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SIXTH ORDER POLYNOMIAL MODEL AND SKYHOOK ALGORITHM BASED FUZZY LOGIC CONTROL OF MAGNETORHEOLOGICAL DAMPER FOR AUTOMOTIVE SUSPENSION SYSTEM

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DECLARATION

I declare that this thesis entitled "*Sixth Order Polynomial Model and Skyhook Algorithm Based Fuzzy Logic Control of Magnetorheological Damper for Automotive Suspension System*" 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.

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z_b	Body displacement
z_t	Tire displacement
k_s	Spring stiffness
c_s	Damping coefficient
k_t	Tire stiffness
m_b	Body mass
m_t	Tire mass
$\boldsymbol{\tau_y}$	Yield stress
$\boldsymbol{\alpha}, \boldsymbol{\beta}$	Intrinsic values
H	Magnetic field
k_e	Stiffness constant due to the gas compliance
x_p	Piston displacement (in Bingham Model)
v	Piston velocity (in Bingham Model)
c_e	Damping constant (in Bingham Model)
z	Evolutionary variable (in Bingham Model)
u	Current applied (in Eq. 2.10)
v	Applied voltage (in Eq. 2.10)
η	Applied voltage (in Eq. 2.10)
c_i	Function of current gain

v_m	Maximum damper velocity
v_1	Sprung mass velocity
v_{12}	Relative velocity
c_{sky}	Skyhook damping constant
F_d	Damping force
c_j^i	Center of membership function
σ_j^i	Spread of membership function
x_j	Controller input
$\mu_{A_j^i}$	Functional form of Gaussian-type
u	The output value
$\mu(s_i)$	Fire strength of the rule
s_i	Singletons
x_{out}	Output displacement
x_{in}	Input displacement
F	Damper force (in Eq.(4.1))
a_i	Experimental coefficient (in Eq.(4.1))
b_i, c_i	Coefficient obtained from the slope and intercept
v	Piston velocity (in Eq.(4.2))
J	Objective function
F_{ai}	Actual force
F_{di}	Predicted force by the model
W_{mr}	Energy dissipated
F_{mr}	MR Damper force
C_{eq}	Equivalent damping coefficient
ω_d	Actuation frequency

X	Excitation amplitude
$u(t)$	PI control signal
$e(t)$	PI control signal
K_p	Proportional constant
K_i	Integral constant
F_d	Desired force
F_a	Actual force
m_1	Sprung mass
c_s	Damping constant
k_s	Spring stiffness
k_t	Tire stiffness
C_{high}	High state damping coefficient
C_{low}	Low state damping coefficient
$\dot{z}_1$	Sprung mass velocity
$\dot{z}_2$	Unsprung mass velocity
F_s	Ideal skyhook damping force
F_u	Semi-active damper force
C_s	Skyhook damping coefficient
C_{max}	Maximum damping coefficient
C_{min}	Minimum damping coefficient
C_p	Passive damping coefficient

ABSTRACT

This study deals with the investigation on the modeling of a Magne-Ride damper and its uses in overcoming the effects of road disturbance to the vehicle ride comfort. It was begun from the study on the performance of a sixth order polynomial approach to model the nonlinear hysteresis behavior of magnetorheological (MR) damper. The polynomial model was developed based on curve fitting from the experimental results which consists of a pair subsystem namely positive and negative acceleration corresponding to the upper and lower curves. The performance of the proposed polynomial model was compared with a well known non-parametric technique namely inverse model. The energy dissipated and equivalent damping coefficient of the MR damper in terms of input current and displacement amplitude were also investigated. From the simulation results, the sixth order polynomial model shows better performance in describing the non-linear hysteresis behavior of MR damper compared to the inverse model. The force tracking control in both simulation and experimental studies demonstrate that a close-loop PI control has the ability to track the desired damping force well. The governing equations of motions were formulated and integrated with skyhook control. Skyhook policy was then adapted in the development of a fuzzy logic control to enhance the ride performance. The performance of fuzzy logic control was compared with the on-off and continuous skyhook control in time domain. The results show that skyhook algorithm based fuzzy logic control gives better performances than its counterparts.

ABSTRAK

Kajian ini adalah mengenai permodelan peredam Magne-Ride dan kegunaannya adalah untuk mengatasi kesan gangguan jalan raya untuk keselesaan pemanduan. Kajian dimulakan dengan analisis terhadap prestasi polinomial peringkat ke-enam yang digunakan untuk permodelan histerisis tidak linear bagi karakteristik peredam magnetorheological (MR). Permodelan polinomial dihasilkan melalui keputusan eksperimen yang mengandungi beberapa sub-sistem iaitu positif dan negatif pecutan di mana ianya mewakili lengkung atas dan bawah yang diperolehi dari keputusan eksperimen. Prestasi permodelan polinomial akan dibandingkan dengan teknik bukan parameter yang diketahui umum iaitu permodelan inverse. Kajian lebih berlandas pada tenaga yang dibebaskan dan pemalar peredam seimbang berdasarkan arus elektrik dan sesaran amplitud bagi peredam MR. Keputusan simulasi menunjukkan bahawa permodelan polinomial menghasilkan prestasi yang lebih baik bagi menerangkan histerisis tidak linear peredam MR berbanding dengan permodelan inverse. Kawalan daya sejajar bagi simulasi dan eksperimen dilakukan dengan menggunakan kawalan PI dan ianya menunjukkan peredam MR dapat menghasilkan daya yang sejajar dengan daya yang dimahukan. Persamaan pergerakkan dihasilkan melalui kawalan skyhook. Polisi kawalan skyhook diadaptasi ke dalam kawalan logik fuzzy untuk meningkatkan prestasi pemanduan. Prestasi kawalan logik fuzzy dibandingkan dengan "on-off" dan kawalan berterusan skyhook di dalam domain masa. Keputusannya menunjukkan algoritma skyhook berlandaskan kawalan logik fuzzy memberikan prestasi yang lebih baik berbanding dengan kawalan lain.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Vibration control of vehicle suspension systems has been a very active subject of research, since it can provide a very good performance for drivers and passengers. For a long time, efforts were performed to make the suspension system works in an optimal condition by optimizing the parameters of the suspension system. Basically, suspension systems are classified into a passive suspension, semi-active suspension and active suspension. Compared with the passive suspension, both semi-active and active suspensions can improve the performance of the suspension system over wide frequency ranges (Ghosh and Dinavahi, 2005).

Active and semi-active suspension systems for ground vehicles have been a very active subject of research since the 1980s owing to their potential to improve vehicle dynamics performance (Yi et al., 1999). It has long been recognized that semi-active suspension can provide substantial performance improvements over the optimized suspensions, nearly as good as the active suspensions (Batterbee and Sims, 2006). Due to the performance benefits of semi-active system, it can be more widely adopted in mass-produced vehicles than the active suspensions because of its lower cost and low demand of power (Caponetto et al., 2003; Yi et al., 1999). Two types of semi-active suspension systems have been developed namely variable orifice damper and variable fluid viscosity damper. The semi-active suspension utilized in this study uses variable fluid viscosity namely magnetorheological fluid (MR fluid).

The intention of the study is to mathematically model the non-linear behavior of magnetorheological damper (MR damper) and implement the semi-active control law. The semi-active damper must be adjustable in real time to achieve better ride performance. In this study, the "traditional" semi-active control law will be explored through simulation and experimental works. The main works of this study include development of a quarter car test rig, MR damper modeling, force tracking control (inner-loop control) and controller implementation (outer-loop control) on a quarter car system. The study begins from computer simulation on a quarter car models. Suspension test machine and quarter car test rig are then developed for MR damper testing and quarter car evaluation. Both damper and quarter car models resulted from computer simulation are then validated and compared with the experimental results as the benchmark. Finally, the potential benefits of implementing the semi-active suspension system using MR damper are evaluated in terms of their performances in improving vehicle dynamics performance.

1.2 Problem Statement

An inaccurate model of MR damper will lead to an inaccurate control strategy in predicting the optimum targeted damping force. The main variable influent the damping force of the MR damper is the supplied current and the piston velocity. The accurate model will provide a good result in predicting the MR damper behavior when a certain current and velocity are applied to the model.

Failure of control strategy in predicting the optimum damping force will also degrade the ride performance. In the implementation of skyhook control, failure in predicting an optimum damping force is often faced since it considers only the sign of multiplication results between damper relative velocities and sprung mass absolute velocity (Carter, 2003). To accommodate the problem and enhance the ride performance, one of artificial intelligence methods namely fuzzy logic control that adopts the skyhook algorithm shall be incorporated and embedded to the system.

1.3 Objective

The objectives of this research are as follows:

1. To build and validate a mathematical model of the MR damper through simulation and experimental works.
2. To develop an inner-loop control (force tracking control) for the MR damper analytically and experimentally.
3. To evaluate the performance of skyhook control and the proposed fuzzy logic based skyhook algorithms through computer simulation and quarter car test rig.

1.4 Scopes of the Study

The scopes of this study are mentioned as the following:

1. The study uses a class of variable viscosity damper namely MR damper.
2. A non-parametric approach is used to model the MR damper.
3. The parameters of quarter car model and quarter car test rig are selected to represent the parameters of a class of light weight passenger vehicle of Malaysian national car.
4. The performance criteria to be evaluated in this study are sprung mass acceleration, sprung mass displacement, suspension travel and unsprung mass acceleration.

1.5 Methodology

The proposed research methodology can be briefly described as follows:

1. Develop the quarter car model for the passive and semi-active suspension system. The quarter car model needs to be validated with the experimental results from the quarter car test rig.
2. Design and develop a quarter car test rig complete with its instrumentation system. This includes the development of the hardware, software, electronic interfacing devices and sensors.
3. Conduct the MR damper characterization using the quarter car test rig. The result of testing in time domain are then processed to obtain the force-velocity and force-displacement behaviors of the damper.
4. Perform an analytical study on the energy dissipation and the equivalent damping coefficient utilizing the developed MR damper model.
5. Perform the simulation and experimental studies on the inner-loop control (force tracking control to check the damping force controllability. A simple close-loop PI control is implemented to achieve the actual damping force as close as possible with the desired damping force.
6. Implement the proposed semi-active control strategies to the validated quarter car and MR damper models through simulation study.
7. Conduct the experimental evaluation using the quarter car test rig. The results are then discussed to observe the enhancement achieved by the proposed control strategies.

1.6 Research Contributions

In the area of MR fluid behavior and MR damper response to harmonic loading in vehicle, the research outcomes can be summarized as follows:

1. The sixth order polynomial model of semi-active MR damper has been successfully developed. The proposed model showed the ability in capturing the non-linear hysteresis behavior of the MR damper in the form of force-displacement and force-velocity. It has also been compared with other non-parametric approach namely inverse model and showed the superiority compared to its counterpart. Numerically, the trend of energy dissipation and equivalent damping coefficient versus the supply current have also been obtained.
2. Fuzzy logic base skyhook algorithm has been successfully implemented in semi-active suspension system and offered better ride performance compared with the skyhook control strategy in both simulation and experimental works.
3. The design and development of an MR damper testing facility has been realized. This rig test is not only used for quarter car performance evaluation but also is used for MR damper characterization

1.7 Thesis Outlines

This thesis consists of eight chapters. Chapter 1 is an introductory section which consists of introduction, statement of the problems, research objectives, scopes of the study, research methodology and research contributions. Literature survey as a pertinent material background is given in Chapter 2. This chapter begins with an overview on the vehicle suspension system and working principal of MR fluid. Several basic descriptions which include the discussion on the different types of MR damper; some MR damper modeling approaches; skyhook control algorithm and an overview on the original fuzzy logic control are described in the next section. The last section of Chapter 2 summarizes the results of literature review from the previously published papers related to semi-active suspension control which relies on MR damper.

Chapter 3 contains the development of a quarter car test rig for testing facility. The description begins from the structural design which includes the frame design and placement, sliding part, sprung mass construction, suspension system and unsprung mass followed by the description about the actuation systems for the quarter car test rig. Controller development which describes the sensory information needed for the rig and current driver circuit are given. Finally, the results of model validation are also presented in the last section of this chapter.

Chapter 4 presents the results of characterization and force tracking control of the MR damper using harmonic excitation. The chapter begins with the explanation of the proposed sixth order polynomial model. Then, the responses of the MR damper model using the proposed sixth order polynomial model are presented and compared with the response of the inverse models as well as the experimental results. The energy dissipated and equivalent damping coefficients resulting from the mathematical derivation of MR damper model are also reported in the next section. In the last section, the results of investigation on MR damper force controllability are then presented.

Chapter 5 explains the results of controller implementation on the quarter car system using on-off skyhook, continuous skyhook and the proposed skyhook based fuzzy logic control algorithm. The simulation results from the quarter car response under several excitation frequencies of road disturbances are reported in the first section. The results of the