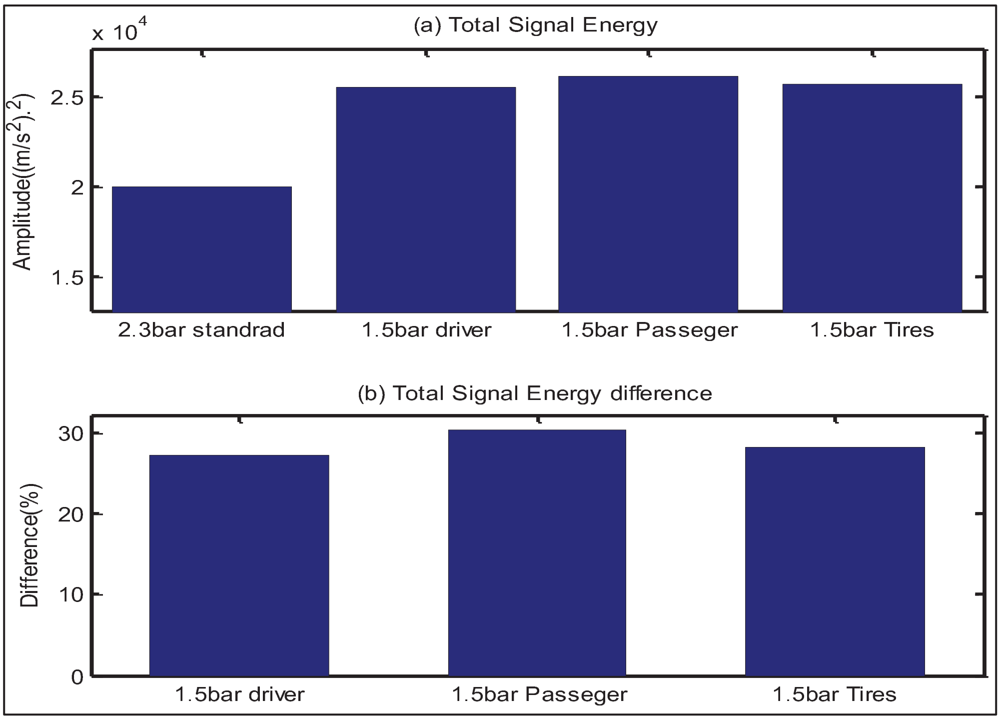

Figure 7 Presents total signal energy and deviation for full range and low frequency at various tire pressure

To quantify the effects of the inflation, the signal energy has been calculated and has been showed in Figure 7 (a). It can be seen that when tyre pressure is lowered, the total energy is increased for all conditions. Figure 7 (b) shows the total signal energy difference comparing with the standard tyre pressure as a baseline condition. It can be noted that the total signal energy is increased by 27 %, 30.5 % and 28.2 % for reduction of tire pressure of driver wheel, passenger wheel and front wheels to 1.5 bars respectively.

CONCLUSION

In the present study mathematical model and experimental investigations have been carried out to identify the effect of under-inflated tyres on suspension system performance by simulating and measuring vertical acceleration (vibration). Time-frequency domains through applying the short time Fourier transform (STFT) method have been adopted for data analysis. The under-inflation of the tyre by approximately 35% (from 2.3bar to 1.5bar), increased the vibration signal energy by 27 %, 30.5 % and 28.2 % for passenger wheel, driver wheel and for both front wheels respectively. The new developed suspension models which correlate all the dynamics of tyre and suspension will have significant application in investigation of tyre and suspension performance in future.

REFERENCE

[1] N. Eslaminasab, M. Biglarbegian, W. W. Melek, and M. F. Golnaraghi, ―A neural network based fuzzy control approach to improve ride comfort and road handling of heavy vehicles using semi-active dampers,” *Int. J. Heavy Veh. Syst.*, vol. 14, no. 2, pp. 135–157, Jan. 2007.

[2] H. John, ―Good Garages | Honest John.” [Online]. Available: http://good-garage-guide.honestjohn.co.uk/. [Accessed: 28-Jun-2013].

[3] Ahmad Faheem, Fairoz Alam, and V. Thomas, ―The suspension dynamic analysis for a quarter car model and half car model,” Dec-2006. [Online]. Available: http://good-garage-guide.honestjohn.co.uk/mot-results/. [Accessed: 2-May-2013].

[4] R. Rao, T. Ram, k Rao, and P. Rao, ―Analysis of passive and semi active controlled suspension systems for ride comfort in an omnibus passing over a speed bump,” Oct-2010. [Online]. Available: http://connection.ebscohost.com/c/articles/55558201/analysis-passive-semi-active-controlled-suspension-systems-ride-comfort-omnibus-passing-over-speed-bump. [Accessed: 28-Aug-2013].

[5] R. Darus and Y. M. Sam, ―Modeling and control active suspension system for a full car model,” in *5th International Colloquium on Signal Processing Its Applications, 2009. CSPA 2009*, 2009, pp. 13–18.

[6] A. S. Saeed Badran, ―Design of Optimal Linear Suspension for Quarter Car with Human Model using Genetic Algorithms,” *Res. Bull. Jordan ACM- ISWSA*, vol. II, pp. 42–51, 2012.

[7] G. Verros, S. Natsiavas, and C. Papadimitriou, ―Design Optimization of Quarter-car Models with Passive and Semi-active Suspensions under Random Road Excitation,” *J. Vib. Control*, vol. 11, no. 5, pp. 581–606, May 2005.

[8] V. Rievaj, J. Vrábel, and A. Hudák, ―Tire Inflation Pressure Influence on a Vehicle Stopping Distances,” 2013. [Online]. Available: http://article.sapub.org/10.5923.j.ijtte.20130202.01.html. [Accessed: 28-Aug-2013].

[9] M. K. Al-Solihat, S. Rakheja, and A. K. W. Ahmed, ―Influence of tyre pressure on an urban bus transient and steady state handling performance,” *Proc. Inst. Mech. Eng. Part J. Automob. Eng.*, vol. 224, no. 7, pp. 893–908, 2010.

[10] N. Persson and F. Gustafsson, ―2002-01-1250 Indirect Tyre Pressure Monitoring Using Sensor Fusion,” *Soc. Automot. Eng. World Congr.*, 2002