INTELLIGENT ACTIVE FORCE CONTROL
OF A VEHICLE SUSPENSION SYSTEM

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INTELLIGENT ACTIVE FORCE CONTROL
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requirements for the award of the degree of
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I dedicated this thesis to my beloved wife Amik Purbowati and
my children Fadhil, Shofy, Faiz, Inas, Farobi, Farhan and Hanin

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ABSTRACT

Active suspension control aims to suppress the undesirable vibration and other loading effects and should provide improvements in term of passenger comfort. This study deals with the design and implementation of robust active force control (AFC)-based schemes that incorporates artificial intelligence techniques plus a number of feedback control strategies applied to a vehicle suspension system. The overall proposed control system essentially comprises four feedback control loops, namely, an innermost loop for force tracking of the pneumatic actuator using a proportional-integral controller, two intermediate loops applying the skyhook and AFC strategy for the compensation of the disturbances and an outermost loop for the computation of the desired force for the actuator using a proportional-integral-derivative controller. Adaptive neural network and adaptive fuzzy were proposed and employed to compute the inverse dynamics of the nonlinear pneumatic actuator and estimated mass of the system within the AFC loop. The integration of all the interrelated elements leads to the formation of two main proposed schemes known as the Skyhook Adaptive Fuzzy Active Force Control and Skyhook Adaptive Neuro Active Force Control. The suspension system was modelled based on a two degree-of-freedom quarter car configuration. A number of road profiles were also modelled as the main disturbance elements to evaluate the system robustness and vehicle dynamic performance related to ride comfort. Simulation results both in time and frequency domains demonstrate the effectiveness of the proposed AFC-based schemes in countering the disturbances and other loading conditions. The schemes show evidence of at least 33.9% improvement in performance over the passive suspension. This is complemented by an experimental study on a developed full scale quarter car suspension test rig which shows a very good agreement with the simulation counterpart.

ABSTRAK

Kawalan ampaian aktif bertujuan untuk mengurangkan kesan getaran dan bebanan yang tidak dikehendaki dan seharusnya dapat memperbaiki kriteria keselesaan penumpang. Penyelidikan ini mengkaji reka bentuk dan pelaksanaan skim lasak terhadap satu sistem ampaian kenderaan berasaskan Kawalan Daya Aktif (AFC) yang memuatkan teknik Kepintaran Buatan dan beberapa strategi kawalan bersuap balik. Sistem kawalan keseluruhan yang dicadangkan merangkumi empat gelung kawalan bersuap balik, iaitu satu gelung terkedalam untuk tujuan penjejakan daya penggerak pneumatik menggunakan pengawal berkadaran-kamiran, dua gelung antara menggunakan strategi *Skyhook* dan AFC untuk memampas daya gangguan dan satu gelung pada kedudukan paling luar untuk mengira daya yang diperlukan oleh penggerak menggunakan pengawal berkadaran-kamiran-terbitan. Rangkaian Neural Adaptif dan Logik Kabur Adaptif telah dicadangkan dan diguna untuk mendapatkan dinamik songsang bagi penggerak pneumatik tak linar dan juga jisim anggaran sistem dalam gelung AFC. Kesepaduan kesemua unsur yang berkaitan menghasilkan dua skim utama yang dikenali sebagai Kawalan Daya Aktif Logik Kabur Adaptif *Skyhook* dan Kawalan Daya Aktif Neuro Adaptive *Skyhook*. Sistem ampaian dimodel berasaskan tatarajah kenderaan sukuan yang mempunyai dua darjah kebebasan. Beberapa profil jalan juga dimodel sebagai unsur gangguan utama bagi menilai kelasakan sistem dan juga prestasi dinamik kenderaan berkaitan dengan keselesaan tunggangan dan pengelolaan jalan. Hasil penyelakuan menunjukkan keberkesanan skim cadangan berasaskan-AFC dalam menghadapi gangguan dan keadaan bebanan lain. Skim juga mempamerkan sekurang-kurangnya 33.9% pembaikan prestasi tercapai jika dibandingkan dengan ampaian pasif. Ini diperkuatkan oleh penghasilan kajian ujikaji terhadap suatu rig ujikaji ampaian kenderaan sukuan berskala penuh yang menunjukkan keserasian yang baik dengan keputusan yang diperoleh melalui penyelakuan.

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LIST OF ABBREVIATIONS

A/D	: Analogue to Digital converter
AFC	: Active Force Control
AF	: Adaptive Fuzzy
BP	: Back Propagation
DOF	: Degree of Freedom
D/A	: Digital to Analogue converter
EC	: Evolutionary Computation
FFT	: Fast Fourier Transform
FLC	: Fuzzy Logic Controller
HILS	: Hardware-in-the-loop Simulation
LQR	: Linear Quadratic Regulator
LQG	: Linear Quadratic Gaussian
LM	: Levenberg-Marquardt
MF	: Membership Functions
MRAC	: Model Reference Adaptive Control
NN	: Neural Network
PI	: Proportional Integral
PID	: Proportional Integral Derivative
RTW	: Real Time Workshop
RMS	: Root Mean Square
SANAFC	: Skyhook Adaptive Neuro Active Force Control
SAFAFC	: Skyhook Adaptive Fuzzy Active Force Control

LIST OF SYMBOLS

A_a	-	Piston effective areas *a*
A_b	-	Piston effective areas *b*
am	-	Amplitude
b	-	Bias
b_s	-	Damping coefficient
B_{sky}	-	Constant value of skyhook
f	-	Frequency
f_s	-	Semi-active damper force
f_a	-	Active damper force
g	-	Gravitational acceleration
I	-	Identity matrix
J	-	Jacobian Matrix
K_p	-	Proportional gain
K_i	-	Integral gain
K_d	-	Derivative gain
k_s	-	Spring stiffness coefficient
k_t	-	Tyre stiffness coefficient
M	-	Mass of the air in the cylinder
m_s	-	Sprung mass
m_u	-	Unsprung mass
P	-	Pressure of the air in the cylinder
P_a	-	Absolute pressures in actuator’s chambers *a*
P_b	-	Absolute pressures in actuator’s chambers *b*
Q	-	Disturbance
R	-	Ideal gas constant
T	-	Temperature
V	-	Volume of the air in the cylinder
w	-	Weight

$\bar{x}_i^l$	-	Centre of Gaussian antecedent MF at rule *l* and input *i*
$\bar{y}^l$	-	Centre of *l* of consequence fuzzy set
z_s	-	Sprung mass displacement
z_u	-	Unsprung mass displacement
z_r	-	Road profile
$z_s – z_u$	-	Suspension deflection
$z_u - z_r$	-	Tyre deflection
$\dot{z}_s$	-	Sprung mass velocity
$\ddot{z}_s$	-	Sprung mass acceleration
$\dot{z}_u$	-	Unsprung mass velocity
ψ	-	Cost function
σ_i^l	-	Width of Gaussian antecedent MF at rule *l* and input *i*
μ	-	LM learning rate

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A suspension system is one of the essential components of any vehicle that carries passenger in its body compartment. It is primarily used to provide the absorption and/or isolation of undesirable vibration and load in the event the vehicle travels on a rough road, thereby, providing some comfort to the passenger in the vehicle (Ellis, 1994). Most vehicle suspension systems are typically made-up of a spring and a shock absorber. When a car hits a bump or a hole, the spring is used to temporarily store the energy generated by the disturbance force and resist the motion that tends to change the car body height level. The shock absorber acts to quickly dissipate the energy stored in the spring and damp out the vibration. Without the shock absorber, the spring will cause the vehicle to vibrate continuously over a certain period of time after the tyre passes over a bump or a hole. Darling and Dorey (1992); Ellis (1994) outlined the requirements for a suspension system as follows:

1. Isolate the passenger from the road irregularities (ride)
2. Maintain contact between the tyre and the road
3. Provide safe handling during manoeuvres
4. React to changes in the load
5. Contain the suspension displacements within the limits of travel
6. Provide control over the pitch and roll motion of the vehicle body.

Thus, it can be deduced that the purpose of a suspension system is to minimize the undesired motions during driving (Darling and Dorey, 1992).

1.2 Research Background

The main idea of a suspension system is to absorb the shock caused by the irregularities on a road surface. Ideally, the suspension should isolate the body from road and inertial disturbances that are typically associated with the acts of cornering and braking or acceleration. In addition, the suspension must also be able to minimize the vertical force transmitted to the passengers of the vehicle for their comfort. This objective can be directly achieved by minimizing the vertical car body acceleration. In any vehicle suspension system, there are a number of performance parameters that need to be optimized to achieve acceptable specification and compromise in ride comfort performance. In literature, the important parameters are (Gaoa *et al.*, 2006; Gillespie, 1992; Wong, 2001):

1. Body acceleration

   Ride comfort is related to the acceleration sensed by passenger in the vehicle when passing over a rough road surface. It is well-known that ride comfort is an important performance specification for vehicle design, which is typically evaluated by the body acceleration in the vertical direction. Therefore, one of the main objectives in controller design is to minimize the vertical body acceleration.

2. Tyre deflection

   Tyre deflection can be attributed to the contact between the tyre and road surface. In order to ensure a firm uninterrupted contact of the wheels to the road surface, the dynamic tyre load should not exceed the static ones, that is,

   $$k_t(z_u - z_r) < 9.8(m_s + m_u) \quad (1.1)$$

   where m_s, m_u, k_t, z_s, z_u, are the sprung mass, unsprung mass, tyre stiffness, displacement of the sprung mass, displacement of unsprung mass, respectively.

3. Suspension deflection

   It refers to the relative displacement between the sprung mass (body) and the unsprung mass (wheel). Because of the mechanical structure constraint, the maximum allowable suspension stroke should be taken into consideration to avoid excessive suspension bottoming, which can possibly result in deterioration of the ride comfort and even structural damage.

4. Actuator saturation

Saturation effect of actuator should be taken into account in view of the limited power of the actuator, implying that the active force for the suspension system should be confined to a certain range, that is,

$$|u| \leq u_{max} \tag{1.2}$$

where u is the active force input of the suspension system.

It is well-known fact that improving the ride quality has always been one of the objectives of vehicle manufacturers. When designing a standard passive suspension system, the trade-offs mentioned above is made upfront (fixed) depending on the types of applications and cannot be easily changed. To overcome this seemingly complex problem, many researchers have studied, proposed and implemented various semi-active and active vehicle suspension systems both theoretically as well experimentally (Appleyard and Wellstead, 1995).

In the case of semi-active and active suspension systems, the trade-off decisions can be usually changed in real-time as the system is in operation. A semi-active suspension has the ability to change the damping characteristics of the shock absorbers as in an electro-rheological or magneto-rheological damper. In an active suspension system, a pneumatic or a hydraulic actuator is typically attached in parallel with both a spring and a shock absorber in between the sprung and unsprung masses. The main advantage of employing an active suspension is the associated adaptation potential the system has where the suspension characteristic can be adjusted in real-time while driving to match the profile of the road being traversed (Cherry and Jones, 1995).

The use of pneumatic actuator as an active suspension device is a relatively new concept and has not been thoroughly explored. Pneumatic actuators demonstrate highly nonlinear characteristics due to the compressibility of air, friction and the nonlinearity of the valves. Thus, they are traditionally used for simple position and speed control applications in industry, automation, being a prime example. In recent years, low cost microprocessors (microcontrollers) and pneumatic components are available which make it possible to adopt a more complex control strategy in pneumatic actuator system control (Wang *et al*., 2001). Hence, investigations have been carried out, employing pneumatic actuators to accomplish a large number of motion control tasks.

The intent of the study is an attempt to introduce a new robust control strategy of a suspension system that is based on active force control (AFC) approach. The AFC has been recognized to be simple, robust and effective compared with conventional methods in controlling dynamical systems, both in theory as well as practice (Hewit and Burdess, 1981; Mailah, 1998; Kwek *et al.*, 2003; Mailah *et al.*, 2005). Thus, the research shall explore the possibility of improving the vehicle suspension dynamic performance using an integrated robust control strategy incorporating intelligent method. The main works of this study include the design of the proposed controller based on a number of established control models, choice of actuator system, AI technique and a number of loading conditions. The research is performed, first through a numerical technique in the form of a rigorous computer simulation and later, complemented by an experimental implementation of the proposed control scheme on a physical quarter car suspension test rig. A quarter car model is chosen as the main model to investigate the effectiveness of the active suspension system due to the simplicity of the model and yet can capture many important characteristics of the full model (Fischer and Isermann, 2004). Finally, performance evaluation both in time and frequency domains is conducted to scrutinize the potential benefits of the proposed active suspension system.

1.3 Problem Statements

The idea of AFC is first coined by Hewit and Burdess (1981). The goal of this control scheme is to ensure that a system remains stable and robust even in the presence of disturbances. The underlying principle of AFC involves direct measurement and estimation of a number of identified parameters to predict its compensation action namely the actuated force, vertical body acceleration and estimated mass of the body. The main computational burden in AFC is the multiplication of the estimated mass of the body with the acceleration of the body. Many control approaches using a simple gain of the actuator have been investigated to obtain the appropriate estimated mass of the body (Mailah and Rahim, 2000; Hussein *et al.*, 2000; Kwek *et al.*, 2003; Mailah *et al.*, 2005). Another problem is associated with acquiring inverse dynamic of the pneumatic actuator as shown in Figure 1.1. The signal values D_f' must be multiplied by inverse dynamic of the pneumatic actuator before being fed into the AFC feed-forward loop. Thus, a suitable method to obtain the inverse dynamics of the pneumatic actuator and estimated mass of the body in the AFC scheme should be appropriately acquired to provide maximum disturbance compensation of the control strategy.

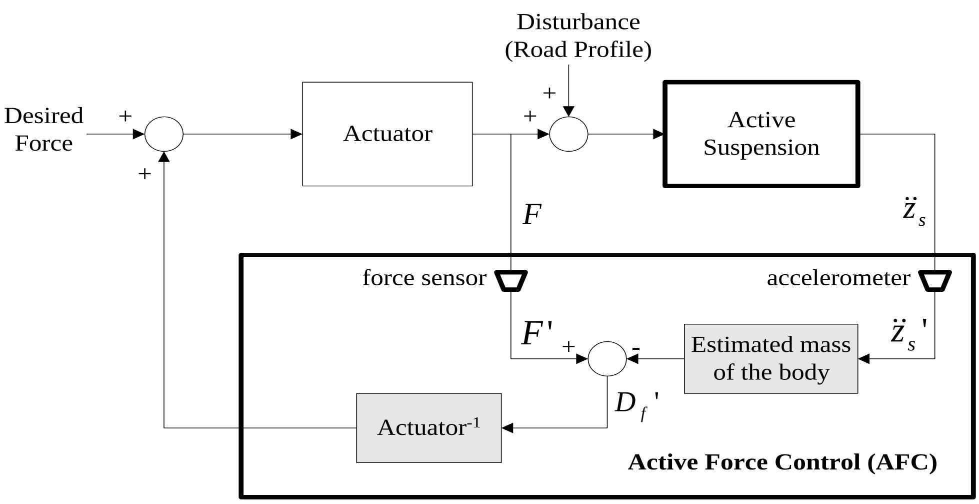

Figure 1.1 AFC concept applied to an active suspension system

The pneumatic actuator of an active suspension system should be able to provide an accurate desired force to match with the different road disturbances. Taking into account the nonlinearities and uncertainties which inherently exist in the vehicle system for active suspension design, a new control strategy is proposed in the undertaken research using a combined and integrated control scheme. The scheme should exhibit practical viability based on the theoretical framework and sufficient robustness in the wake of a number of introduced disturbances, nonlinearities and uncertainties. The proposed control system essentially comprises four feedback control loops, namely the innermost loop for the force tracking control of the pneumatic actuator using a PI controller, the intermediate loops applying skyhook and AFC strategy to reduce disturbances and the outermost loop for the computation of the desired force using the PID controller. Artificial intelligence (AI) method shall be incorporated and embedded into the system to enhance the system performance.

1.4 Objectives and Scope of the Research

The main objectives of this research are stated as follows:

1. To design and analyse the implementation of adaptive fuzzy (AF) and neural network (NN) methods in the computation of the inverse dynamics of the actuator and estimated mass parameter in the AFC scheme to improve the ride performance of the active suspension system by simulation study.
2. To evaluate and validate the performance of an AFC-based controller for the active suspension system through an experimental study.

The scope of this research covers the followings:

1. A two degree-of-freedom (DOF) quarter car suspension model is considered. It is assumed that there is no slipping between the tyre and road surface and only the vertical movement of the system is considered. The actuator used in the study is a nonlinear pneumatic type.
2. The theoretical framework involves the study of various principles related to the AFC-based methods, proportional-integral-derivative (PID) control, skyhook method, the adaptive neural network (NN) and the adaptive fuzzy (AF) techniques.
3. The performance of the suspension system subjected to various road profiles is evaluated based on vertical sprung mass acceleration,

suspension deflection and tyre deflection. In addition, the sprung mass displacement parameter is also considered for useful observation. The effect of load variation pertaining to the sprung mass is also investigated. Results shall be presented and analysed both in time and frequency domains.

4. The parameters of both quarter car model and quarter car test rig are selected based on a Malaysian National car, namely, the Kelisa.
5. An experimental quarter car suspension test rig shall be designed and developed to verify a selected proposed control scheme through a hardware-in-the-loop simulation (HILS).

1.5 Research Contributions

The main research contributions from this study are as follows:

1. Two new robust AFC-based control schemes were proposed, designed and implemented for the control of a vehicle suspension system using skyhook adaptive neuro active force control scheme (SANAFC) and skyhook adaptive fuzzy active force control (SAFAFC).
2. New approximation methods that could make decision to compute continuously and adaptively the appropriate estimated mass of the AFC strategy of the active suspension in order to improve the performance were employed using adaptive NN and AF techniques.
3. New approximation methods to identify the inverse dynamics of the pneumatic actuator in the AFC strategy using the adaptive NN and AF schemes were proposed and implemented.
4. A quarter car test rig with instrumented experimental system has been developed in the laboratory for experimental evaluation and verification of the theoretical element. A HILS configuration is particularly highlighted.

1.6 Organization of the Thesis

Chapter 2 presents the literature review on related subjects concerning this thesis. In this chapter, the classification of vehicle suspension system, performance index to be considered in suspension system design, properties of pneumatic actuator, review on recently published articles related to pneumatic active suspension control strategies and application of the active force control strategy are described.

In Chapter 3, the methodology of the research is presented. This methodology is divided into a number of stages describing the corresponding tasks that need to be carried out plus the tools that are associated with them. Essentially, there are two main research activities to be accomplished, namely, the theoretical modelling and simulation of the suspension system and the practical implementation of the proposed methods for validation purpose.

Chapter 4 describes the general introduction and principle of adaptive fuzzy system. Then, the simulation study of the new proposed scheme namely Skyhook Adaptive Fuzzy Active Force Control (SAFAFC) is presented. The overall proposed control system essentially comprises of four feedback control loops, namely the innermost loop for force tracking of the pneumatic actuator performance using PI controller, intermediate loops applying skyhook and AFC strategy for compensation of the disturbances and outermost loop for the computation of the desired force using PID controller. The parameter gains of PID controller are determined using Ziegler-Nichols method. Adaptive fuzzy (AF) with back-propagation (BP) training algorithms are used to approximate the inverse dynamic model of the pneumatic actuator and to approximate the estimated mass in the AFC loop. Performance of the suspension system is evaluated in terms of the sprung mass acceleration, sprung mass displacement, suspension deflection and tyre deflection, both in time and frequency domains. A measure of performance improvement has been included in this chapter to benchmark all the five control schemes considered in the study.

Chapter 5 presents the simulation study of the new proposed scheme known as Skyhook Adaptive Neuro Active Force Control (SANAFC). The structure of the proposed controller is almost similar to that given in Chapter 4 in which it also consists of four feedback control loops, but in this case, adaptive neural networks (NN) are used to approximate the estimated mass and the inverse dynamics of the pneumatic actuator. The adaptive NN uses modified Levenberg-Marqurdt (LM) training algorithms. Performance of the suspension system is evaluated both in time and frequency domains. Finally, the results of the proposed scheme are presented and compared with those obtained using the SAFAFC method.

Chapter 6 describes the design and development of the experimental quarter car suspension test rig that incorporates the proposed SANAFC scheme. Mechatronic system design approach is adopted to realize the suspension test rig prototype. The specifications of the active suspension system, PC-based controller and its instrumentation system are described at length with particular emphasis on the implementation of the HILS setting. The experimental results are presented both in time and frequency domains and a comparative study is made between the proposed SANAFC, PID controller and passive suspensions.

Chapter 7 discusses the differences that can be highlighted between the simulation and experimental works that have been carried out in the research study. The issues associated with implementing intelligent active force control on a quarter car active suspension system using pneumatic actuator.

Finally, Chapter 8 concludes the research project. The directions and recommendations for future research works are outlined. A list of publications related to the study, relevant results from both simulation and experimental studies are enclosed in the appendices.