DEVELOPMENT OF EXTERNAL ORIFICE SEMI ACTIVE SUSPENSION SYSTEM (EOSASS) FOR ARMORED VEHICLE

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ABSTRACT

Suspension system considered as the most important component that defines the handling and ride performance of an armored vehicle. A good suspension system provides a reliable damping force in order to maintain a good contact between the vehicle‘s tires and road surface. Commonly, the suspension system installed in current armored vehicle is passive type suspension system where it produces a constant damping value. Therefore, the armored vehicle shows a poor performance in term of handling and ride performance during off-road condition due to the suspension system could not varies it damping values with extreme road conditions. In order to overcome this problem, a new suspension system design known as External Orifice Semi Active Suspension System (EOSASS) is proposed. In this design, the existing passive damper was modified by combining with an additional hydraulic unit. The hydraulic unit is designed to control the orifice area of the suspension system during extension and compression stages using DC motor. This enables the damping value to be controlled and varied depending on the road conditions and handling maneuver. The experimental characterizations on force-velocity and force-displacement behaviors of EOSASS prototype were conducted using Instron Testing system. Then, the behavior of EOSASS is modeled by Adaptive Neuro-Fuzzy Inference System (ANFIS) interpolation technique. The model is then validated with the behavior of EOSASS obtained from the experimental data. The performance of the ANFIS interpolation model then evaluated through force tracking control simulation to investigate the performance of the developed model. Next, a seven degree of freedom (DOF) vehicle ride model developed using MATLAB/Simulink as a plant for inner and outer loop controllers to evaluate the vehicle’s dynamic response by applying the proposed control strategies. The inner loop consists of ANFIS interpolation model of EOSASS that actuated by DC motor. Hybrid control comprising Skyhook and PID controller utilized for outer loop control strategies. In the meantime, the seven (7) DOF ride model with control strategies then optimized by Particle Swarm Optimization (PSO) technique in order to provide an optimum parameter to the proposed control strategies. The vehicle dynamic response such as body, pitch and roll acceleration responses that

optimized by PSO exhibits the most outstanding performance compared to non-optimized hybrid control strategies, PID control strategies and passive system.

ABSTRAK

Sistem gantungan merupakan bahagian yang penting bagi mendefinasikan pengendalian dan prestasi kenderaan perisai. Sistem gantungan yang baik akan memberikan daya penyerap hentakan untuk mengekalkan sentuhan yang baik di antara tayar dan permukaan jalan. Walau bagaimanapun, sistem gantungan pasif yang sedia ada pada kenderaan perisai menunjukkan prestasi yang tidak memberangsangkan semasa melalui permukaan jalan yang tidak rata kerana sistem gantungan ini tidak mampu mengubah daya penyerap hentakan mengikut permukaan jalan ekstrem. Tujuan kajian ini dijalankan adalah untuk merekabentuk sistem gantungan separa aktif (*EOSASS*) yang dikawal oleh mekanisme injap tirusan yang diubah suai daripada sistem gantungan pasif yang sedia ada manakala bagi unit hidraulik diletakkan di bahagian luar sistem gantungan untuk menghasilkan daya penyerap hentakan yang diperlukan oleh kenderaan berperisai ketika melalui permukaan jalan yang tidak rata. Penyifatan prototaip sistem gantungan separa aktif telah dilakukan dengan menggunakan mesin Instron 8801 bagi menilai daya-pecutan dan daya-anjakan pada sistem tersebut. Tambahan lagi, perwatakan sistem gantungan separa aktif telah dimodelkan dengan menggunakan kaedah interpolasi *Adaptive Neuro-Fuzzy Inference System* (*ANFIS*). Pemodelan telah disahkan dengan membezakan tingkah laku *EOSASS* diperolehi daripada keputusan eksperimen. Seterusnya, pemodelan simulasi kawalan kuasa pengesanan di lakukan dengan menggunakan kaedah interpolasi ANFIS untuk menilai prestasi model tersebut. Seterusnya, model 7 darjah kebebasan (DOF) pemanduan kenderaan dibangunkan dengan menggunakan perisian MATLAB/Simulink sebagai gegelung pengawal dalaman dan luaran bagi mengkaji prestasi kenderaan dengan menggunakan strategi kawalan yang dicadangkan. Gegelung dalaman terdiri daripada model interpolasi ANFIS yang digerakkan oleh model motor DC. Sementara itu, strategi kawalan hibrid terdiri daripada *Skyhook* dan PID adalah dicadangkan untuk mengawal gelung luar. Dalam pada itu, model 7 darjah kebebesan pemanduan kenderaan dengan struktur kawalan akan dioptimumkan dengan menggunakan teknik *Particle Swarm Optimization* (*PSO*) bagi memberikan nilai yang paling optimum kepada pengawal yang dicadangkan dalam

kajian ini. Hasil daripada kajian ini menunjukkan tindak balas kenderaan secara dinamik; anjakan pecutan pada badan kenderaan, anjakan pecutan menjunam dan tindak balas anjakan pecutan gulingan oleh strategi kawalan yang dicadangkan dan dioptimumkan oleh *PSO* telah menunjukkan prestasi yang paling cemerlang berbanding dengan strategi kawalan hibrid dengan tanpa dioptimumkan, strategi kawalan PID dan sistem pasif.

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APPROVAL

I certify that an Examination Committee has met on **28TH OCTOBER 2016** to conduct the final examination of **MOHAMAD HAFIZ IKHWAN BIN MOHD AMIN** on his degree thesis entitled **'DEVELOPMENT OF EXTERNAL ORIFICE SEMI ACTIVE SUSPENSION SYSTEM (EOSASS) FOR ARMORED VEHICLE'**. The committee recommends that the student be awarded the degree of Master of Science (Mechanical Engineering).

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This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science (Mechanical Engineering). The members of the Supervisory Committee were as follows.

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DECLARATION OF THESIS

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LIST OF ABBREVIATION

EOSASS	External Orifice Semi Active Suspension System
ANFIS	Adaptive Neuro-Fuzzy Inference System
DOF	Degree Of Freedom
PID	Proportional, Integral, Differential
SAS	Stability Augmentation System
PSO	Particle Swarm Optimization
FIS	Fuzzy Inference System
GA	Genetic Algorithm
EP	Evolutionary Programming
DC	Direct Current
SEM	Sensor Conditioner Module
$O_{1,i}$	Membership Grade of Fuzzy Set
a_i, b_i, c_i	Fuzzy Parameter Set
W_i	Firing Strength of Rule
p_i, q_i, r_i	Adaptive Parameter Set
$O_{4,i}$	Consequent Parameter
$O_{5,i}$	Summation of All Incoming Adaptive Signal
GUI	Graphical User Inference
$\bar{W}_i$	Normalized Firing Strength

CG	Centre of Gravity
$F_{tfl}, F_{tfr}, F_{trl}, F_{trr}$	Tire Force at Each Corner of Vehicle
$m_{zfl}, m_{zfr}, m_{zrl}, m_{zrr}$	Unsprung Mass
$\ddot{Z}_{wfl}, \ddot{Z}_{wfr}, \ddot{Z}_{wrl}, \ddot{Z}_{wrr}$	Unsprung Mass Acceleration
l_r	Length Between Rear Unsprung Masses and CG
l_f	Length Between Front Unsprung Masses and CG
I_p	Pitch Axis Moment of Inertia
$\ddot{\theta}$	Pitch Acceleration at Body CG
w	Wheel Base
I_r	Roll Axis Moment of Inertia
$\ddot{\varphi}$	Roll Acceleration at Sprung Mass CG
$K_{tfl}, K_{tfr}, K_{trl}, K_{trr}$	Tire Constant at Each Corner of Vehicle
M_s	Sprung Mass
HMMWV	High Mobility Multi-Purpose Wheel Vehicle
$\dot{Z}$	Body Velocity
$\dot{\varphi}$	Body Roll Rate
$\dot{\theta}$	Body Pitch Rate
F_Z	Bounce Force for Sprung Mass
M_θ	Moment for Pitch

M_{φ}	Moment for Roll
F_{sky}	Skyhook Damping Force
C_{sky}	Skyhook Gain
$U[0,1]$	Samples a Uniform Random Distribution from 0 to 1
t	Relative Time Index
c	Weights Trading Off The Impact of The Local Best Solutions
s	Weights Trading Off The Impact of The Global Best Solutions
X_i	Particle Position
p_{best}	Best Position
g_{best}	Global Best Position
d	Dimension
RMS	Root Mean Square

CHAPTER 1

INTRODUCTION

1.1 Introduction

The armored vehicle has been a key weapon in the ground battlefield due to its excellent operational mobility, tactical offensive and defensive capabilities (Dhir & Sankar, 1997). In addition, the armored vehicle designed to operate on extreme conditions and it has a long firing system which conceded to be beneficial in any enemy attack. In recent technologies, armored vehicles well equipped with numerous safety system to enhance the ride and handling performance in various condition, especially during combat. One of the most important safety system equipped in an armored vehicle is the suspension system.

The armored vehicle system can be divided into two category known as wheeled and tracked, and both system are equipped with suspension system(Chen *et al.,* 2012). For military application, wheeled and tracked armored vehicle were designed to operate in a rough road terrain (Uddin, 2009), which emphasize the importance of well-designed suspension system. Hence, it helps to maintain the comfort level of soldiers travelling in an armored vehicle as well as to minimize the component damage during maneuver (Trikande *et al.,* 2014).

The main function of the armored vehicle suspension is to increase the comfort level of passengers by isolating the soldier compartment from the road vibration. According to (Liang & Wu, 2013), the conventional passive suspension system accomplish this by supporting the soldier compartment via springs. Theoretically, as the spring rate is reduced, the ride quality of the sprung mass increased. However, this situation increase the roll moment acting on armored vehicle during cornering. A higher stiffness spring required to reduce the roll moment during cornering. Subsequently, passive suspension system result in conflict between ride comfort and handling of the armored vehicle.

Another function of a suspension system is to maintain the contact between the tires and the road surface in order to provide steering stability for good handling performance and to ensure the comfort of the soldiers (Hayes *et al*., 2005). A good armored vehicle equipped with best suspension system will be able to provide safety and also increases the comfort level of the passenger.

1.2 Problem Statement

Armored vehicles normally operates on multipurpose tasks where it uses either on-road or off-road operating conditions. For on-road condition, the armored vehicle is used as a recovery vehicle to help the injured soldiers in a battlefield. Meanwhile, for the off-road condition, the armored vehicles widely used for battle training purpose with the trained soldiers or in the battlefields. For on-road condition, it is observed the passive suspension system is able to show good performance because of the absence of irregularities on the road surface. However, the same passive suspension system cannot be used during off-road condition since the damper system cannot be varied with the uneven road profile. In addition, the spring stiffness as well as the damping value of the passive suspension system cannot be controlled according to the disturbance occurred in the vertical direction of the armored vehicle. On the other hand, the impulse force created during firing also causes instability to the armored vehicle.

Due to the above said problems, the performance of an armored vehicle badly affected in terms of ride performance and stability. Thus, passive suspension system absolutely not suitable for armored vehicles. As a solution, an advanced suspension system such as semi-active and active suspension system can be used to replace the passive suspension system. However, the active suspension system requires larger energy, costly and also have difficulties to be implemented in the armored vehicles. Hence, this study proposes a semi-active suspension system to improve the quality of the armored vehicle in term of comfort, stability and safety during on and off-road condition. This study takes an initiative to design a single acting semi-active suspension system for the armored vehicle by modifying the existing passive damper of the armored vehicle to a semi-active damper. This semi active suspension system were optimized to improve the ride performance and stability of the armored vehicles.

1.3 Background of the Research

High-mobility wheel armored vehicle, such as military battle tanks and armored carriers, were designed to perform over rough off-road terrain surfaces. The mobility performance of these vehicles limited by the operator's endurance to withstand the transmitted shock and vibrations. Besides that, its speed limit varies with the roughness of a particular terrain, and is primarily influenced by the suspension system design. Generally, the wheel armored vehicles are generally fitted with passive suspension systems utilizing torsion bars and shock absorbers to attenuate the terrain-induced shocks and vibrations (Dhir & Sankar, 1995). The suspension system must be equipped with an advance system such as Semi-active suspension or active suspension system. Thus, it increases the ability of safety, ride handling and performance for the armored vehicle during battlefield (Hayes *et al*., 2005).

Currently, challenges for armored vehicle occurs from external disturbances such as rough off – road terrain, impulse from gun firing, side wind force, inconsistent braking or throttle torques on all four wheels and un-uniform tire grip in all four tires. Hence, it requires good maneuverer ability, a strong driving force, stability and ride comfort to overcome the problems affected the vehicle during in driving (Aparow *et al*., 2012). A