# CONTROLLERS DESIGN OF AN ACTIVE SUSPENSION SYSTEM BASED ON HALF CAR MODEL

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A project report submitted in partial fulfillment of the
requirements for the award of the degree of
Master of Engineering (Electrical-Mechatronics and Automatic Control)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

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JANUARY 2015

Dedicated to my children, Faruq Isma'il Umar (Aiman), Musa Isma'il Umar (Adnan), my parents, my wife, my entire family and to all that believe in me.

**ACKNOWLEDGEMENT**

First and foremost, my unlimited gratitude goes to Almighty Allah, the Lord of the heavens and earth for His endless mercies, blessings and guidance through from birth till now and forever. All thanks be to Almighty Allah.

I wish to express my sincere appreciation to my supervisor in person of Dr. Herman Bin Wahid for his thorough and sustained supervision, encouragement and guidance to ensure this research work is successfully completed. I can say with confidence that without his inputs and continued support, this thesis might not have been possible. I would like to also thank all my lecturers for the knowledge they impart, their dedication to duties, hard work and selfless service to humanity. Thank you all.

My deepest thankfulness and appreciation also goes to the Management of Bayero University Kano for the opportunity given to me to go for further studies. To you all, I say thank you.

Last but not the least; I shall forever remain grateful to my parents, my brother/Mentor Dr. Musa A. Auyo and my entire family. I am very proud of my wife Umamatu Uwaisu Muhammad and my children Aiman and Adnan for their understanding, support and encouragement. This is quite memorable to me. I pray to Almighty Allah to reward you abundantly. Thank you very much.

# ABSTRACT

Most automobile suspension systems use passive components which are combination of spring and damper only. These components can only store and dissipate energy, and lack the capability to inject energy into the systems. The parameters of these components are generally fixed and do not vary with operating conditions. In this project, hydraulic actuators are considered in parallel with the passive components to make the systems active suspension so that the system will have the ability to store, dissipate and introduce energy to the system. The mathematical model of the active and passive suspension systems based on half car was derived and represented in state space form for controllers design, analysis and comparison. The control of these active suspensions will improve the load carrying, road handling and ride quality of the car. Three suitable controllers, one state feedback-Linear Quadratic Regulator (LQR), one intelligent-Fuzzy Logic (FL) and Proportional Integral Derivative (PID) controllers were designed and applied to control active suspension in order to improve ride comfort. This was achieved by minimizing the vertical displacement and acceleration of the car body through simulation results. Comparison and analysis of the performance of each controller in relation to ride comfort and road handling was presented. The simulation results were obtained using Matlab/Simulink software with a road profile as input to the system.

# ABSTRAK

Kebanyakan sistem suspensi kereta menggunakan komponen-komponen pasif seperti gabungan spring dan peredam sahaja. Komponen-komponen ini hanya boleh menyimpan dan menyebarkan tenaga sahaja tetapi kurang berupaya untuk menyuntik tenaga ke dalam sistem. Secara umumnya, parameter komponen-komponen ini adalah tetap dan tidak berubah dengan keadaan operasi. Dalam projek ini, penggerak hidraulik dianggap berada dalam keadaan selari dengan komponen-komponen pasif bagi menjadikan sistem suspensi adalah aktif supaya sistem ini akan berupaya untuk menyimpan, menyebarkan dan memperkenalkan tenaga ke dalam sistem. Bagi tujuan mereka bentuk pengawal, analisis dan perbandingan, model matematik bagi sistem suspensi aktif dan pasif telah diperolehi dan dibentangkan dalam bentuk 'state space'. Kawalan terhadap sistem suspensi aktif akan meningkatkan keupayaan membawa bebanan, pengendalian jalan dan kualiti pemanduan kereta. Tiga pengawal sesuai seperti 'State Feedback Linear Quadratic Regulator (LQR)', 'Intelligent Fuzzy Logic (FL)' dan 'Proportional Integral Derivative (PID)' telah direka bentuk dan digunakan untuk mengawal sistem suspensi aktif bertujuan untuk meningkatkan keselesaan pemanduan. Ini dicapai dengan mengurangkan anjakan menegak dan pecutan badan kereta melalui keputusan simulasi. Perbandingan dan analisis prestasi setiap pengawal disampaikan dalam bentuk keselesaan pemanduan dan pengendalian jalan raya. Keputusan simulasi untuk pelbagai jenis permukaan jalan telah diperoleh dengan menggunakan perisian Matlab/Simulink

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| | | |
|---|---|---|
| $A$ | - | System matrix of the active suspension system |
| $A_c$ | - | Closed-loop system matrix of the active suspension |
| $A_p$ | - | System matrix of the passive suspension system |
| $B$ | - | Input matrix of the active suspension system |
| $B_p$ | - | Input matrix of the passive suspension system |
| $B_f$ | - | Damping coefficient of the front car damper (Ns/m) |
| $B_r$ | - | Damping coefficient of the rear car damper (Ns |
| $C$ | - | Output matrix of the system |
| $Co$ | - | Controllability matrix |
| $D$ | - | Feedforward matrix of the system |
| $F$ | - | Disturbance matrix of the active suspension system |
| $J$ | - | Performance index of the LQR controller |
| $J_y$ | - | Centroidal moment of inertia for the car body ( $kg/m^2$ ) |
| $K$ | - | State feedback gain of the LQR controller |
| $K_d$ | - | Derivative gain of the PID controller |
| $K_i$ | - | Integral gain of the PID controller |
| $K_p$ | - | Proportional gain of the PID controller |
| $K_f$ | - | Stiffness of the front car body spring (N/m) |
| $K_r$ | - | Stiffness of the rear car body spring (N/m) |
| $K_{tf}$ | - | Stiffness of the front car tire (N/m) |

| | | |
|---|---|---|
| $K_{tr}$ | - | Stiffness of the rear car tire (N/m) |
| $M_b$ | - | Mass of the car body (kg) |
| $M_{wf}$ | - | Mass of the front wheel (kg) |
| $M_{wr}$ | - | Mass of the rear wheel (kg) |
| $P$ | - | Constant auxiliary matrix of the LQR controller |
| $Q$ | - | An 8 by 8 diagonal weighting matrix of the LQR controller |
| $R$ | - | A 2 by 2 diagonal weighting matrix of the LQR controller |
| $Z$ | - | State variable matrix of the active suspension system |
| $Z_b$ | - | Vertical displacement of the car body at the centre of gravity (m) |
| $Z_{bf}$ | - | Vertical displacement of the car body at the front location (m) |
| $Z_{br}$ | - | Vertical displacement of the car body at the rear location (m) |
| $Z_f$ | - | An irregular excitation from the road surface at the front car (m) |
| $Z_p$ | - | State variable matrix of the passive suspension system |
| $Z_r$ | - | An irregular excitation from the road surface at the rear car (m) |
| $Z_{wf}$ | - | Vertical displacement of the car wheel at the front wheel (m) |
| $Z_{wr}$ | - | Vertical displacement of the car wheel at the rear wheel (m) |
| $\theta_b$ | - | Rotary angle of the car body at the centre of gravity (rad) |
| $a$ | - | Distance of the front suspension location with reference to the centre of gravity of the car body (m) |
| $b$ | - | Distance of the rear suspension location with reference to the centre of gravity of the car body (m) |
| $f_f$ | - | Front actuator force |
| $f_r$ | - | Rear actuator force |
| $r_y$ | - | Radius of gyration (m) |

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The importance of car suspension systems cannot be over emphasized. This is because, it provides steering stability and takes care of friction between the tires and the road surface. It also gives support to the vehicle and equally ensures maximum comfort of the passengers. Typically, the performance of the suspension systems is measured using three criteria; ride comfort, suspension deflection and the road handling. This means that, reducing the angular acceleration and the numerical body axis of the vehicle will improve the quality of ride comfort. The utility of suspension deflection in the restricted rattle space is the major target of all suspension systems designed to achieve ride comfort. Good handling prevents the car from excessive rolling and pitching during maneuvers while passengers comfort isolates vehicle passengers from road disturbances (Readman et al, 2008).

A suspension system is a mechanism that separates the car body from the car wheel. It is also a combination of spring, shocks absorbers and linkages that connect a vehicle body to its wheel. The suspension systems are of three types; passive, semi-active, and active.

A passive suspension possesses the capability to stored energy using spring and also dissipates the energy using damper. The parameters of the passive suspension are fixed and chosen to arrive at a certain level of compromise between road handling, load carrying and the ride comfort. If the suspension is being controlled externally, it is referred to as semi-active or active suspension.

Meanwhile, active suspension also has the capability to store, dissipate as well as inject energy to the systems and its parameters may vary depending on operating conditions.

## 1.2 Problem Statement

The open loop control nature of the passive suspension systems makes it difficult to be adjusted by any mechanical part. This means that in the design consideration if it is critically damped (the suspension is too hard), a lot of energy will be transferred to road input. That is to say the car will be thrown on unevenness on the road. While if it is lightly damped (suspension is very soft), the stability of the car is reduced and consequently will make the vehicle to change lane or even swing on the road. Therefore, it can be stated that the performance of the passive suspension depends on various road profiles.

However, the closed-loop control nature of the active suspension systems using hydraulic force actuator will provide better performance in terms of stability and ride comfort. This actuator is a mechanical part incorporated inside the systems so as to be controlled and manipulated by controller. The controller with the help of data of road profile provided by sensors as input will calculate to add or dissipate energy from the system. This makes it more stable, efficient and effective.

In such a situation, there is a need for active element inside the system which possesses the ability of absorbing the vertical acceleration of the wheel to allow the frame and car body to ride without any disturbances while the wheels follow the bump on the road. Therefore, this research work is intended to investigate the performance of active suspension system with the application of three different controllers.

## 1.3 Research Objectives

The following are the objectives of this research project:

i. To obtain the mathematical model for passive and active suspension systems based on half car model.
ii. To design a state feedback and an intelligent controllers to control the active suspension system (LQR, FL and PID).
iii. To compare the performance of each controller with the passive suspension system using simulation results from Matlab/Simulink software with a road profile as input to the system.

## 1.4 Project Scope

The following are the scope of work for this project:

i. The research will consider derivation of mathematical equations of passive and active suspension systems for half car model only.

ii. Controllers will be designed to implement the mathematical model of the passive and active suspension systems.
iii. Matlab/Simulink software will be used to obtain the simulation results for comparison and analysis.

## 1.5 Overview of Research Methodology

To understand passive and active suspension components:

i. Literature review on passive and active suspension systems
ii. Review on the types of suspension systems
iii. Review on the control strategy.

To obtain mathematical models of passive and active suspension systems for half car model:

i. Applying physical laws to the suspension components to find the state space equations for passive half car model, then proceed to get the equations for active half car model.
ii. Manipulating matrix equations to find the state space equations

To implement the controller design into systems for performance analysis and comparison:

i. Literature review on the control techniques
ii. Comparison of the performance of each controller with passive and active suspension systems

To obtain the computer simulation results:

i By changing the state space equations into Simulink diagrams
ii Using simulation results for analysis.

Below is the flow chat to show the overall process for this project:

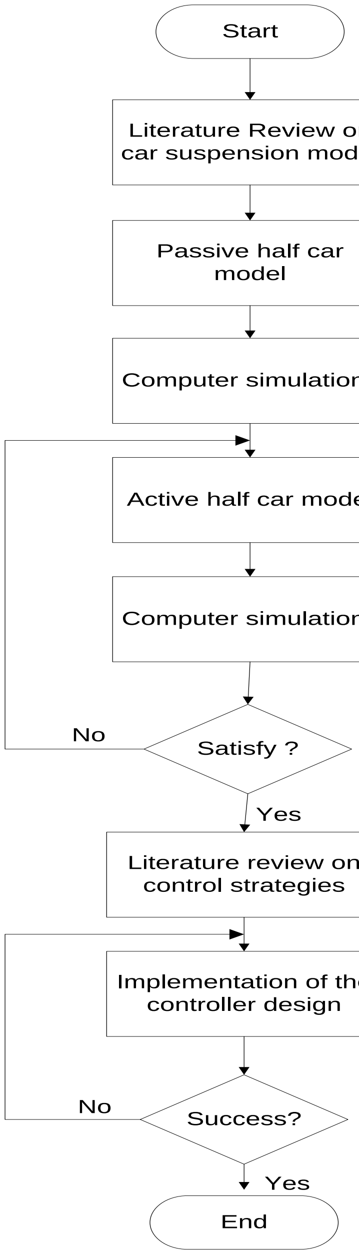


**Figure 1.1** Project process flow chat

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