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# The Influence of Vehicle Tyres Pressure on the Suspension System Response by Applying the Time-Frequency Approach

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***Abstract*— Maintaining correct inflation pressure in tires helps to keep vehicle handling, passenger comfort and braking at its best, as well as improving fuel efficiency and tire life. Therefore it is very important that the tires are correctly inflated. To address this problem, in the present study experimental investigations have been carried out to identify the effect of under-inflated tires on suspension system performance by measuring vertical acceleration (vibration) of the suspension system. The experimental work has been conducted by driving a car on the road with range of inflation pressure at four conditions (e.g. at standard pressure (2.3bar) and at 1.5bar of passenger wheel, driver wheel and front wheels). During the experiment the signals of tire pressure, the suspension vibration and the car speed were measured.**

**To analyze the signals, the Short-Time Fourier Transform (STFT) method was used to detect the effects of tire inflation on the performance of suspension. The STFT technique has provided time-frequency information and the frequency components of the signal with relative maximum energy transmitted to the car body.**

**The results show that, when the tires were under-inflated by approximately 35 percent, it was significantly increased the vibration of the car body by up to 30 percent. The analysis has also shown that STFT analysis is more accurate than the spectrum analysis for distinguishing of the tire fault. These effective measurements potentially will use to develop an on-line condition monitoring system in future.**

***Keywords-Suspension performance; Vibration measurement; Condition monitoring; vehicle tyres inflation; Short-Time Fourier Transform***

## I. INTRODUCTION

The main function of suspension system is to support and carry the vehicle weight, to protect drivers and passengers from vibrations, and to maintain significant contacts between the tire and the road surface [1]. The suspension is linked with tires which provide traction between the vehicle and the road while providing a flexible cushion that absorbs shock. Tires are the most important parts of a car. They have to transmit all drive, brake and steering forces to the road through a very small contact patch. In addition, provide friction to allow the vehicle performs its normal operations.

The selection of a correct inflation pressure is critical to the successful operation of the tire. It is well-known that operation of a tire at higher inflation pressure than the required pressure may cause uneven tread wear, degrade vehicle ride and comfort, and increase susceptibility to impact damage. Similarly, operating the tire at lower than required pressure may also cause uneven tread wear, but can potentially lead to fatigue breakdown of the tire's internal structure resulting in tread separation or other structural failure and also degrade the car performance by increasing vibrations [2]. In addition, under-inflated tires are associated with environment costs such as increased greenhouse gases, higher fuel consumption and tire lifetime decreases with 20 percent for every 0.2 bar under-inflation [3].

The tire pressure is not supervised regularly by the drivers. It is estimated nearly 50 percent of all cars drive with reduced tire pressure [4].

TABLE I. LIGHT VEHICLE CRASHES WHERE A VEHICLE DEFECT WAS A FACTOR

| Year | Vehicle accidents | Involvement of equipment/vehicle factor | Tire failure/ fault | Tire fault accountancy (%) |
|---|---|---|---|---|
| 2003 | 78,630 | 525 | 266 | 51 |
| 2004 | 75,365 | 493 | 242 | 49 |
| 2005 | 72,054 | 492 | 247 | 50 |
| All | 226,049 | 1510 | 755 | 50 |

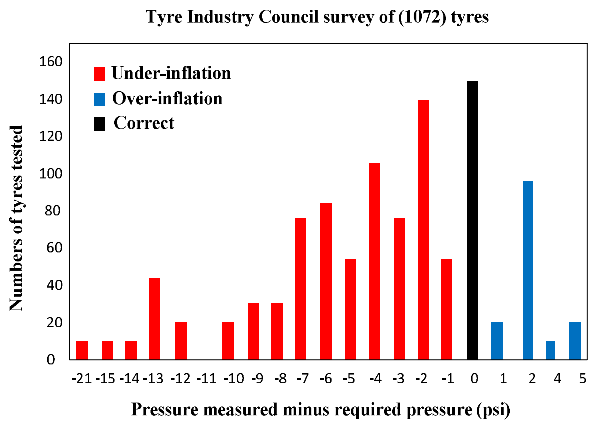


Figure 1. UK Tire Industry Council survey of 1072 tires [5]

Paine *et al* [5] presented in a report for Heads of Compulsory Third Party Insurance in Australia and New Zealand that 'in the three years(from 2003 to 2005), tire defects accounted for up to 50 percent of light vehicle crashes where a vehicle defect was identified as a likely factor in crashed vehicle study as shown in Table I.

As per the Tire Industry Council in the UK road side surveys, the tire pressure effects on the car performance are neglected. They found that from the survey of over 1000 tires in 2002, only 15 percent were correctly inflated and 72 percent were under inflated as it is shown in Fig. 1.

According to the World Energy Outlook 2006 [6] road transport is responsible for increasing energy uses and Carbon dioxide ($CO_2$) emissions globally. Roughly 20% of a motor vehicle's fuel is estimated to be used to overcome rolling resistance of tires. Therefore, tire is responsible for energy consumption and $CO_2$ emissions. Furthermore, additional fuel is required when tires are under-inflated. Data presented at the 2005 International Energy Agency (IEA) Tire Workshop indicates, the tires in service are under- inflated by 0.2 to 0.4 bar on average for passenger cars and 0.5 bar for trucks [7]. It is generally understood that these numbers correspond to an increase in energy consumption and $CO_2$ emissions of roughly 1 to 2.percent for passenger cars, and 1 percent for trucks.

Rievaj *et al* [8], has presented the effect of tire pressure on stopping distance. Three probable options such as overcrowding, under-inflation and adherence to the values specified by the manufacturer have been tested. This study concluded that, the vehicle´s handling and stability worsens when the tires are under-inflated. In addition, the tire pressure has impact on the vehicle driving characteristic.

The influence of the variation in the tire 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 tire inflation pressure generally yields higher yaw and roll rates, a higher lateral acceleration of the sprung mass, and greater roll deflections of the unsprung masses, leading to higher load transfer. This is mostly attributable to the reduced effective roll stiffness due to the low-pressure tires.

An indirect tire pressure monitoring system based on vibration and wheel radius analysis has been presented by Persson and Gustafsson [3]. These two approaches are combined for optimal performance concerning sensitivity to detect pressure losses and robustness to different driving conditions. The results show that, a pressure loss up to 25 percent can be detected.

Borner *et al* [10], has presented a supervision of the tire pressure with estimation of the signal spectrum. Accelerometers have been used to measure the wheel vibrations and the results show that, it is possible to detect tire pressure losses of approximately 0.5 bars.

A signal-based approach has been adopted by Weispfenning [11], to estimate the tire stiffness with spectrum analysis, to check the tire pressure with parameter estimation. He has claimed that, only the vertical acceleration of the wheel has to be measured, because the frequency range of the body vibrations is significantly lower than the range of the axis vibrations.

Konieczny *et al* [12] was presented the analysis process of short time Fourier transform (STFT) with superposition of rectangles window and with zero complement method, to detect faults of front shock absorber with simulated fault (oil leak – the volume of oil was changed in the range 100 percent, 50 percent with 10 percent step). The result of investigation was presented on diagrams with changeable value of estimator for different technical conditions of shock absorber.

A study of a fatigue data editing technique by using (STFT) has been discussed by Abdullah *et al* [13]. Two input signals were measured on the left and right lower arm suspension of a car that was travelling on a country road. The analysis results suggested that the STFT power spectrum shows relatively adequate with damage event in the fatigue signal.

As per aforementioned review, most of previous researches have focused on the suspension faults which are only arisen from the main parts of the suspension. However, based on the geometrical and application relation, the tire pressure may have significant effect on the performance of the suspension. Therefore, the first objective of this study is to investigate the effects of the tire pressure on the performance of the suspension. Secondly, most of the previous researches on vehicle vibration systems were analyzed the vibration signals depend on the assumption that, the vehicles are running at constant speeds and the signal of vibrations are stationary. Due to vehicle starting, accelerating and breaking conditions, vehicles will run with variable speeds, as a result, the vibration signals generated are non-stationary. Subsequently, the second objective of this study is to apply the STFT analysis to obtain information of the signal in time and frequency simultaneously.

## II. THE EXPERIMENTAL SET UP AND TEST PROCEDURES

This section presents the experimental set up of a driving car on the road to collect the vibration response of the suspension for range road surface. It comprise the experimental facilities and test procedures.

### *A. Experimental Facilities*

In this study a 2003 Volkswagen Polo car, 4 cylinder engines, with a front wheel drive has been used. The detail specification of the car is presented in the Table II.

TABLE II. CAR SPECIFICATIONS

| | |
|---|---|
| Body style | Hatchback |
| Length | 3970 mm - 13'0" |
| Width | 1682 mm - 5'6" - exc. mirrors |
| Height | 1462 mm - 4'10" |
| Wheel Base | 2470 mm - 8'1" |
| Gross Weight | 1550 kg |
| Front suspension | Independent with McPherson struts and coil springs |
| Rear suspension | Torsion beam with trailing arms |
| Wheel size front and rear | 165/70 R14 81T 1 |

In order to collect, record and later to analyses the data, a measurement system was designed and installed in the car. The schematic of the measurement system is shown in Fig. 2. This measurement system was comprised of:

- Vibration sensors (IEPE accelerometer)
- Data acquisition system with 4-channel parallel
- Laptop Computer

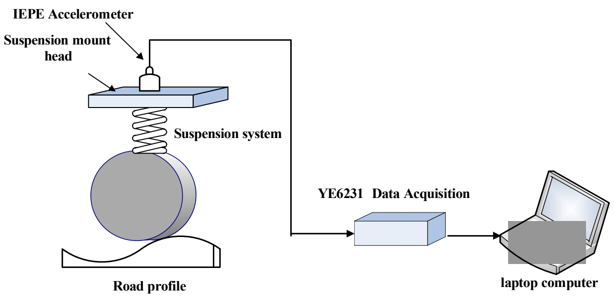


Figure 2. Schematic of the measurement system

The tested car was equipped with one IEPE accelerometer for measuring acceleration signal of the suspension system. Table III presents the specification of the sensor which has been mounted on the upper mounting point of the front left shock absorber in this study as shown in Fig. 3. To ensure a significant installation for the sensor, an adapter has been designed and manufactured in the University.

TABLE III. 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 ℃ |

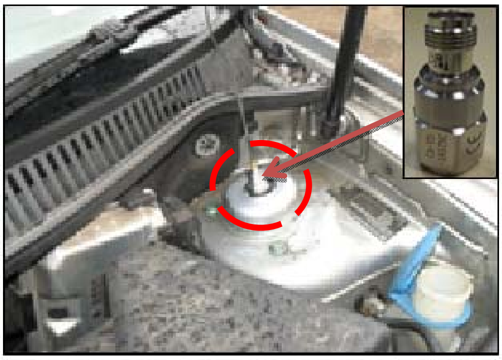

Figure 3. IEPE Accelerometer fixed on the top of front left suspension

## B. *Test Procedures*

The main aim of this test was to obtain the acceleration (vibration) response of suspension system, in order to analysis the influence of under-inflation of car tiers on the performance of suspension. In this test, conditions of the suspension system are constant and no changes on damping value of shock absorbers. The test has been conducted for different tire pressure in four cases as described in Table IV.

TABLE IV. EXPERIMENTAL SET UP

| Tests | 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 |

The road profile used in this experimental is a bump which is located in the University of HUDDERSFIELD. The bump profile is about 5.80 m width (B), 0.45 m length of the Obstacle (L) and 0.050 m height (H). A sketch diagram and photo for the bump is shown in Fig. 4.

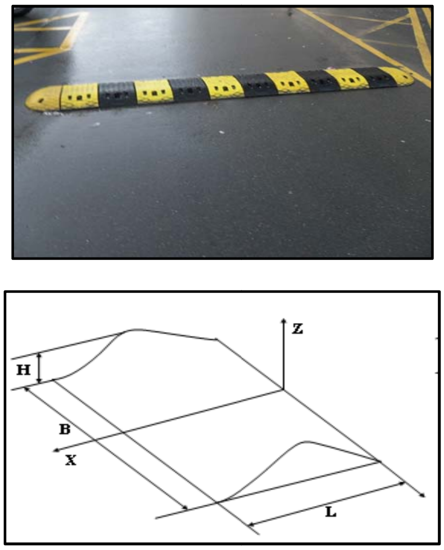


Figure 4. Photo and sketch diagram for the bump

Where:
H = Height of profile [m],
B = Width of profile [m]
L = Length of the obstacle [m]

## III. Results and Discussion

In this study an experimental investigation has been carried out to investigate the effect of under-inflated tires on suspension system performance by measuring vertical acceleration (vibration) of the suspension system. The tests were carried out based on the experimental setup presented in Table IV. The measured data has been analyzed using the MATLAB code by considering the accelerometer specification which is presented in Table III. The acceleration of the suspension system versus time is shown in Fig. 5 which shows the amplitude of vibration signal when front wheels and rear wheels passing over the bump at standard tire pressure. From this figure, it can be noted that, there are spikes in acceleration were recorded at places other than the bump. This can be attributed to road disturbances like potholes, cracks on the road and etc.

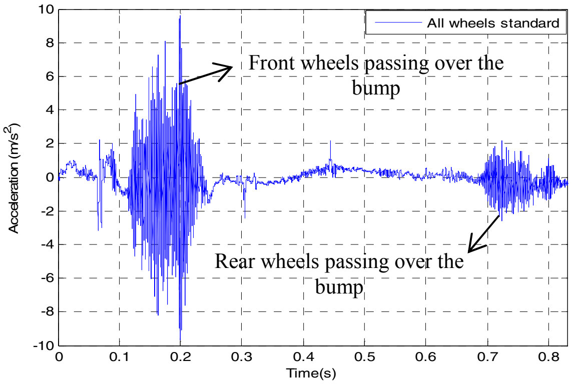


Figure 5. Presets the acceleration of the car body in the case of standard pressure

Fault-detection can be considered using the signal energy rate in different frequencies, caused as a result of changing of tiers pressure. Due to the difficulty to estimate the accurate diagnosis of pick points on time domain curves and also due to incapability of using Fourier transform in transition signals in this analysis, the signal in time domain was converted into joint time-frequency domain by applying the STFT method. In order to obtain an optimal analysis resolution, there are two main parameters have to be determined. The first parameter is directed to the analyzed window size and the second one is the number of the overlapped samples. Subsequently, to present a clear and accurate joint time-frequency resolution for the original signal, the window size of 512 and overlapped samples of 400 have been selected. So, to calculate the signal energy contained in each window, the Fourier transform has been applied for each window.

Fig. 6 (a, b, c, d) shows the STFT plot of a two dimensional view of the signal energy distribution in the high frequency range of the vibration signal for all tests at standard condition and by lowering the tire pressure of passenger wheel, driver wheel and both front wheels as presented in Table III. In Fig. 6, the energy distribution level in the signal was presented by different color counters, where the red color 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 of 350 $(m/s^2)^2$/Hz in the test where all tiers pressure are standard as a baseline (a) than other tests where the amplitude of the highest frequency shows a dramatic increase to 500 $(m/s^2)^2$/Hz, 450 $(m/s^2)^2$/Hz and 450 $(m/s^2)^2$/Hz with tests when the pressure was lowered in passenger wheel (b), front wheels (c) and driver wheel (d) respectively. Moreover, detail information about the time and the frequency of the car when passing over the bump can be obtained. For example, for wheels at standard pressure front wheels start passing the bump at around 0.1226 sec and run out at around 0.22 sec. The highest amplitude of the signal can be specified by the time and frequency, the time was at around 0.197 sec and at frequency of 3960.9 Hz.

The energy distribution for the vibration signal in low frequency has been illustrated in Fig. 7. From this figure, the amplitude of the signal has less value of 250 $(m/s^2)^2$/Hz in the test of standard pressure as a baseline Fig 7 (a) than other tests where the amplitude of the signal was dramatically raised to 500 $(m/s^2)^2$/Hz, 450 $(m/s^2)^2$/Hz and 450 $(m/s^2)^2$/Hz with the test when the pressure was lowered in passenger wheel Fig 7 (b), front wheels Fig 7 (c) and driver wheel Fig 7 (d) subsequently.

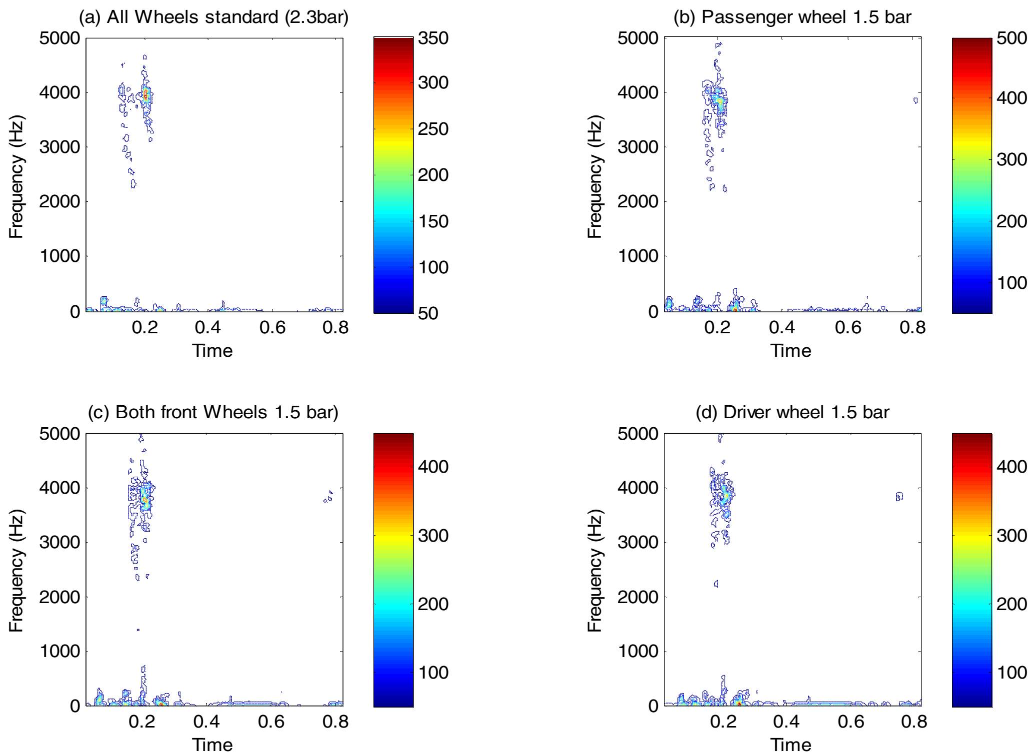


Figure 6. The STFT energy distribution for range of tire pressure conditions

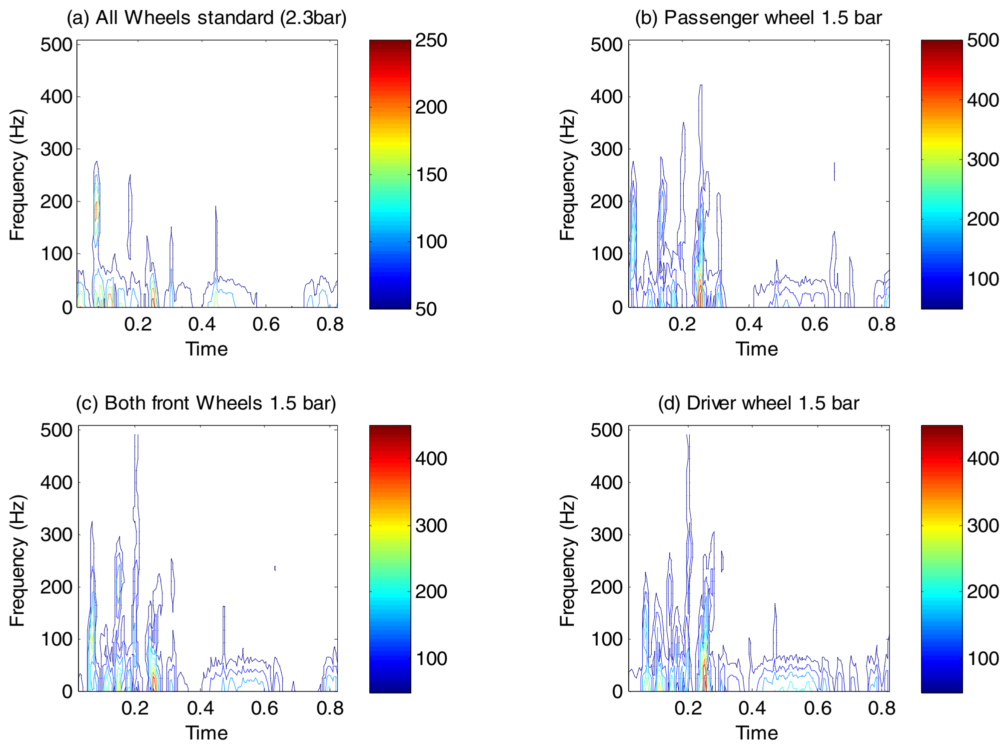


Figure 7. The STFT energy distribution in low frequency

Fig. 8 (a) presents the total energy transmitted to the suspension system; it can be seen that when tiers pressure is lowered, the total energy is increased for all conditions. Fig. 8 (b) shows the total signal energy difference comparing with the standard tire pressure as a baseline condition. It can be noted that the total signal energy is increased by 23 percent, 26 percent and 23.6 percent for reduction of tire pressure of front wheels, passenger wheel and driver wheel to 1.5 bars respectively.

The energy transmitted to the car in low frequency is depicted in Fig. 8 (c).

It is shown that the increase in energy is a result of fault in the system by lowering tiers pressure. The energy transmitted to the car has less value when car tires are standard pressure and the energy is dramatically increased by lowering tiers pressure for other cases. Fig. 8 (d) shows the difference in percentage of about1 2.3 percent, 10.6 percent and 19.3 percent between the energy of standard pressure as a baseline condition and the energy of other tests where the pressure was lowered to 1.5 bars in front wheels, passenger and driver wheel respectively

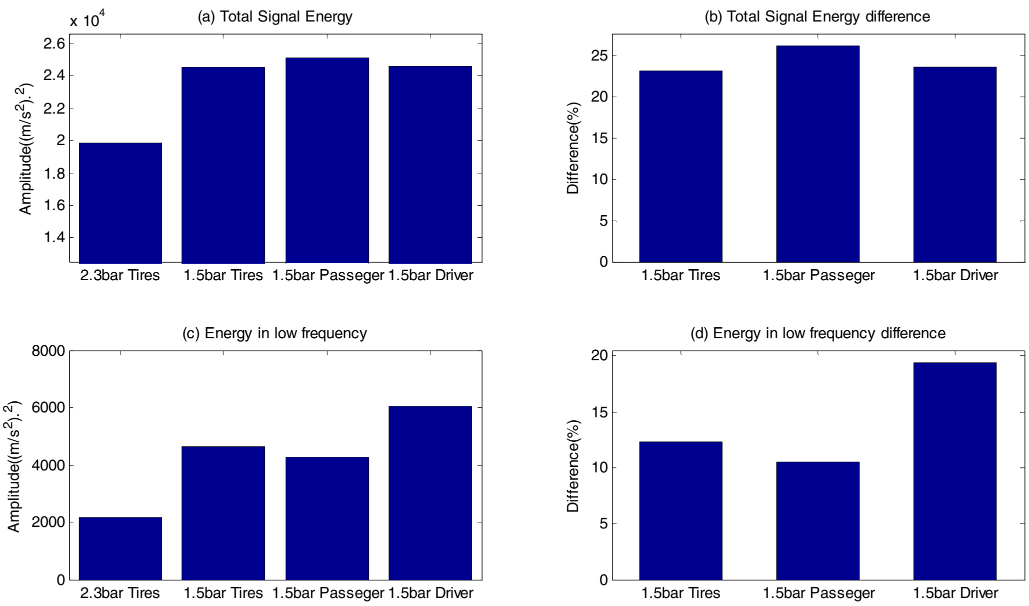


Figure 8. Presents total signal energy and deviation for full range and low frequency at various tire pressure

## IV. CONCLUSION

In the present study experimental investigations have been carried out to identify the effect of under-inflated tires on suspension system performance by measuring vertical acceleration (vibration) of the suspension system. Time-frequency domains through applying the short time Fourier transform STFT method have been adopted for data analysis.

Based on the simulation analysis, it can be concluded that under-inflation of the tires by approximately 35% in different cases (from 2.3bar to 1.5bar), for passenger wheel, driver wheel and for both front wheels was significantly detected by measuring the acceleration of the car body. As a result of this pressure drops the total energy transmitted to the car was increased by approximately 23 percent, 26 percent and 23.6 percent with tests of front wheels, passenger wheel and driver wheel respectively.

Fault-detection by using the signal energy distribution analysis by using STFT shows more accuracy for distinguishing of the fault than the spectrum analysis; this technique has the potential of giving information in the time and frequency domain simultaneously. In addition, the combined time and frequency domain analysis allows fast and user friendly calculation of the analysis and real-time animation of the studied part. These effective measurements potentially will use to develop on-line condition monitoring system for suspension in future.

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