Faculty of Manufacturing Engineering

AUTOMATIC TYRE PRESSURE REPLENISHING SYSTEM DEVELOPMENT ASSISTED BY MATHEMATICAL MODELLING AND FINITE ELEMENT ANALYSIS

Ainol Suhada Bin Dahlan

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AINOL SUHADA BIN DAHLAN

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DECLARATION

I declare that this thesis entitled "Automatic Tyre Pressure Replenishing System Development Assisted by Mathematical Modelling and Finite Element Analysis" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : …….

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APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Doctor of Philosophy.

Signature : …….

Supervisor Name : ASSOCIATE PROFESSOR IR. DR. SIVARAO SUBRAMONIAN

Date : ……

DEDICATION

To my beloved father and mother

ABSTRACT

Tyre pressure loss is a common phenomenon whereby, air from the tyre chamber would be naturally released to the atmosphere causing its pressure to drop from time to time. It has been reported that, almost 80% vehicles on the road are running with underinflated tyres which is due to lack of user awareness of the importance running their cars with properly inflated tyres. Running with below recommended/pre-set pressure often leads to catastrophic tyre failure which leads in major road accidents. One of the main reasons for the negligence in maintaining tyre pressure is due to the hassle of having to check and inflate the tyre manually. Therefore, many ideas and systems have been initiated since the past to ensure correct tyre pressure is maintained at all time. Unfortunately, there is no one complete system found in the market to date for the matter. Therefore, a novel Tyre Pressure Replenishing System (Pre-Rep) has been researched, which has also been filed for patent. This research successfully established a system which could ensure the tyre pressure is sustained at a safe pre-set limit at all time without human intervention. The system design has been verified to contain the maximum operational pressure by using the finite element method to analyse the strength of the pressure capsule design. The structural analysis of the system has been verified by Finite Element Analysis incorporating maximum pressure obtained from mathematical modelling, and maximum tyre temperature obtained from thermal investigation which experimentally conducted over a travelled distance with two sets of speed limit. Finite element analysis being the critical engineering analytical tool reveals that, the structural design advocated AISI 304 Stainless Steel as the work material which resulted factor of safety to be 1.2 which is considered safe for pressure vessel fabrication. The proposed technology comprises a combination of high pressure capsule called pressure capsule to automatically replenish air into the tyre when deflation occurs so that the pressure in the tyre is always maintained to its set value without one having to worry about checking or even monitoring the pressure. This system works as an embedded unit where it is installed onto a standard automobile wheel. The research methodology with critical considerations has successfully enabled the development of successful Pre-Rep after incorporating the mathematical modelling output into the finite element analysis which was later tested and experimentally validated using Proton Perdana V6. The compensation performance and the results show that Pre-Rep is capable to compensate the tyre pressure loss with pressure check sensitivity of 7 kPa pressure cut-off accuracy 14 kPa. This very much complies with the tyre pressure monitoring system sensitivity range used worldwide proving agreement of the designed system to automatically inflate the tyres. Pre-Rep besides overcoming all the hustles to maintain safe tyre pressure, it is also able to provide comfort and economical drive besides lifesaving by reducing or eliminating major road accidents due to tyre explosion.

ABSTRAK

Kehilangan tekanan angin tayar adalah suatu fenomema biasa di mana udara daripada ruang tayar meresap keluar ke atmosfera yang mengakibatkan tekanan angin tayar hilang secara semulajadi dari masa ke masa. Menurut laporan, hampir 80% kenderaan di jalan raya bergerak dengan tayar yang kurang tekanan disebabkan kurang kesedaran oleh pengguna terhadap kepentingan mengekalkan tekanan angin yang betul. Tayar yang mempunyai tekanan di bawah tekanan yang disyorkan, cenderung untuk gagal dan boleh mengakibatkan kemalangan jalan raya. Salah satu sebab pengabaian penjagaan tekanan angin adalah kerana kesulitan untuk memeriksa dan mengisi angin tayar secara manual. Pelbagai idea dan sistem telah direka sebelum ini, tetapi malangnya tiada satu pun sistem yang lengkap boleh didapati di pasaran sehingga kini. Oleh kerana itu, satu sistem yang diberi nama Sistem Pengisian Tekanan Angin Tayar (Pre-Rep) telah dilakukan penyelidikannya. Penyelidikan ini berjaya membangunkan satu sistem yang dapat memastikan tekanan angin tayar sentiasa berada pada nilai tetapan yang selamat tanpa campur tangan manusia. Pembangunan konsep sistem telah dilakukan dengan pemilihan konsep dilaksanakan menggunakan kaedah proses analisis hierarki. Sistem berupaya menyimpan angin bertekanan pada tekanan maksima operasi sistem dan pengesahan telah dilakukan menggunakan kaedah unsur terhingga dengan analisis dilakukan ke atas rekabentuk kapsul tekanan. Analisis struktur bagi sistem telah disahkan menggunakan kaedah analisis unsur terhingga dengan nilai tekanan maksima diperolehi daripada model matematik dan suhu maksima tayar diperolehi daripada penyiasatan haba di mana satu eksperimen telah dilakukan ke atas kereta yang bergerak untuk satu jarak yang ditetapkan bagi dua set had laju. Rekabentuk struktur yang direka terdiri daripada keluli tahan karat AISI 304 sebagai bahan kerja, mempunyai faktor keselamatan bernilai 1.2 di mana ia dikira selamat bagi fabrikasi bekas penyimpanan bertekanan. Teknologi yang dicadangkan terdiri daripada kombinasi kapsul tekanan tinggi yang dipanggil kapsul tekanan untuk mengisi angin secara automatik ke dalam tayar apabila pengurangan tekanan berlaku. Sistem ini beroperasi sebagai unit terbina dalaman di mana ia dipasang pada bahagian dalam rim tayar kereta. Kaedah penyelidikan dengan pertimbangan kritikal telah memberi kejayaan kepada pembangunan Pre-Rep selepas menggunakan hasil keputusan yang diperolehi daripada model matematik ke dalam analisis unsur terhingga di mana ia kemudiannya diuji secara eksperimen menggunakan kereta Proton Perdana V6. Prestasi pengimbangan tekanan angin menunjukkan Pre-Rep berupaya untuk mengimbang semula tekanan angin tayar yang telah hilang dengan sensitiviti pemeriksaan tekanan bernilai 7 kPa dengan ketepatan pemutusan tekanan bernilai 14 kPa. Prestasinya jelas menepati julat sensitiviti sistem pemantauan tekanan angin tayar yang diaplikasi seluruh dunia. Selain itu, Pre-Rep berjaya mengatasi segala kesulitan untuk mengekalkan tekanan angin tayar yang selamat dan ia juga berupaya memberi penjimatan dan keselamatan pemanduan selain daripada menyelamatkan nyawa.

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LIST OF ABBREVIATIONS

3D	-	Three Dimensional
AHP	-	Analytical Hierarchy Process
AISI	-	American Iron and Steel Institute
CP	-	Centrifugal Pump (CP)
CRH	-	Compression of Routed Hoses (CRH)
CTIS	-	Central Tyre Inflation System
DB	-	Deformable Bladder (DB)
DSTS	-	Dynamically Self-Inflating Tyre System
EPIS	-	Electromagnetic Pump Inflation System (EPIS)
FEA	-	Finite Element Analysis
FOS	-	Factor of Safety
HOQ	-	House of Quality (HOQ)
IGES	-	Initial Graphic Exchange Specification
MPDS	-	Micromechanical Pump Driven System (MPDS)
NEDC	-	New European Driving Cycle
NHTSA	-	National Highway Traffic Safety Administration
OEM	-	Original Equipment Manufacturer
PDS	-	Product Design Specifications (PDS)
Pre-Rep	-	Tyre Pressure Replenishing System
QFD	-	Quality Function Deployment (QFD)
RSD	-	Road Safety Department Malaysia
STP	-	Self-Inflating Tyre Pump (STP)
TREAD	-	Transportation Recall Enhancement, Accountability, and Documentation
VOC	-	Voice of Customer (VOC)

LIST OF SYMBOLS

kg	-	kilogram
kPa	-	kilopascal
mm	-	millimetre
n	-	moles
P	-	pressure
psi	-	pound per square inch
R	-	ideal gas constant
T	-	temperature
V	-	volume

LIST OF PUBLICATIONS

M.J., Raguvaran, A.S., Dahlan, Sivaraos, M.A., Amran, T.J.S., Anand, Qumrul, and R., Izamshah, 2015. Way Forward to Halt Pressure Loss in Automotive Tyres. Applied Mechanics and Materials, Volume 761, pp. 510-514.

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CHAPTER 1

INTRODUCTION

1.1 Background

Having properly inflated tyres are advantageous to vehicle owners as it enhances tyre lifetime and promotes safer driving conditions. The main factors for the crashes due to loss of control are speed and underinflated tyre (U.S. Department of Transportation, 2000a).

A special investigation was carried out by the Department of Transportation in the United States of America using Goodyear tyres. The investigation revealed that, skidding occurred due to the effect of tyre pressure which was related to the speed of the car. Besides, the findings indicated that tyres with 207, 186 and 138 kPa were found to start skidding at speeds of 61, 59.5 and 56.3 km/h respectively. The investigations also revealed that, cars running with lower tyre pressure tend to skid at a much lower driving speed. It was reported that, when the tyre pressure is low, it requires a greater steering angle to generate the same cornering force in a curve (U.S. Department of Transportation, 2000a).

The agency had also performed several other tests using the 2001 Toyota 4-runner automobile where, tested with 80.5 km/h at constant speed/decreasing radius circle to observe the effects of the inflated pressure on lateral road condition. It was concluded that, much lower tyre pressure had proportional lower lateral g-force, where higher lateral g-force is seen better in providing track on the road. Lower pressure causes the wheel

radius to turn smaller, thus alternately increases the speed of the wheel. On the other hand, higher speed relates to higher fuel consumption and this causes underinflated tyre to consume more fuel in comparison to the properly inflated tyre in the same vehicle which moves at the same speed. Goodyear indicates that, fuel efficiency is reduced by one percentage for every 20.4 kPa of under inflation (Varghese, 2013). The findings also bring to light that, in cases of accidents, blowout to the front tyre would cause roadway departure, which would also lead to the lane change resulting in a head-on crash. Alternately, blowouts of a rear tyre could lead to spinning out and loss of control (U.S. Department of Transportation, 2000b). Puncture is the most common reason for a blowout, where, rapid pressure decreases in the remaining core and is often associated with the loss of tyre tread which drastically increases the risk for a vehicle to roll over (Willis, 2000).

Tyre wear at the outer tread area usually is the result from tyres running consistently in underinflated conditions. When a tyre runs with an underinflated condition, there would be too much contact with the road by the outer treads and this causes pre-mature wear-off which would result in tyre failure due to a high built-up of temperature (Murray, 2009). When tyres are underinflated, the shape of the tyre footprint and its pressure exertion mechanics onto the road surface would both be altered very much out of what it's supposed to be with proper pressure. This phenomenon degrades the tyre ability to transmit braking force to the road surface thus increasing the chance for undesirable stopping distance either in the form of rolling or skidding.

Underinflated tyre, even with little reduction of its pressure will cause excessive heat to be absorbed into the tyre through road contacted tread which often leads to a sudden tyre failure which results in undesired catastrophic events (Bridgestone, 2012). Tyre wear at the outer tread area usually is a result of consistent running with under

inflated tyre condition. When a tyre runs in an underinflated condition, there will be too much of contact with the road surface, mostly at the outer treads and this causes premature wear-off (Murray, 2009) which fails the tyre unexpectedly. According to the Technology and Maintenance Council of the American Trucking Associations (Berg, 2004), a tyre which is underinflated by 20% will lose 30% of its life due to build-up heat causing hot running condition. The primary tyre defect which is tread separation often causes blowout as shown in Figure 1.1, which will severely limit the control of a driver over the vehicle (Willis, 2000).

Figure 1.1 : Tyre Blowout due to Tread Separation (Willis, 2000)

Properly maintained tyre pressure also greatly improves vehicle fuel efficiency as compared to running with underinflated tyres. A full-vehicle model developed by Varghese (2013) exhibited the results for the New European Driving Cycle (NEDC city cycle) with fuel consumption reduction of up to 5 %, simply by increasing the tyre pressure from 2 to 3 bar. In a road survey conducted by Tyre Industry Council in the UK, it has been strongly highlighted that, a very small number of people pay attention to tyre pressure, whereby out of 1000 tyres, only 5% were correctly inflated and 72% were found to be running with underinflated tyres without realising (Paine et al., 2007).

Government of The United States finally came out with the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) act in the year 2000 which mandates that, all new vehicles need to be equipped with Tyre Pressure Monitoring System (TPMS). This system is capable in alerting the user when the tyre pressure drops by 25% to 30% of the original/safe tyre pressure. It is proven with this Act, the US government insists on the awareness among vehicle users about the importance of running with properly inflated tyres (U.S. Government, 2000). Besides that, all latest BMW automobiles have been fitted with tyre pressure control system (RDC) which electronically monitors tyre pressure on all the four wheels by means of sensors as of March 2014 (BMW, 2014). This system merely monitors the pressure but, not able to replenish the loss tyre pressure automatically. Visual methods, kicking, or thumping of the tyres to inspect underinflated tyre conditions are not practical to know the correct tyre pressure as some tyres always look underinflated, some even have stiff sidewalls and normally look well inflated. Differences in tyre pressure cannot be easily identified, unless reliable pressure gauges are used (Weissler, 2002).

Users don't regularly inflate their tyres at the gas station as required due to main reasons where operation failure of air pressure kiosks due to poor maintenance. Besides that, long awaiting queue at the kiosk and not knowing the exact required tyre pressure of their own vehicle are causes for tyres being run with improper pressure (Paine et al., 2007). Therefore, Automatic Tyre Pressure Controller (ATPC) has been developed to ensure correct pressure is inflated into the tyres regardless of the setting value on the pressure source e.g. kiosk, compressor, foot inflator, etc. (Sivarao et al., 2009). The device will alert the user upon reaching the appropriate pressure by a hissing sound, indicated the tyre pressure is sufficient.