Faculty of Mechanical Engineering

MULTI-ORDER PROPORTIONAL-DERIVATIVE CONTROL FOR ACTIVE VEHICLE SUSPENSION TO IMPROVE RIDE PERFORMANCE

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MULTI-ORDER PROPORTIONAL-DERIVATIVE CONTROL FOR ACTIVE VEHICLE SUSPENSION TO IMPROVE RIDE PERFORMANCE

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DECLARATION

I declare that this Choose an item. entitled " Multi-Order Proportional-Derivative Control For Active Vehicle Suspension To Improve Ride Performance" is the result of my own research except as cited in the references. The Choose an item. has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : Mohammad Shazwan Bin Ahim

Date : 18. 5. 2022

APPROVAL

I hereby declare that I have checked this project report and in my opinion, this project report is adequate in terms of scope and quality for the award of the degree of Master of Mechanical (Automotive)

Signature : ....

Supervisor Name : Mohd Hanif Bin Harun

Date : 18.5.2022

DEDICATION

I am dedicating this thesis to my parent, Allahyarham Haji Ahim bin Osman and Allahyarhamah Hajjah Hawa binti Jaamat who have always loved me and have taught me since childhood. May Allah bless and reward them both. To my beloved wife, children and all my family, I acknowledge my sincere appreciation to them for their love, vision, and sacrifice throughout my life. I am thankful for their understanding, tolerance, and consideration that were essential to make this effort possible. Their support has always inspired me from the day I continued my formal journey of learning until this moment. I am unable to find the most appropriate words that could properly describe my appreciation for their devotion, encouragement, and faith in my ability to reach my dreams. Lastly, I would like to extend my gratitude to any person who has contributed to this project either directly or indirectly. I am truly grateful for their comments and suggestions, which are crucial for the successful completion of this research.

ABSTRACT

Suspension system designs will determine the performance of the vehicle in terms of ride comfort, ride handling, and stability. These requirements often contradict each other, so they cannot meet all the needs and circumstances at the same time. Therefore, conventional suspension systems are usually optimised for certain types of terrain and still represent the main compromise between the quality of travel, handling, suspension travel, and control of body movements. Researchers focused on reducing these trade-offs have led to the development of advanced suspension systems. An advanced suspension system is achieved through the manipulation of forces provided by the suspension system at the compression and extension stages applied between the sprung and unsprung masses of each wheel assembly. Generally, the well-known method for manipulating suspension forces can be categorised into two types: semi-active and active suspension systems. An active suspension system combined with the controller can manipulate suspension forces to reduce the vibration and vertical motion of the vehicle. The purpose of this research is to develop an active suspension for the quarter-car model of a passenger car in order to improve its performance by using a multi-order proportional-derivative (MOPD) controller. The controller design deals with the selection of proportional and derivative gain parameters for the error of multiple variables, which are displacement, velocity, and acceleration. To verify the performance of this controller for active suspension systems, the simulated results of a closed-loop system for sinusoid road profile input using MATLAB and Simulink tools were used to compare the MOPD active suspension with PD active suspension as well as passive suspension. The PD active suspension and passive suspension were developed and investigated first. The simulation results reveal that active suspension with MOPD reduces the RMS value of body displacement, body acceleration, and wheel acceleration when compared to PD active suspension and passive suspension. However, only the RMS value for suspension deflection showed an inconsistent trend. In conclusion, multi-order PD control can improve vehicle ride performance when compared to PD control with passive suspension.

KAWALAN BERKADARAN-TERBITAN BERBILANG PERINGKAT BAGI PERGANTUNGAN AKTIF KENDERAAN UNTUK MENINGKATKAN PRESTASI PERJALANAN

ABSTRAK

Reka bentuk sistem penggantungan akan menentukan prestasi kenderaan dari segi keselesaan perjalanan, pengendalian perjalanan, dan kestabilan. Keperluan ini sering bercanggah antara satu sama lain, jadi ianya tidak dapat memenuhi semua keperluan dan keadaan pada masa yang sama. Oleh itu, sistem penggantungan konvensional biasanya dioptimumkan untuk jenis rupa bumi tertentu dan masih mempunyai kompromi utama antara kualiti perjalanan, pengendalian, gerakan penggantungan, dan kawalan pergerakan badan. Penyelidik yang memberi tumpuan kepada mengurangkan perdagangan ini telah membawa kepada pembangunan sistem penggantungan termaju. Sistem penggantungan termaju dicapai melalui manipulasi daya yang dihasilkan oleh sistem penggantungan pada peringkat mampatan dan regangan yang digunakan antara jisim badan kenderaan dan jisim roda kenderaan bagi setiap pemasangan roda. Secara amnya, kaedah yang terkenal untuk memanipulasi daya penggantungan boleh dikategorikan kepada dua jenis: sistem penggantungan separa aktif dan aktif. Sistem penggantungan aktif yang digabungkan dengan pengawal boleh memanipulasi daya gantungan untuk mengurangkan getaran dan gerakan menegak kenderaan. Tujuan penyelidikan ini adalah untuk membangunkan penggantungan aktif bagi model suku kereta kenderaan penumpang untuk meningkatkan prestasinya dengan menggunakan pengawal berkadaran-terbitan berbilang peringkat (MOPD). Reka bentuk pengawal adalah berkaitan dengan pemilihan parameter perkali perkadaran dan terbitan untuk ralat kepada pelbagai pembolehubah, yang merupakan anjakan, halaju, dan pecutan. Bagi mengesahkan prestasi pengawal aktif untuk sistem gantungan aktif ini, keputusan simulasi daripada sistem gelung tertutup bagi profil jalan jenis sinusoid yang diperolehi melalui perisian MATLAB dan Simulink digunakan untuk membandingkan hasil simulasi gantungan aktif MOPD dengan sistem gantungan aktif PD dan juga sistem penggantungan pasif. Sistem penggantungan aktif PD dan penggantungan pasif telah dibangunkan dan disiasat terlebih dahulu. Keputusan simulasi mendedahkan bahawa penggantungan aktif dengan MOPD mengurangkan nilai RMS anjakan badan, pecutan badan, dan pecutan roda jika dibandingkan dengan penggantungan aktif PD dan penggantungan pasif. Walau bagaimanapun, hanya nilai RMS untuk pesongan penggantungan menunjukkan keputusan yang tidak konsisten. Kesimpulannya, kawalan MOPD dapat meningkatkan prestasi perjalanan kenderaan jika dibandingkan dengan kawalan PD dan penggantungan pasif.

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LIST OF SYMBOLS AND ABBREVIATIONS

DOF	-	Degree of Freedom
FLC	-	Fuzzy Logic Controller
KBF	-	Knowledge-Based Fuzzy
LQR	-	Linear Quadratic Regulator
MOPD	-	Multi-order Proportional-Derivative
PD	-	Proportional-Derivative
PID	-	Proportional-Integral-Derivative
RMS	-	Root-mean-square
Kp	-	Proportional Gain
Ki	-	Integral Gain
Kd	-	Derivative Gain
e(t)	-	Error in time domain
C_s	-	Damper Coefficient (Ns/m)
K_s	-	Body Spring Stiffness (N/m)
K_t	-	Tyre Stiffness (N/m)
M_b	-	Body Mass (kg)
M_w	-	Wheel Mass (kg)
Z_b	-	Distance of Body (m)
Z_w	-	Distance of Wheel (m)
Z_r	-	Distance of Road (m)

CHAPTER 1

INTRODUCTION

1.1 Background

The requirement for vehicle safety and comfort is a critical criterion for vehicles development. Factors like handling and stability were focused by manufactures to maintain the comfort of vehicles especially when moving at high speed and uneven road profiles. So, it is not surprising that most vehicle is equipped with various control systems to ensure comfort and safety to vehicles and users. New technologies also are being developed by the automotive research industry along the time to ensure stability and handling of the vehicle at the best design condition.

Vehicle suspension systems have been widely used on vehicles for a long time ago. Typically, conventional vehicle suspension systems perform a few basic functions, including isolating the vehicle body from road disruptions to ensure a comfortable ride, maintaining a good road handle based on angle, braking ability, and traction, and supporting the static weight of vehicle to maintain the rattle space requirement in small vehicles (Doumiati *et al.*, 2012; Rajamani, 2012).

Unfortunately, these requirements often contradict each other where they cannot meet all the needs and circumstances. Therefore, conventional suspension systems are usually optimized for certain types of terrain and still represent the main compromise between the quality of travel, handling, suspension travel and control of body movements. The demand for improved ride comfort and road vehicle handling in vehicles such as passenger cars has prompted the development of new, more sophisticated suspension systems called semi-active and active suspension systems that improve passive conventional suspension systems. This electronically controlled suspension system has the potential to significantly improve vehicle comfort, ride quality, and operation on the road. The active suspension system of the system is capable of self-adjustment in response to changing the condition of road. It improves road sense, handling, responsiveness, and safety by adapting responses to changing road conditions.

Research of active suspension systems for a car is lately increasing because it offers better ride comfort to the passenger than semi-active suspension system and passive suspension systems (Mántaras and Luque, 2006; Alexandru and Alexandru, 2011; ElMadany, 2012). While active control schemes cannot optimise performance in all suspension rating criteria simultaneously (ride comfort, road holding, body motion, and suspension displacement requirements), they do provide the best overall vehicle performance improvement over passive and semi-active suspension systems.

The motivation of the study in this thesis is to investigate the possibilities of improving the dynamic performance of a vehicle by employing a multi-order proportional-derivative (MOPD) controller for the active suspension system. The main work of this study includes modelling of a quarter car suspension system using a PD controller and the development of a multi-order PD controller for an active suspension system.

1.2 Research Background

As previously mentioned, the suspension system design will dictate the vehicle's performance in terms of ride comfort, road handling, and stability. The efforts of researchers to minimise these trade-offs resulted in the development of improved suspension systems. Advanced suspension systems are achieved through the suspension system's manipulation of forces applied between the vehicle's body masses and wheel masses of each wheel assembly during the compression and extension stages. In general, the well-known way of manipulating suspension forces is classified into two categories: semi-active and active systems.

Active suspension systems have recently been investigated by a large number of researchers in order to increase the vehicle's stability and ride handling capabilities. Active suspension systems are usually combined with control strategies to ensure proper operation. Numerous control approaches have been utilised in the area of active suspensions systems, including linear quadratic regulator (LQR), adaptive sliding control, H∞ control, sliding mode control, fuzzy logic, and neural network methods. Control methods can be used to enhance the performance of the active suspension system. However, these solutions require refined processes or a customised performance determination table, as well as some application complexity (Ahmed *et al.*, 2015; Nagarkar *et al.*, 2018). The proportional-integral-derivative (PID) controller is the most widely used type of controller in industrial control systems because to its straightforward structure, ease of implementation, and strong performance over a wide range of applications. Additionally, it is simple to maintain and integrate a real system (Åström and Hägglund, 2000).

This study provides a mathematical model of a quarter car for the passive suspension and active suspension systems using MOPD controller. The behaviour of these controllers was analysed by simulating road disturbances with a sinusoid road profile. Prior to implementing MOPD, a proportional-derivative (PD) active system is used and evaluated. A comparison is made between passive and active suspension systems. The controller's performance will be compared to that of a MOPD controller, a PD controller, and a passive suspension system via computer simulations in the MATLAB and SIMULINK environments.

1.3 Problem Statement

In the construction of a vehicle, suspension system is an important system in vehicles to achieve the comfort and safety to vehicles and users while traveling on uneven, bumpy and potholed roads. A good suspension system is capable of providing comfort to the driver and passengers by producing minimal vibrations to the vehicle body when passing through uneven roads. The suspension system of a passive vehicle is composed of springs and dampers. The purpose of the damper is to disperse energy, meanwhile the spring works as an energy storage element. Both of these pieces never add energy to the system, which is why this sort of vehicle suspension system is referred to as a passive suspension system. This system has fixed settings that can be changed to achieve a desired amount of trade-off between ride comfort, road holding, and load carrying.

The primary issue with this type of suspension system is the damper's design. If the damper is too heavy, it will throw the car off balance on an imbalanced of road. If the damper is lightweight in design, it will have a negative influence on the vehicle's stability when turning or changing lanes. Occasionally, a vehicle may swing as a result of its design. The road profiles have a significant impact on the performance of the suspension system. When spring stiffness is increased in a passive suspension system, ride comfort falls and vice versa. To overcome this situation, active suspension systems are used with controller that can supplies additional external forces to suspension according to road profiles. The multi-order PD control system will be used to ensure that ride performance can be improved compare with passive suspension.

1.4 Project Objective

The purpose of this project is to study the MOPD control strategy for an active suspension system with the goal of improving ride performance. The controller is expected to have the capability to reduce vibration, providing a more comfortable ride for the driver. This project's objective is as follows:

a) To develop a proportional-derivative (PD) and multi-order proportional-derivative (MOPD) control scheme for active suspension system

b) To implement and evaluate the proposed control strategy in the active suspension system using a quarter car suspension system to improve ride performance of the vehicle.

1.5 Scope of Study

The scopes of this study are defined as follows:

a) Development of 2 degrees of freedom (DOF) mathematical model of quarter car passenger vehicle. It is assumed that the tyre is modelled as a linear spring without damping, there is no rotational motion in wheel and body, the movement of wheel and body are perfectly vertical, the behaviour of spring and damper are linear, and the effect of friction is neglected so that the residual structural damping is not considered into vehicle modelling.

b) Development of simulation model of passive and active suspension system. The active suspension system is assumed to be a perfect system, and the actuator system will be ignored.

c) Verification of the simulation model of vehicle with the validated simulation model using several input frequencies of road profile.

d) Controller design by simulation on the validated 2-DOF full vehicle model using MATLAB/Simulink Software.

e) Ride comfort and road holding analysis is performed in this study.

f) The controller's performance is determined by its capability to minimise the impacts of road-induced disturbances.

1.6 Contribution of Study

This study presents the development of a linear control strategy for active suspension that can be used to deliver a level of performance without incurring the associated high costs study and long-time use. This study is believed to make the following contributions to the present research areas:

a) A understanding of new active control strategy using a multi-order PD controller, which can be used to improve active suspension performance, has been developed and tuning through simulation.

b) The proposed control method is applied to vertical suspensions of the passenger car vehicle in this study and the improvements in the ride quality are evaluated with several different road data.

1.7 Thesis Outline

This thesis is divided into five (5) chapters, the contents of which are summarised as follows:

a) Chapter 1 : Introduction. This chapter presents the background of the study, research problems, objectives, scopes and contributions of the study.

b) Chapter 2 : Literature review. This chapter begins with a quick introduction of car suspension system classification. In terms of mode operation and control system, this section discusses passive suspension systems, semi-active suspension systems, and active suspension systems. Following that, this chapter provides a concise overview of the various active suspension system control strategies.

c) Chapter 3 : Methodology. This chapter discussed the methodology that has been developed to study performance of multi-order PD control for active suspension system starting from modelling and verification, proportional-derivative control approach and multi-order proportional-derivative control approach.

d) Chapter 4. Result and Discussion. In this chapter, result from simulation have been showed and discused. Improvement achieved for PD control and MOPD control has been discussed.

e) Chapter 5. Conclusion and future works. This chapter highlights the study's major conclusions and accomplishments and makes recommendations for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter focuses on related research on the study. This chapter provides an overview of vehicle dynamics and models, as well as an explanation of the suspension system concept, classification of suspension systems, and reviews of active suspension and various types of controllers. The literature review is critical to obtaining all the information from related field research and will be used as a reference to complete this project.

2.2 Vehicle Dynamics and Model

Industrial research and development have placed heavy emphasis on vehicle dynamic performance. While vehicle dynamics performance can be assessed in numerous ways, ride comfort and handling are the two most critical components of performance that are clearly linked to the vehicle suspension system. Typically, a vehicle suspension system performs several basic functions. The primary function of the vehicle suspension is to separate the automobile body from road disturbances in order to give a comfortable ride. The vertical acceleration of the passenger locations can be used to quantify ride quality in general. By decreasing the vibratory forces transmitted from the axle to the vehicle body, a well-designed suspension provides isolation. Another critical role is to maintain the vehicle's road holding capabilities in terms of cornering, braking, and traction. And last, the suspension system's final purpose is to sustain the vehicle's static weight in order to keep rattling space requirements within the car to a minimum (Rajamani, 2012).

Unfortunately, the design of automotive suspension systems involves several compromises (Alexandru and Alexandru, 2011; Farid et al., 2018). For example, vehicles with an excellent ride quality typically include suspensions with low spring rates and low damping rates, which results in a large suspension travel. Meanwhile, vehicles with excellent handling typically include suspensions with high spring and damping rates, which results in less suspension deflection. These trade-offs arise because passive suspension is fundamentally dependent on the spring's ability to store energy and the damper's ability to dissipate it. While the specifications of passive suspension are generally fixed, the design was developed to achieve an acceptable level of compromise between road holding and ride comfort under typical road conditions (Marzbanrad, 2013). Once the spring has been determined based on the suspension's load-carrying capacity, the damper is the only remaining variable to specify. Low damping results in inadequate resonance management at the body (sprung mass) and wheel (unsprung mass) natural frequencies but offers the requisite high frequency isolation for a comfortable ride. On the other hand, a high damping ratio results in excellent resonance control at the expense of high frequency isolation. As a result, these passive suspension systems are often tuned for a specific type of terrain but nevertheless constitute a significant compromise in terms of ride quality, handling, suspension travel, and body motion control. However, recent advancements in force generators, sensors, and microprocessors have resulted in the development of advanced suspension systems that outperform passive suspension systems in terms of performance (Fischer and Isermann, 2004).

According to previous research, controlling vehicle suspension is an important factor for improving ride comfort while keeping the car's handling characteristics and reducing vibration caused by varied road profiles (Appleyard *et al.*, 1995). Further, performance can be enhanced by maintaining the vehicle's body's relative position and movement in relation to the wheels. Suspension system was developed using three distinct models: quarter-car, half-car, and full-car. The quarter-car model is frequently used for suspension analysis, as demonstrated by Ahmed *et al.*(2015), Shelke *et al.* (2018), Kilicaslan (2018) because towards its simplicity and ability to capture essential characteristics of the full model. By incorporating vertical forces on the sprung and unsprung masses, the equation for the model movements is found. According to Figure 2.1, most quarter-car suspension models will treat the car body's mass as the sprung mass and the wheels' mass as the unsprung mass. The model of the quarter-car suspension is a two-degree-of-freedom system. The quarter car model can be expanded into a half-car model and a full-car model as done by Kruczek and Stribrsky (2004), ElMadany (2012) and Gandhi *et al.* (2017).

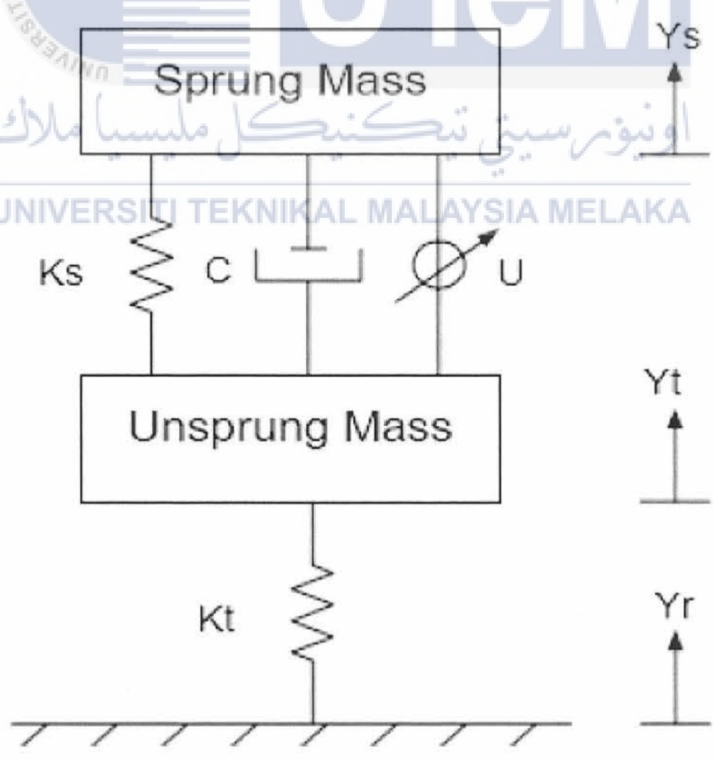

Figure 2.1: Quarter car model for suspension system