Design, Construction and Performance Characterization of a Solar Energy-Powered Tyre Pressure Control System


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Abstract: Appropriate tyre inflation pressure plays an important role in ensuring safe and economical driving. In this study, tyre pressure control unit was developed using 205/65R16 tyre and its performance evaluated experimentally. The design of the tyre pressure control system was divided into solar, mechanical, electrical and electronic modules. Static and dynamic tests were conducted to determine the inflation time and power requirement for the tyre size considered. Inflation times obtained during static and dynamic tests and tyre sizes were used as input data for the computer simulation of the control unit using Genetic Algorithm function approximation and Artificial Neural Networks. The essence of the simulation was to validate the experimental data and predict tyre inflation time and power requirements for both static and dynamic conditions. The results of the static test for the time to inflate the tyre for the nominal pressures considered were 423, 378, 336, 294, 252, 210, 168, 126, 85 and 42s. The results during dynamic test were 302, 275, 240, 211, 183, 151, 122, 90, 61, and 33s. The simulated results obtained were used to predict inflation time and power requirements for different tyre sizes.

Keywords: Performance, Evaluation, Solar Energy-powered, compressor, Inflation, Pressure

1. Introduction

1.0 INTRODUCTION

Research studies show that maintaining proper tyre inflation level contributes to improved fuel efficiency, reduced CO₂ emissions, decreased tyre wear, and longer casing life (Pressure Guard, 2013; Triton, 2007; Kubba and Jiang, 2014; Valenti, 2011; etc.). CODA (2008) and NHTSA (2008) reported that 27% of passenger cars and 32% of light trucks and Sport Utility Vehicles (SUVs) have at least one tyre under-pressure by more than 25%. This leads to 660 fatalities and 1.24 billion gallons of wasted fuel. Similarly, 38% of cars in Europe drive on under-inflated tyres (1). This also results in 5.3 billion litres of wasted fuel worth of 7 billion EUR, and an extra 12.3 million tons of CO₂ released into the atmosphere (Lum and Reagan, 1995). These figures can be estimated to be similar in emerging populous countries like Nigeria (FRSC, 2008). A simple inflation system that is easy and inexpensive to produce would bring enormous savings in fuel, pollution, and human lives when implemented on a large scale.

2. Tyre pressure can be controlled automatically by using any of the following methods: (i) by changing the pressure only when a selection is made (a different load or terrain type). Here, the pressure can be changed at the moment when the vehicle moves from one type of surface to another, or when the mass of the cargo changes, thus allowing a different tyre pressure than the current one. This means that the pressure inside the tyres will be at the exact pressure only when the temperature of the air in the tyre is the same at the moment when the pressure change has been selected (ii) by continuous monitoring and adapting the tyre pressure. This method allows the pressure to be adjusted when necessary, updating it continuously or within short time frame. The time constant can easily be adjusted in the control program. It also enables the pressure inside the tyre to be at the correct value for the whole duration of the journey. The effect of temperature variations due to hysteresis is excluded by this method. Continuous adjustment of the pressure furthermore includes the benefit of allowing a tyre to be inflated continuously when it has a slow puncture.

3. MATERIALS AND METHODS

4. Description of the unit components

The mechatronic engineering approach of system integration was used for this work. The design of the solar-energy powered tyre pressure control system was initially considered holistically. The system was divided into its core functions and modules. The design comprised mechanical, solar, electrical, and electronic modules. Essentially, the design consisted of the solar collector surface panel, actuator, air compressor, micro-controller, pressure sensor, hose, LED indicator, LCD display unit and relay circuit. Construction and assembly of the subsystems
followed the design phase. A test rig was constructed which was used to perform static test in order to evaluate the performance of the pressure control system at static position (Eaton and Smith, 1997). Figure 1 shows the assembly drawing of the control system.

Figure 1: Assembly drawing of the tyre pressure control system developed

2.1 Air compressor
This study used isothermal process as a basis for evaluating power requirement. The following assumptions were made during the design for the flow of air from the compressor through the hose of a fixed section area as used by Javid et al. (2004): the flow is homogeneous and isothermal, the flow direction is parallel to the pipe axis, in every section of the hose, the flow is homogeneous and isothermal. Law of compression \( p_1 \frac{v_1}{v_2} = \text{constant} \)

Free air delivery, (FAD) conditions: 30°C and pressure 1.01 Bar. Compressor mechanical efficiency=85% \( P_1 = \text{Compressor’s intake pressure (bar (a))} = 1.01 \text{ bar (a)} \)
\[ T_1 = \text{Compressor’s maximum intake temperature (K)} = 273 + 30 = 303 \text{ K} = T_2 \text{(isothermal)} \]
\[ P_2 = \text{Compressor’s outlet pressure} \]

The pressure drop in the hose is 15% of compressor outlet pressure. The tyre pressure specification from the manufacturer of 205/65R16 is given as 3.45 bar. \( P_3 = 0.85 P_2 \) \( P_2 = \text{Pressure in the tyre (is the maximum inflation pressure)} \) (1)

To calculate \( P_2 \), compression ratio is given by: \( \frac{P_2}{P_3} = 0.85 \) \( P_2 = 3.45 \quad \text{bar} \)

Tyre specifications:

Tyre size used: \( \frac{205}{65} \text{ R16, 89V} \) (Pressure Guard, 2013)

Diameter of a tyre is given as \( \text{pressure wheel} = (\text{SW x 2}) + \text{Diameter of the wheel. (mm)} \)
Where SW is given as the aide wall of the tyre. Diameter of the wheel = \( 16 \times 25.4 = 406.4 \text{ mm} \)
Sidewallheight= \( \frac{65}{100} \times 205 = 133.25 \text{ mm} \)

Therefore, the diameter of the tyre, \( d_1 = (133.25 \times 2) + 406.4 = 672.9 \text{mm} \).

To calculate the circumference of the tyre: (i.e. how far the tyre travels in one revolution):
\[ \pi \times \text{Diameter of the tyre} = 3.142 \times 672.9 = 2114.25 \text{ mm} \]
\[ \rho = \text{density of air} = \frac{1.275 \text{ kg}}{m^2} \]
\[ Q = a_1 c_1 = a_2 c_2 \] (Yahya, 2012)
(3)
Where,
\[ Q = \text{volume flow rate in m}^3/s \]
\[ a_1 = \text{area of the hose in m}^2 \]
\[ a_2 = \text{area of the tyre in m}^2 \]
\[ c_1 = \text{velocity of air in the hose in m/s} \]
\[ c_2 = \text{velocity of air in the tyre in m/s} \]

Angular velocity of air stream in the tyre is given by:
\[ W = \frac{\theta}{\tau} = \frac{2 \times \pi}{60} = \frac{2 \times 3.142}{60} = 0.1047 \text{ rad/s} \] (4)

Velocity of air stream, \( C_2 \) in the tyre= \( rw = \frac{0.6729}{2 \times 0.1047} = 0.3532 \text{m/s} \)

Area \( \alpha_2 = \pi \times \frac{d_1^2}{4} = \frac{3.141 \times 0.67292}{4} = 0.3557 \text{m}^2 \) (5)

Mass flow rate of air into the tyre = density of air x volume flow rate = \( 1.275 \times 0.0125 = 0.01594 \text{kg/s} \)

For isothermal process, work required per kg of air is given by:
\[ W = RT \text{log}_{e} \left( \frac{P_2}{P_1} \right) \text{ joules} \] (Yahya,2012)
(6)
\[ W = \frac{287 \times 300 \times \log_{e} \left( \frac{4.06}{3.45} \right) = 6087.49 \text{joules} \]

Similarly, isothermal power is given by:
\[ W_p = \text{mass flow rate x work required per kg of air. (in j/s or watt)} \]
Therefore, isothermal power \( W_p = 0.01594 \times 6087.49 = 97.04 \text{ W} \)

Hence, actual power required = isothermal power / mechanical efficiency = \( \frac{97.04}{0.85} = 114.16 \text{ W} \)

2.2 SENSOR

Four pressure sensors were used. Each attached to a tyre. The sensor was designed using equation

\[
B_2 = \left( 0.62 \right) \frac{PR^2(1-V^2)}{E^2} \quad \text{(Mohapatra, 2011)}
\]

Where, \( B_2 \) = output voltage per volt of excitation, \( P \) = maximum pressure, \( E \) = Young’s modulus, \( V \) = Poison’s ratio, \( R \) = Radius of the diaphragm and \( t \) = thickness of the diaphragm.

2.3 Solar panel and Battery charging system

Solar technology has in recent times gained attention. It is a device that converts the readily available photons in sunlight into electrical energy. In this study, the solar panel was incorporated so as to make the device more effective and avoid any frequent battery replacement problems. Solar panels are classified according to their rated power output in watts. This rating is the amount of power the solar panel would be expected to produce at standard testing conditions (STC) of sunlight, intensity, 1000w/metre at 25 degrees centigrade (Green, 2003). Different geographical locations receive different quantities of average sun hours per day. Nigeria, lying approximately between 4°N and 13°N has an annual average of 6 sun hours per day (Ikponmwosa et al, 2014).

Power rating of each electrical components = power required x operating hours in Watt-hour.

Compressor: \( 0.11415 \text{ kW} \) (as calculated above) = 114.15 x 6 = 684.9 Wh

Note: operating hour is assumed to be 6hours

Sensors: \( 5 \text{ W} = 5 \times 6 = 30 \text{ Wh/sensor} \)

Therefore, for four sensors : \( 4 \times 30 = 120 \text{ Wh} \)

LCD: \( 10 \text{ W} = 10 \times 6 = 60 \text{ Wh} \)

Total power required daily = \( 684.9 + 120 + 60 = 864.9 \text{ Wh} \)

To calculate the number of solar panel required:

Total power required/Number of charge hour in Nigeria = \( \frac{864.9}{6} = 144.15 \text{ W} \)

Therefore, 150W standard solar panel was used. The collector surface panel was placed on the roof rack of the vehicle.

A forward biased diode was placed as a blocking diode, between the solar panel and the battery to ensure that current flows in one direction, i.e from the solar panel to the battery and not the other way round. This current is used to charge the battery source and ensure that the battery is not completely drained out. The solar panel specifications are shown below.

Table 1: Specification of the Solar Panel

<table>
<thead>
<tr>
<th>S/N</th>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Product type</td>
<td>150 Watt photovoltaic solar panel.</td>
</tr>
<tr>
<td>2</td>
<td>Rated output voltage</td>
<td>12 volts</td>
</tr>
<tr>
<td>3</td>
<td>Solar cell Grade (A,B,C)</td>
<td>Grade A</td>
</tr>
<tr>
<td>4</td>
<td>Cell Type</td>
<td>Polycrystalline Silicon</td>
</tr>
<tr>
<td>5</td>
<td>Life time</td>
<td>20 years</td>
</tr>
<tr>
<td>6</td>
<td>Output (watts)</td>
<td>150 Watts</td>
</tr>
<tr>
<td>7</td>
<td>Connector type</td>
<td>cables attached to junction box</td>
</tr>
</tbody>
</table>

2.4 Actuator

Four actuators were used to control flow of air into the tyres. The opening and closing of the actuators are done by the opening and closing of the relay attached to each side of the tyre.

2.5 Microcontroller

Pic16f876a micro controller was used. It reads sensors connected to the tyres and subtracts this measurement from the set point to determine the error. The 4mhz crystal provides the operating speed of the microcontroller.

2.6 Hoses

The flow rate, Q, is dictated by the cross section area, A, of the air hose and the velocity of the flow, V, as stated in the equation below:

\[
Q = Q_1 = Q_2 = AV. \quad \text{(Yahya, 2012)}
\]

(9)

2.7 Experimental Methods

Static tests

A test rig was constructed and used to perform experiments when 205/65R16 tyre was in static position at varying nominal pressures. The test rig comprised 12Vdc battery, actuator, 14.0bar air compressor, micro controller, pressure sensor, hose, LED indicator, liquid crystal display unit and relay circuit. Known weights increased by 72 kg were introduced the system at varied nominal pressures. The inflation time at every 0.35 bar change in pressure was recorded. The inflation times during static test were 423, 3768, 336, 294, 252, 210, 168, 126, 85, and 42s
2.8 Dynamic test
A Mazda (2.0, V6 engine) car was used for this test. The setup for dynamic test comprised the aforementioned components used for static test and a 17.5 bar compressor. Solar energy obtained through the solar panel mounted on the roof of the vehicle was used as source of power for pressure control unit during dynamic test. The speed of the vehicle during dynamic tests ranged from 5 to 50 km/h. The nominal pressures used during a dynamic test were 0, 0.35, 0.70, 1.05, 1.40, 1.75, 2.10, 2.45 and 2.85 bar. Weights of driver and four passengers measured as 49, 51, 63, 68 and 71 kg were introduced one after the other into the vehicle. The inflation time at every 0.35 bar change in pressure was also recorded. The inflation times during dynamic tests were 302, 275, 240, 211, 183, 151, 122, 90, 61, and 33 s.

2.9 Computer simulation
Genetic algorithms (GA) function approximation based on the Darwinian principle of reproduction and survival of the fittest was used to imitate natural inflation environment of the tyre (Abe et al. 2004; Day and Robert, 2002). The inflation times obtained during static, dynamic test and tyre sizes were used as input data for computer simulation of the control unit using genetic algorithm function approximation and artificial neural network. The aim of the function approximation problem is to find the best approximation function for the input data. The number of neurons was calculated based on closer correlation of networks output with desired values. This algorithm imitates the natural evolution process of the pressure control system using the numerical data obtained from static and dynamic tests as the input variables. After creating the initial population, P each iteration was made to pass through crossover and mutation. The fitness value, h of each individual was then calculated and selection of individuals for the new generation took place. This algorithm is as follows:

Step 1: Initialize population P (P₀, dP*, t*)

Step 2 Generate p trees at random, for each tree:–
Randomly generating a rooted tree with ordered branches

Step 3 Randomly select functions from function set to be root

Step 4 Create Z(f) and each function has Z(f) arguments

Step 5 Repeat recursively until tree is completely labeled with terminal as leaves

Step 6 Evaluate: For each h in P, compute Fitness(h) While [maxFitness(h)]<Fitnessthreshold

Step 7 Create a new generation Ps:

Step 8 Crossover: applying the Crossover operator. Add all offspring to Ps

Step 9 Mutate: Choose m percent of the members of P with uniform probability. For each, replace a subtree by a randomly generated new tree.

Step 10 Update P with Ps

Step 11 Evaluate: for each h in P, compute Fitness (h) Return the hypothesis (function) from P that has the highest fitness

3.0 RESULT AND DISCUSSION
The results obtained for static, dynamic and simulated were as presented in tables 2 and 3 for tyre sizes R16, R15, R14 and R12. Figure 2, 3, 4 and 5 also show the comparison of static, dynamic and simulated results for the tyre sizes considered. Table 2

Plate 1: Test rig for static test
Plate 2: Setup for dynamic test
Tables 1 and 2 show the experimental and simulated results obtained for static and dynamic tyre positions. The result depicted that as tyre sizes increase the inflation time and electrical energy required also increase for both experimental and simulated. Figures 2, 3, 4 and 5 also compare the relationship between the static, dynamic and simulated results obtained for tyre size R16, R15, R14 and R12. The inflation time behaviour for the dynamic position moves towards the simulated inflation time behaviour. This was due to the higher compressor capacity (17 bar) used for the dynamic test. The dynamic test result shows that increase in capacity of the compressor will enhance better performance of the tyre pressure control unit by decreasing the inflation time.

6. References


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