INTELLIGENT CONTROLLERS FOR VEHICLE SUSPENSION SYSTEM USING MAGNETORHEOLOGICAL DAMPER

MAT HUSSIN BIN AB TALIB

A thesis submitted to fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

APRIL 2017

Dedicated:

To my lovely spouse

Siti Aishah Binti Mohd Daud

To my adorable son

Muhammad Khairun Nasirin Bin Mat Hussin

To my beloved parents

Allahyarham Ab Talib Bin Che Lin

Khadijah Binti Yusof

To my mother in law

Che Mas Binti Daud

And all family.

ACKNOWLEDGEMENT

Alhamdulillah, all praise is due to Allah S.W.T, the Most Beneficent and the Most Merciful, who has taught me what I knew not. First and foremost, I would like to express special thanks and deepest gratitude to my main supervisor, Associate Professor Dr. Intan Zaurah Binti Mat Darus, who has provide continuous support, guidance, advice and generous amount of time in helping me to complete this research. My deep gratitude is also extended to my co-supervisor, Associate Proffesor Ir. Dr. Pakharuddin Bin Mohd Samin for his continuous guidance, encouragement and invaluable advice throughout my research.

Sincere appreciation to my friends who give me a continuous support and helping throughout in the completion of this study. My deepest respect and thanks go to my family especially my beloved wife Siti Aishah Binti Mohd Daud for their support and amount of time in encourage me to complete this research. Without their endless sacrifices, constant love and steadfast support, I would never have reach this level. To my son Muhammad Khairun Nasirin, it is to you I dedicate this effort.

Finally, above all, I would like to offer my deepest appreciation and thanks giving to Allah S.W.T. There is no way to measure what you've worth. You are The One who has made things possible. You deserve all glory and honor

ABSTRACT

Semi-active suspension control with magnetorheological (MR) damper is one of the most fascinating systems being studied in improving the vehicle ride comfort. This study aims to investigate the development of intelligent controllers for vehicle suspension system using MR damper, namely, the proportional-integral-derivative (PID) and fuzzy logic (FL) controllers optimized using particle swarm optimization (PSO), firefly algorithm (FA) and advanced firefly algorithm (AFA). Since the conventional optimization method always has a problem in identifying the optimum values and it is time consuming, the evolutionary algorithm is the best approach in replacing the conventional method as it is very efficient and consistent in exploring the values for every single space. The PSO and FA are among of the evolutionary algorithms which have been studied in this research. Nevertheless, the weakness of FA such as getting trapped into several local minima is an attractive area that has been focused more as a possible improvement during the evolutionary process. Thus, a new algorithm based on the improvement of the original FA was introduced to improve the solution quality of the FA. This algorithm is called advanced firefly algorithm. A parametric modelling technique known as Spencer model was proposed and employed to compute the dynamic behaviour of the MR damper system. The Spencer model was experimentally validated and conducted to capture the behaviour of the Lord RD-1005-3 MR damper with the same excitation input. A simulation of a semi-active suspension system was developed within MATLAB Simulink environment. The effectiveness of all control schemes were investigated in two major issues, namely the ability of the controller to reject the unwanted motion of the vehicle and to overcome the damping constraints. The result indicates that, the PID-AFA control scheme is more superior as compared to the PID-PSO, PID-FA, FL-PSO, FL-FA, FL-AFA and passive system with up to 27.1% and 19.1% reduction for sprung mass acceleration and sprung mass displacement, respectively. Finally, the performance of the proposed intelligent control schemes which are implemented experimentally on the developed quarter vehicle suspension test rig shows a good agreement with the results of the simulation study. The proposed control scheme of PID-AFA has reduced the sprung mass acceleration and sprung mass displacement over the FL-AFA and passive system up to 28.21% and 16.9%, respectively.

ABSTRAK

Kawalan ampaian separa-aktif dengan peredam magnetorheologi (MR) adalah salah satu bidang menarik yang dikaji dalam meningkatkan keselesaan semasa menaiki kenderaan. Penyelidikan ini mengkaji tentang pembangunan pengawal-pengawal pintar untuk sistem ampaian kenderaan dengan menggunakan peredam MR, iaitu pengawal terbitan-kamiran-berkadaran (PID) dan kawalan logik samar (FL) yang dioptimumkan dengan menggunakan pengoptimuman kawalan zarah (PSO), algorithma kelip-kelip (FA) dan algorithma kelip-kelip termaju (AFA). Oleh sebab kaedah pengoptimuman konvensional sentiasa mempunyai masalah dalam mengenal pasti nilai-nilai optimum dan ia juga memakan masa, algoritma evolusi adalah pendekatan yang terbaik untuk menggantikan kaedah konvensional kerana ia adalah sangat cekap dan konsisten dalam meneroka nilai untuk setiap ruang tunggal. PSO dan FA adalah antara algoritma evolusi yang telah dikaji dalam penyelidikan ini. Walaubagaimanapun, kelemahan yang ada pada FA seperti mudah terperangkap dalam beberapa minima tempatan adalah satu bidang menarik yang telah ditumpukan lebih sebagai peningkatan yang mungkin semasa proses evolusi. Oleh sebab itu, algoritma baru berdasarkan penambahbaikan daripada FA yang asal telah diperkenalkan bagi meningkatkan penyelesaian kualiti untuk FA. Algoritma ini dikenali sebagai algorithma kelip-kelip termaju. Satu teknik pemodelan yang berparameter dikenali sebagai model Spencer telah dicadangkan dan digunakan untuk mengira perilaku dinamik sistem peredam MR. Model Spencer telah disahkan dan dijalankan secara eksperimen untuk menangkap perilaku bagi peredam MR Lord RD-1005-3 dengan input pengujaan yang sama. Simulasi bagi sistem ampaian separa-aktif telah dibangunkan dalam persekitaran MATLAB Simulink. Keberkesanan bagi semua skim kawalan telah disiasat dalam dua isu utama, iaitu keupayaan skim kawalan untuk membuang pergerakan yang tidak diperlukan bagi kenderaan dan juga untuk mengatasi kekangan redaman. Keputusan menunjukkan bahawa kawalan PID-AFA lebih unggul berbanding dengan PID-PSO, PID-FA, FL-PSO, FL-FA, FL-AFA dan sistem pasif sehingga 27.1% dan 19.1% penurunan masing-masing bagi pecutan dan juga sesaran badan kenderaan. Akhirnya, prestasi bagi skim kawalan yang telah dilaksanakan secara eksperimen ke atas suatu rig ujikaji ampaian kenderaan sukuan telah menunjukkan keserasian dengan keputusan yang diperolehi melalui kajian simulasi. Skim kawalan yang dicadangkan bagi PID-AFA telah berkurang sehingga 28.21% dan 16.9% masing-masing bagi pecutan badan kenderaan dan sesaran badan kenderaan berbanding dengan FL-AFA dan sistem pasif.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABC	-	Artificial bee colony
ACO	-	Ant colony optimization
AFA	-	Advance firefly algorithm
AFC	-	Active force control
ANFIS	-	Adaptive neuro fuzzy inference system
AI	-	Analog input
AO	-	Analog output
D	-	Derivative
DAQ	-	Data acquisition
DE	-	Differential Evolution
DOF	-	Degree of freedom
ER	-	Electrorheological
EA	-	Evolutionary algorithm
FA	-	Firefly algorithm
FLC	-	Fuzzy logic controller
FL	-	fuzzy logic
FL-AFA	-	fuzzy logic controller tuned using advanced firefly algorithm
FL-FA	-	fuzzy logic controller tuned using firefly algorithm
GA	-	Genetic algorithm
GC		Gain coefficient
GRV	-	Gain relative velocity
GSV	-	Gain sprung velocity
HILS	-	Hardware-in-loop-simulation
HSASF	-	Hybrid Stability Augmentation System-Force
HTGA	-	Hybrid taguchi genetic algorithm

I	-	Integral
FL-PSO	-	Fuzzy logic controller tuned using particle swarm optimization
LQR	-	Linear quadratic controller
MR	-	Magnetorheological
MSE	-	Mean square error
NF	-	Neuro-fuzzy
NI	-	National instrument
NPLDD	-	Non-parametric linearized data driven model
P	-	Proportional
PID	-	Proportional-integral-derivative
PID-AFA	-	Proportional-integral-derivative controller tuned using advance firefly algorithm
PID-FA	-	Proportional-integral-derivative controller tuned using firefly algorithm
PID-GA	-	Proportional-integral-derivative controller tuned using genetic algorithm
PID-PSO	-	Proportional-integral-derivative controller tuned using particle swarm optimization
PSO	-	Particle swarm optimisation
QFT	-	Quantitative feedback theory
RMSE	-	Root mean square error
SADFE	-	Semi active damping force estimator
SMC	-	Sliding mode control
RPSU	-	Road profile simulator unit

LIST OF SYMBOLS

α	-	Parameters of hysteresis loop model
β	-	Attractiveness
β_o	-	Attractiveness when $r=0$
γ	-	Fixed light absorption coefficient
η	-	Filter time constant
υ	-	Voltage input of first filter
τ_y	-	Field dependent yield stress
$\mu_i(x)$	-	Aggregated membership function
$\Delta Fitness$	-	The error function between the i^{th} particle with the current fitness function
ΔP	-	Sum of two components
ΔP_n	-	Viscous pressure loss
ΔP_τ	-	Yield stress pressure loss
A	-	Parameter controlling hysteresis amplitude
$A(t)$	-	State/system matrix
a	-	Lower limit
B	-	Feedback gain
$B(t)$	-	Input matrix
b	-	Upper limit
C_{D1}	-	Dashpot
C_{SKY}	-	Skyhook damping coefficient
$C(t)$	-	Output matrix
c	-	Viscous coefficient

c_1, c_2	-	Acceleration constants
c_o	-	Viscous damping parameter
cs	-	Proposed control system
c_s	-	Damping coefficient
$D(t)$	-	Feedthrough/feedforward matrix
$e(t)$	-	Error of input and output
F	-	Damping force
F_{SA}	-	Semi active skyhook damper force
F_d	-	Desired force estimated from control algorithm
F_n	-	Damping force at a given current supply
f_a	-	Actuator force
f_c	-	Frictional force
f_d	-	Semi active damping force
G	-	Forward gain
g	-	Gap of fluid
I	-	Desired current
i, j	-	Number of particles
K_D	-	Derivative gain
K_I	-	Integral gain
K_P	-	Proportional gain
k	-	Stiffness
k_D	-	Accumulator stiffness
k_s	-	Spring stiffness
k_t	-	Tire stiffness
L	-	Length of the pole
m^i	-	Output membership of each rule
m_s	-	Sprung mass

m_u	-	Unsprung mass
$m(t)$	-	Control signal
p_{id}	-	p_{best} (particle personal best position)
p_{gd}	-	g_{best} (the global best position)
ps	-	Passive suspension system
Q	-	Flow rate
r	-	Distance between any two fireflies
r_1, r_2	-	Random number
u	-	Output first order filter
$u(t)$	-	Control/input vector
V_1	-	Sprung mass velocity (Skyhook)
V_{12}	-	Relative velocity (Skyhook)
v_{id}	-	Current velocity of the particle
v_s	-	Sprung mass velocity
v_t	-	Unsprung mass velocity
v_{st}	-	Relative velocity
w	-	Inertia weight/the pole width
w_i	-	Inertia weight
x	-	Damper displacement (Bouc-Wen model)
x_D	-	Damper displacement (Spencer model)
x^*	-	Damper displacement
$\dot{x}$	-	Damper velocity
x_0	-	Initial damper displacement
x_i	-	First particle of firefly, i /initial displacement
x_{id}	-	Current position of the particle
x_f	-	Final displacement
x_j	-	Second particle of firefly, j

x_u	-	Unsprung mass displacement
$\ddot{x}_u$	-	Unsprung mass acceleration
x_s	-	Sprung mass displacement
$\dot{x}_s$	-	Sprung mass velocity
$\ddot{x}_s$	-	Sprung mass acceleration
x_r	-	Road profile displacement
x_1	-	Body displacement
$\dot{x}_1$	-	Body velocity
$\ddot{x}_1$	-	Body acceleration
x_2	-	Tire displacement
$\dot{x}_2$	-	Tire velocity
$\ddot{x}_2$	-	Tire acceleration
$x_1 - x_2$	-	Suspension deflection
$x(t)$	-	State vector
y_D	-	Damper displacement
$y(t)$	-	Output vector
z	-	Hysteretic variable

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Global vehicle control systems are currently subjected to many important issues, not just in the present but also for the future. Controllability and stability of the vehicle is necessary to ensure the comfort of the driver and passengers. One of the essential issues is the ability of the suspension system to ensure that the vehicle body achieves a combination of good road handling, load carrying and ride comfort. The suspension system has its own mechanism which gives a great comfort and safety for driver and passengers inside the vehicle, especially when the vehicle hit a bump, a hole or taking a corner. The input disturbance, namely load disturbance and road disturbance always lead to a number of undesirable conditions for the vehicle system.

In order to have the best performance of the suspension, particular characteristics which are dealing with the regulation of body movement, the regulation of suspension movement and force distribution must be considered. There are several types of automotive suspension, namely, passive, semi-active and active suspension systems. Every each of these types has their own mechanisms and functions to act as the right contact between body and tires. However, the passive suspension system has a limitation to control the stability of vehicle which has motivated extensive researches on active and semi-active suspension systems (Aleyne and Hedrick, 1992).

Semi-active system contains a variable damping mechanism, such as an MR damper system, which is an alternative way to be either passive or active system. Due to the intelligent damper installation, a controllable system can be produced dynamically and the majority of the performance of a fully active system can potentially be achieved. For the active system, an additional actuator is installed into the system to produce an additional force for good vehicle performance. Although an active system produces a good ride quality and superior than the semi-active system, it has a major limitation such as the need for a large power source as well as being very expensive due to the high cost for design and development (Rao *et al.,* 2010; Krishnan, 2013).

In recent years, semi-active suspension system has become an attractive area of research. This is because the system can be as an active device without requiring a large power source. In addition, it can offer the reliability of passive devices (Tsang *et al.,* 2006). Unlike passive system, variable damper of semi-active system can actually be effectively controlled in terms of damper stiffness based on required values in a particular situation. Generally, semi-active systems with variable damping force are divided into two types, namely, hydraulical and rheological. Among these, rheological damper is a current research attention due to the great advance in the rheological fluid development. Mainly, there are two types of rheological based damper which are magnetorheological (MR) and electrorheological (ER) dampers. Both principles are used to provide adjustable damping forces based on the alteration of the damping mediums' of viscosity (Fischer and Isermann, 2004).

The MR damper system has drawn significant attention from many researchers due to its fast time response, low power requirement, high dynamic range and mechanical simplicity (Koo *et al.,* 2004). There are four major areas of MR damper technology research including mathematical and numerical research (Yao *et al.,* 2009; Ye *et al.,* 2010), researches on fluid (Yang, 2002), researches on design and development (Fujitani *et al.,* 2003) and researches on MR damper control strategies (Caponetto *et al.,* 2003; Yao *et al.,* 2012; Khiavi *et al.,* 2013).

The semi-active MR damper model can be effectively used by considering the accuracy of the damper model and suitable controller for the damper. In the past few years, several promising control strategies have been introduced such as linear quadratic gaussian controller (Taylor *et al.,* 1999), $H\infty$ controller (Du *et al.,* 2005) and linearly parameterized controller (Mori and Nilkhamhang, 2007). However, it could be realized that the alternative control algorithms can be introduced for further improvements.

1.2 Problem Statement

Vibration and road disturbance are always leads to a number of undesirable circumstances. The problem of automobile car when hitting the bump or any road disturbance for instance can lead to driver discomfort, restlessness and eventually fatigue. The semi-active and active suspension systems lead a major research area in automotive industries. However, due to the limitations of active suspension system such as high power consumption, expensive hardware and its complexity, semi-active suspension system is a possible way to be used in order to achieve the performance as good as a fully active system (Rashid *et al.*, 2007; Ubaidillah *et al.*, 2011)

One of the main issues needs to be addressed in the use of semi-active MR damper in the vehicle suspension system is how to design a suitable control strategy to overcome damping constraint and to reduce unwanted motion of body vehicle due to passing road profile disturbance based on existing MR damper model. This is due to the fact that, improper design of control scheme will lead the optimum target force is unpredicted. In addition, a proper design of control strategy is also important in overcoming the damper constraint by providing the same direction between target force and damper velocity. The advantages in the use of MR damper control strategy in improving the vehicle dynamics have been investigated extensively through simulation and experimental studies by many researchers such as Hudha *et al*., (2008), Samin, (2010) and Kasemi *et al.,* (2012). In these previous works, the conventional method such as sensitivity analysis study was used to optimize the parameter value of the control scheme. It is important to be mentioned that, the parameters of the control scheme tune using conventional method could not give the best results for the controller. This is due to the fact that, the process was not fully covered for every single space of data in achieving the minimum values of the objective function. Thus, the intelligent method based on evolutionary algorithm is the best approaches in replacing the conventional method for optimization process of the controller. The evolutionary algorithm is an efficient method which consistently able to explore every single space. While the conventional method resembles trial and error mechanisms, and depends on computational capacity, the evolutionary algorithm is a method that can learn faster as they run, and tend to be more intelligent and adaptive (Madić *et al.*, 2013).

The particle swarm optimization (PSO) and firefly algorithm (FA) are among of the evolutionary algorithms that could be used in this study. This is due to the fact that, these two algorithms have several advantages such as simple and easy to be used that leads many researchers to be focused more on these two algorithms (Bhushan and Pillai, 2013). In comparison, most of the previous research proves that, the performance of both PSO and FA are always competing each other in solving the linear and non-linear problems (Jones and Boizanté, 2011; Pal *et al.*, 2012). Nevertheless, the weakness of FA such as getting trapped into several local optima is an attractive area that could be focused more as a possible improvement during the evolutionary process. Thus, this is another issue that can be addressed in this study. A possible alternative in solving this problem is by introducing the scout position in firefly algorithm which can improve the quality solution of the original firefly algorithm. This algorithm is called advanced firefly algorithm (AFA).

The intent of the study is to attempt and explore the possibility of improving vehicle dynamics performance by introducing intelligent optimization techniques, namely, AFA, PSO and FA which is to be integrated with proportional-integral-derivative (PID) and fuzzy logic (FL) controllers by the use of semi-active MR dampers. The intelligent optimization techniques are effectively proposed to improve the accuracy of the parameter values for the proposed controllers instead the use of conventional optimization method.

The main works of this study include modelling of quarter vehicle suspension model, MR damper modelling, optimization algorithms, force tracking control and disturbance rejection control of semi-active MR damper system. This research is performed by first, through a simulation study of quarter vehicle and MR damper models using mathematical equations. Second, developments of proposed intelligent controllers are described to cancel out the road-induced disturbances effectively. Then, the research is continued with validation and evaluation of the proposed control scheme via experimental implementation in the platform of quarter vehicle suspension test rig and instrumented experimental vehicle.

1.3 Research Objectives

The main objectives of this study are described as the following:

1. To develop an advanced firefly algorithm as a new intelligent tuning method for PID and FL based controllers in comparison with PSO and FA tuning methods for improvement of the body vehicle suspension system.
2. To model a semi-active quarter vehicle model integrated with the MR damper actuation system through simulation studies.
3. To evaluate the performance of the proposed intelligent control strategies via simulation evaluation and experimental validation.

1.4 Scope of the Study

The scopes of the research are as follows:

1. In this study, simulation of two degree of freedom (DOF) quarter vehicle suspension system is developed via MATLAB Simulink environment. The parameters of the model are selected based real parameters on the quarter vehicle experimental rig developed in this research. The model can be assumed to have no slipping between tire and road surface and limited to vertical motion.

2. The MR damper characteristic is investigated in this study. A parametric approach using Spencer model is used to identify the actual damping force through the system based on force-velocity characteristic.
3. Intelligent control scheme are limited using PID and FL based controllers tuned using PSO, FA and AFA algorithms, and developed via simulation environment. The performances of the proposed control schemes are investigated in order to attenuate the unwanted effects of road disturbances and to improve ride comfort.
4. A quarter vehicle experimental rig completed with data acquisition (DAQ) and instrumentation system is developed. A semi-active suspension system with actuation system using the MR damper is integrated with the rig. The rig serves as a platform for the implementation of MR damper using the proposed control schemes.
5. The performance of the semi-active suspension system is evaluated based on the vertical body displacement, vertical body acceleration, suspension deflection and tire deflection only. Results are presented and analysed in time and frequency domains.

1.5 Research Contributions

A brief on the main contributions of this research is given as follows:

1. A new AFA is introduced to improve the weakness of the original FA and later to be compared with the FA and PSO.
2. This research gives details regarding the implementation of the AFA, FA and PSO tuned PID and FL controllers for the semi-active suspension system. This tuning method can be an alternative to the widely adopted heuristic or sensitivity analysis tuning method.
3. This research provides a detail development of the quarter vehicle suspension test rig with a small scale ratio and simple structure design. This experimental rig can be used as a platform to evaluate, validate and verify the performance of the proposed control schemes.

1.6 Significant of the Study

The main work of the suspension system is to support the vehicle weight and to isolate the vehicle body from any road profile disturbance. Thus, the semi-active MR damper is an alternative system that can be effectively used to improve the reliability of the passive system by implementing the active control device without considering very high power consumption. An appropriate controller is very important to overcome the damping constraint and to predict the optimum target force. Another important issue that can be addressed in this study would be the optimization method to identify the parameters of the controllers. It is said that, by using the conventional method approach, the parameters of the controllers could not give the best results since it was not fully covered for every single space values. Thus, it is important to study the intelligent optimization approach based on evolutionary method to improve the conventional method which is able to explore consistently for every single space values. It can also be noted that, the evolutionary method has the weaknesses that can be significantly addressed for the further improvement. Hence, it will be also a major investigation that can be focused in this study.

1.7 Research Methodology

This study begins with a literature review on the subject of interest related to the semi-active MR damper including MR damper modelling and MR damper control strategy. Since the optimization strategy based on evolutionary algorithm is one of the main interests in this study, an extensive review of the past research in different applications was also carried out.

The essential role in designing a semi-active suspension control depends on the accuracy of the semi-active damper model (Hudha, 2005). Thus, this study begins with the development of the MR damper model using a parametric Spencer model (Spencer *et al.*, 1997). The capability of the Spencer model with an appropriate parameter value is very important to predict the force-velocity and force-displacement characteristics of the semi-active MR damper. To ensure that the Spencer model used in this study is able to capture the same dynamic behaviour with the real model of the semi-active MR damper, an experimental work was conducted. The behaviour of the semi-active MR damper was investigated based on the different voltage that can be sent to the damper coils. The performance of the closed loop force control was also studied theoretically.

This study proceeds with the development of the control strategy if the semi-active MR damper model has been established accurately. In this study, the effectiveness of the PID and FL controllers to induce the disturbance rejection form road profile were investigated. The PSO, FA and AFA algorithms were investigated as an alternative optimization technique for tuning process of the proposed controllers. Performance evaluation of the control strategies including the proposed evolutionary algorithms were characterized by the ability of the proposed intelligent controllers to cancel out the unwanted motion from road disturbance transmitted to the body vehicle as well as their consistency in providing the same sign between the target force and damper velocity. The controller strategies were evaluated on a quarter vehicle model in both time and frequency domains.

The effectiveness of the control strategies with the best results in the simulation study to induce disturbance rejection were also followed by experimental validation using quarter vehicle test rig. The test rig was accomplished complete with its instrumentation system including the quarter vehicle mechanical system, electrical and electronics involving sensors (accelerometers, laser displacement sensor and force sensor) and PC-based interfacing, programming and control (software control using MATLAB Simulink). A road profile simulator unit was also part of the test rig that can provide the main disturbance element and to be controlled manually. Finally, the performance evaluation of the semi-active control system was performed on the quarter vehicle test rig. The proposed research strategy in the form of a flow chart is graphically shown in Figure 1.1.

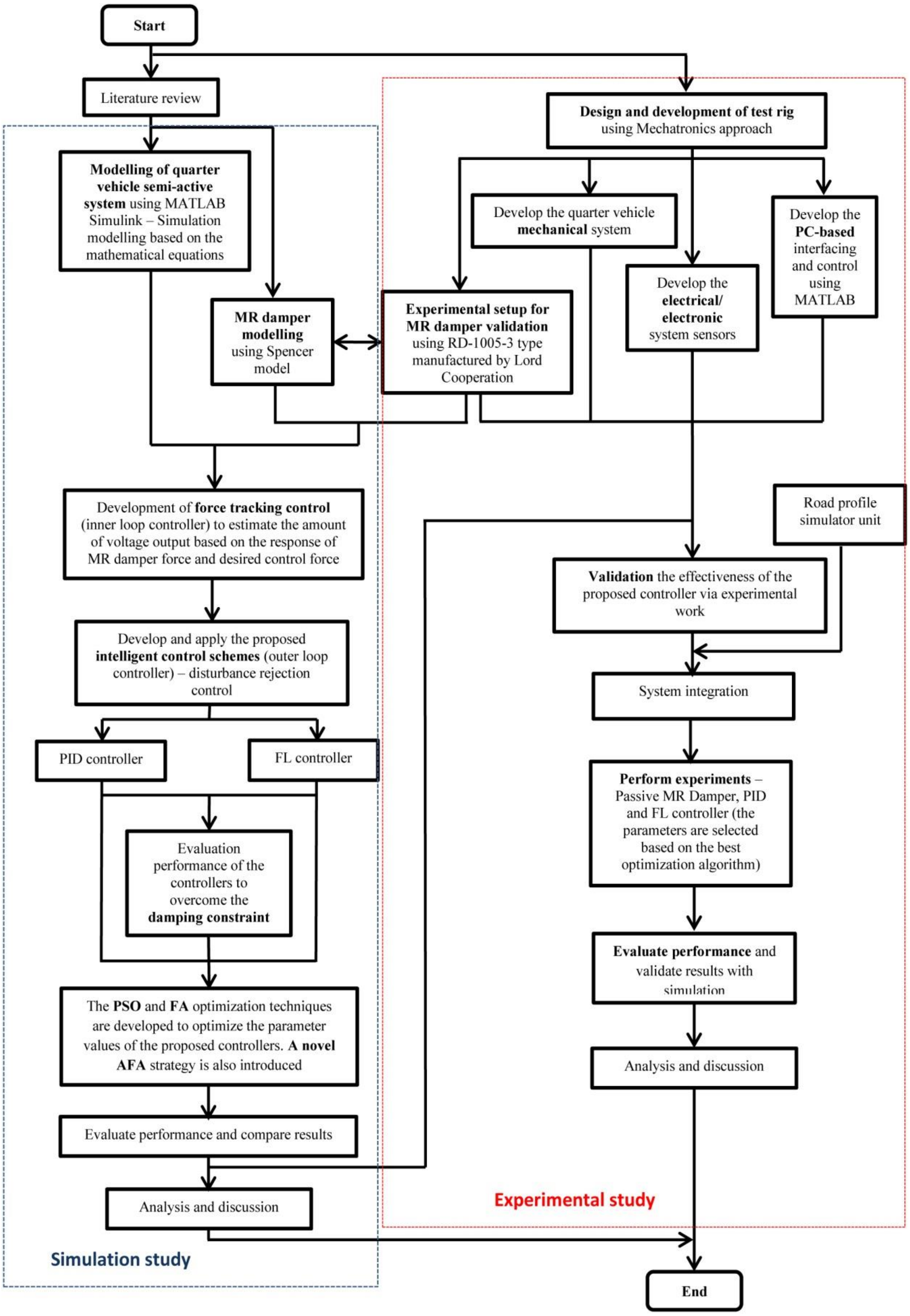

Figure 1.1 Research methodology flowchart

1.8 Thesis Outline

The thesis consists of seven chapters. Chapter 1 presents an introduction which includes an overview on the background of study, problem statement, research objectives and scopes. The contributions of the research, significance of the study, research methodology and the overall outline of this thesis are also presented.

Chapter 2 presents the literature review related to the subjects concerning this thesis. A review of suspension system, which includes vehicle classification as well as performance index of the MR damper system, is given thoroughly. In addition, brief overviews of the existing control strategies in all research areas are also highlighted in this chapter. Besides that, research gaps in the MR damper control strategy for vehicles' semi-active system is identified and discussed briefly.

Chapter 3 presents the simulation study of a quarter vehicle model and modelling of semi-active MR damper using a parametric Spencer model. An experimental work was also carried out to validate the Spencer model with the real damper model used in this study. Finally, model validation and force tracking control performance are also highlighted.

Chapter 4 describes an overview of the PID controller scheme concerning the road-induced disturbance rejection of semi-active system. The PID controller is first used to investigate the ability of this controller to overcome the damping constraint based on three different sinusoidal road profile disturbance (below sprung natural frequency, between sprung and unsprung natural frequencies and above unsprung natural frequency). Then, evolutionary algorithms based on the PSO, FA and AFA are described details as an alternative optimization technique to optimize the parameter values of the PID controller. A novel AFA as a new intelligent tuning method is also introduced in this chapter. Then, a new AFA is validated and tested using several benchmark functions in comparison with an original FA. The intelligent controller using PID tuned by PSO, FA and AFA are developed. The simulation study of three control schemes known as PID-PSO, PID-FA and PID-AFA are presented. The effectiveness of the semi-active suspension system and the active control schemes of the vehicle model are defined. A comparative study is conducted to evaluate the performance of these three control schemes for improvement of ride comfort of the quarter semi-active vehicle system. All simulation results will be presented based on frequency and time domains analysis. The performance of the suspension system is evaluated in terms of body vehicle displacement, body vehicle acceleration and tire acceleration.

In chapter 5, another controller approach, namely, the FL control scheme is presented in this chapter. A general working principle of the fuzzy logic controller is highlighted. The effectiveness of the proposed controller to overcome damping constraint is also investigated. The optimization tuning algorithms using the PSO, FA and AFA are implemented in order to optimize the gain scaling of each input and output of the FL control scheme. Three control schemes known as FL-PSO, FL-FA and FL-AFA are presented. The performance of the proposed control schemes are compared to the passive suspension system. Finally, the advantages of the best evolutionary algorithm for both FL and PID control schemes over the passive system are also highlighted.

Chapter 6 presents the design and development of the experimental quarter vehicle suspension test rig equipped with the MR damper actuation system. The design of the vehicle system, measurement instruments and interfaces between the data signals and computer are further elaborated. The effectiveness of the control strategies with the best results in the simulation study are evaluated and validated experimentally. Comparative assessments of all controllers are presented. Finally, the limitation of the experimental study and differences over the simulation study is also highlighted.

Finally, Chapter 7 presents the conclusion of the research project. Recommendations of future works for further improvement are also discussed.

REFERENCES

Abachizadeh, M., Reza, M., Yazdi, H., & Yousefi-koma, A. (2010). Optimal Tuning of PID Controllers Using Artificial Bee Colony Algorithm. *IEEE International Conference on Advanced Intelligent Mechatronics*. July 6-9. Montreal, 379-384.

Aggarwal, M. L. (2012). Fuzzy of Semi-Active Quarter Car Suspension System With MR Damper. *Proceedings of the National Conference on Trends and Advances in mechanical Engineering*, 296–304.

Aggarwal, M. L. (2014). Fuzzy Logic Control of a Semi-Active Quarter Car System. *International Journal of Mechanical, Aerospace, Industrial and Mechatronic Engineering*, *8*(1), 154–158.

Ahmadian, M., & Pare, C. A. (2000). A Quarter-Car Experimental Analysis of Alternative Semiactive Control Methods. *Journal of Intelligent Material Systems and Structures*, *11*(8), 604–612.

Al-Holou, N., Joo, D. S., & Shaout, A. (1995). The Development of Fuzzy Logic Based Controller for Semi-Active Suspension System. *Circuits and Systems, 1994., Proceedings of the 37th Midwest Symposium* (Vol. 2). August 3-5. Lafayette, LA, 1373- 1376.

Al-wagih, K. (2015). Improved Firefly Algorithm for Unconstrained Optimization Problems. *International Journal of Computer Applications Technology and Research*, *4*(1), 77–81.

Albertos, P., & Sala, A. (1998). Fuzzy Logic Controllers. Advantages and Drawbacks. *VIII International Congress of Automatic Control*, *3*, 833–844.

Aleyne, A., & Hedrick, J. K. (1992). Nonlinear Control of a Quarter Car Active Suspension. *American Control Conference*. June 24-26. Chicago, IL, USA, 21-25.

Ali, O. A. M., Ali, A. Y., & Sumait, B. S. (2015). Comparison Between the Effects of Different Types of Membership Functions on Fuzzy Logic Controller

Performance. *International Journal of Emerging Engineering Research and Technology*, *3*(3), 76–83.

Ambhore, N. H., Hivarale, S. D., & Pangavhane, D. R. (2013). A Comparative Study of Parametric Models of Magnetorheological Fluid Suspension Dampers. *International Journal of Mechanical Engineering and Technology*, *4*(1), 222–232.

Ang, K. H., Chong, G., & Li, Y. (2005). PID Control System Analysis , Design , and Technology. *IEEE Transaction on Control System and Technology*, *13*(4), 559–576.

Arslan, A., & Kaya, M. (2001). Determination of Fuzzy Logic Membership Functions using Genetic Algorithms. *Fuzzy Sets and Systems*, *118*(2), 297–306.

Ashfak, A., Saheed, A., Rasheed, K. K. A., & Jaleel, J. A. (2009). Design, Fabrication and Evaluation of MR Damper. *World Academy of Science, Engineering and Technology*, *3*(5), 312–317.

Ashtekar, J. B., & Thakur, A. G. (2014). Simulink Model of Suspension System and It's Validation on Suspension Test Rig. *International Journal of Mechanical Engineeroing and Robotics Research*, *3*(3), 811–818.

Azad, S. K. (2011). Optimum Design of Structures using an Imroved Firefly Algortihm. *International Journal of Optimization in Civil Engineering*, *2*, 327–340.

Bakar, S. A. A., Samin, P. M., Jamaluddin, H., Rahman, R. A., Masuda, R., & Hashimoto, H. (2011). Modelling of Magnetorheological Semi-Active Suspension System Controlled by Semi-Active Damping Force Estimator. *Int. J. Computer Applications in Technology*, *42*(1), 49–64.

Barros, R. C., Baratta, A., Corbi, O., Paredes, M. M., & Frias, R. R. (2009). Some Research on Control of Vibrations In Civil Engineering Under Covicocepad Project. *3rd International Conference on Integrity, Reliability and Failure*. July 20-24. Portugal, 1-28.

Bendjeghaba, O., Ishak, B. S., & Zemmour, N. (2013). Firefly Algorithm for Optimal Tuning of PID Controller Parameters. *4th International Conference on Power Engineering*. May 13-17. Istanbul, Turkey,1293-1296.

Bhushan, B., & Pillai, S. S. (2013). Particle Swarm Optimization and Firefly Algorithm : Performance Analysis. *Advance Computing Conference (IACC), 2013 IEEE 3rd International*. Feb 22-23. Ghaziabad, 746-751.

Bidar, M., & Kanan, H. R. (2013). Modified Firefly Algorithm Using Fuzzy Tuned Parameters. *13th Iranian Conference of Fuzzy System*. August 27-29. Qazvin, Iran, 1-4.

Biglarbegian, M., Melek, W., & Golnaraghi, F. (2008). A Novel Neuro-Fuzzy Controller to Enhance the Performance of Vehicle Semi-Active Suspension Systems. *Vehicle System Dynamics*, *46*(8), 691–711.

Boada, M. J. L., Calvo, J. A., Boada, B. L., & Díaz, V. (2011). Modeling of a Magnetorheological Damper by Recursive Lazy Learning. *International Journal of Non-Linear Mechanics*, *46*(3), 479–485.

Bogdan, S. (2002). Parametric idenification of MR linear automotive size damper. *Journal of Theoretical and Applied Mechanics*, *3*(40), 703–722.

Bogdan, S., & Filus, J. (2003). Analysis of Parametric Models of MR Linear Damper. *Journal of Theoretical and Applied Mechanics*, *41*(2), 215–240.

Bouc, R. (1967). Forced Vibration of Mechanical Systems with Hysteresis. *Proceedings of the Fourth Conference on Nonlinear Oscillation* (Vol. 46). Prague, Czechoslovakia, 315.

Bourke, M. M. (1995). *Self Learning Predictive Control Using Relational Based Fuzzy Logic*. PhD Thesis, University of Alberta.

Caponetto, R., Diamante, O., Fargione, G., Risitano, A., & Tringali, D. (2003). A Soft Computing Approach to Fuzzy Sky-hook Control of Semiactive Suspension. *IEEE Transactions on Control Systems Technology*, *11*(6), 786–798.

Chantranuwathana, S., & Peng, H. (1999). Adaptive Robust Control for Active Suspensions. *Procceedings of the American Control Conference*. June. San Diego, California, 1702-1706.

Chauhan, S. (2016). Optimization of Fuzzy Controller Parameter by Using a Firefly Algorithm. *International Journal of Engineering Studies and Technical Approach*, *2*(3).

Chiha, I., Liouane, N., & Borne, P. (2012). Tuning PID Controller using Multiobjective Ant Colony Optimization. *Applied Computational Intelligence and Soft Computing*, *2012*(1), 1–7.

Choi, S. B., Dong, X. M., & Liao, C. R. (2008). Fuzzy Neural Network Control for Vehicle Stability Utilizing Magnetorheological Suspension System. *Journal of Intelligent Material Systems and Structures*, *20*(4), 457–466.

Darus, R., & Sam, Y. M. (2009). Modeling and Control Active Suspension System for a Full Car Model. *2009 5th International Colloquium on Signal Processing & Its Application* (Vol. 4). March 6-8. Kuala Lumpur, Malaysia, 13-18.

Dong, X., & Yu, M. (2013). Genetic Algorithm Based Fuzzy Logic Control for a Magneto-rheological Suspension. *Journal of Vibration and Control*, *20*(9), 1343–1355.

Du, H., Yim Sze, K., & Lam, J. (2005). Semi-Active H∞ Control of Vehicle Suspension with Magneto-rheological Dampers. *Journal of Sound and Vibration*, *283*(3-5), 981–996.

Ehrgott, R. C., & Masri, S. F. (1992). Modeling The Oscillatory Dynamic Behaviour of Electrorheological Materials in Shear. *Smart Material and Structure*, *1*, 275–285.

Fallah, M. S., Bhat, R., & Xie, W. (2010). H∞ Robust Control of Semi-Active Macpherson Suspension System: New Applied Design. *Vehicle System Dynamics*, *48*(3), 339–360.

Fang, Z., Shu, W., Du, D., Xiang, B., He, Q., & He, K. (2011). Semi-Active Suspension of a Full-Vehicle Model Based on Double-Loop Control. *Procedia Engineering*, *16*, 428–437.

Farahani, S. M., Abshouri, A. A., Nasiri, B., & Meybodi, M. R. (2011). A Gaussian Firefly Algorithm. *International Journal of Machine Learning and Computing*, *1*(5), 448–453.

Fujitani, H., Tomurac, T., Hiwatashid, T., Shiozakie, Y., Hatac, K., Sunakodab, K., & Mopjshita, S. (2003). Development of 400kN Magnetorheological Damper For a Real Base-Isolated Building. *Smart Structures and Materials 2003: Damping and Isolation*, *5052*(2003), 265–276.

Gao, W., Zhang, N., & Du, H. P. (2007). A Half-Car Model For Dynamic Analysis Of Vehicles With Random Parameters. *5th Australasian Congress on Applied Mechanics, ACAM 2007* (Vol. 1). December 10-12. Brisbane, Australia.

Gavin, H., Hoagg, J., & Dobossy, M. (2001). Optimal Design of MR Dampers. *Smart structures for Improved Seismic Performance*, (8), 225–236.

Giuclea, M., Sireteanu, T., Stancioiu, D., & Stammers, C. (2004). Modelling of Magnetorheological Damper Dynamic Behaviour by Genetic Algorithms Based Inverse Method. *Proceeding of The Romanian Academy*, *5*(1), 1–10.

Goncalves, F. D. (2005). *Characterizing the Behavior of Magnetorheological Fluids at High Velocities and High Shear Rates by Characterizing the Behavior of Magnetorheological Fluids at High Velocities and High Shear Rates*. Phd Thesis, Virginia Polytechnic Institute and State University.

Guidaa, D., Nilvetti, F., & Pappalardo, C. M. (2010). Parameter Identification of a Full-Car Model for Active Suspension Design. *Journal of Achievement in Materials and Manufacturing Engineering*, *40*(2), 138–148.

Guo, D. L., Hu, H. Y., & Yi, J. Q. (2004). Neural Network Control for a Semi-Active Vehicle. *Journal of Vibration and Control*, *10*, 461–471.

Hanafi, D. (2010). PID Controller Design for Semi-Active Car Suspension Based on Model from Intelligent System Identification. *2010 Second International Conference on Computer Engineering and Applications*. March 19-21. Bali, Indonesia, 60-63.

Hingane, A. A., Sawant, P. S. H., Chavan, P. S. P., & Shah, P. A. P. (2013). Analysis of Semi Active Suspension System with Bingham Model Subjected to Random Road Excitation using MATLAB / Simulink. *IOSR Journal of Mechanical and Civil Engineering*, *3*(1), 1–6.

Hsiao, W. Y., & Chiang, H. Y. (2012). Observer-Based Fuzzy Sliding Mode Control for Vehicle Semi-Active Suspensions. *2012 IEEE International Conference on Fuzzy Systems*. June 10-15. Brisbane, QLD, 1-6.

Hudha, K. (2005). *Non-Parametric Modeling and Modified Hybrid Skyhook Groundhook Control of Magnetorheological Dampers for Automotive Suspension System*. PhD Thesis, Universiti Teknologi Malaysia.

Hudha, K., Jamaluddin, H., Samin, P. M., & Rahman, R. A. (2008). Non-parametric Linearised Data Driven Modelling and Force Tracking Control of a Magnetorheological Damper. *International Journal of Vehicle Design*, *46*(2), 250–269.

Ihsan, S., & Blanchard, E. D. (2009). Ride Performance Analysis of Half-Car Model for Semi-Active System using RMS as Performance Criteria Ride Performance Analysis of Half-Car Model for Semi-Active System using RMS as Performance Criteria. *Shock and Vibration*, *16*(6), 593–605.

Ikhouane, F., Mañosa, V., & Rodellar, J. (2007). Dynamic Properties of the Hysteretic Bouc-Wen Model. *Systems & Control Letters*, *56*(3), 197–205.

Jin, Z., & Bimal K., B. (2002). Evaluation of Membership Functions for Fuzzy Logic Controlled Induction Motor Drive. *28th Annual Conference of the Industrial Electronics Society IECONO2* (Vol. 1). Nov 5-8. Spain, 229-234.

Jones, K. O., & Boizanté, G. (2011). Comparison of Firefly Algorithm Optimisation, Particle Swarm Optimisation and Differential Evolution. *Proceedings of the 12th International Conference on Computer Systems and Technologies - CompSysTech '11* (Vol. 578). June 16-17. Vienna, Austria, 191-197.

Jones, R. P., Cherry, A. S., & Farral, S. D. (1994). Application of Intelligent Control in Automotive Vehicles. *IEEE International Conference on Control '94*. March 21-24. Coventry, U.K, 159- 164.

Karaboga, D. (2005). An Idea Based on Honey Bee Swarm for Numerical Optimization. *Technical Report-tr06, Erciyes University, Engineering Faculty, Computer Engineering Department*, *200*, 1–10.

Karnopp, D., Crosby, M. J., & Harwood, R. A. (1974). Vibration Control using Semi-Active Force Generators. *Journal of Engineering for Industry*, *96*(2), 619–626.

Kasemi, B., Muthalif, A. G. A., Rashid, M. M., & Fathima, S. (2012). Fuzzy-PID Controller for Semi-Active Vibration Control using Magnetorheological Fluid Damper. *Procedia Engineering*, *41*, 1221–1227.

Katal, N., & Singh, S. K. (2012). Optimization of PID Controller for Quarter-Car Suspension System using Genetic Algorithm. *International Journal of Advance Research in Computer Engineering & Technology*, *1*(7), 30–32.

Kaya, M. A., Bayrakceken, M. K., & Celik, E. (2011). Integrated Identification and Control of Magneto-rheological Dampers for Manned Space Missions. *Proceedings of 5th International Conference on Recent Advances in Space Technologies - RAST2011*. June 9-11. Istanbul, 89-94.

Kciuk, M., Kciuk, S., & Turczyn, R. (2009). Magnetorheological Characterisation of Carbonyl Iron Based Suspension. *Journal of Achievement in Materials and Manufacturing Engineering*, *33*(2), 135–141.

Kennedy, J., & Eberhart, R. (1995). Particle Swarm Optimization. *Proceedings of ICNN'95 - International Conference on Neural Networks* (Vol. 4). Nov 27-Dec 1. Perth, Australia, 1942-1948.

Khiavi, A. M., Mirzaei, M., & Hajimohammadi, S. (2013). A New Optimal Control Law For The Semi-Active Suspension System Considering the Nonlinear

Magneto-rheological Damper Model. *Journal of Vibration and Control*, *20*(14), 2221–2233.

Klausen, A., Tørdal, S. S., Karimi, H. R., Robbersmyr, K. G., Jecmenica, M., & Melteig, O. (2014). Firefly Optimization and Mathematical Modeling of a Vehicle Crash Test Based on Single-Mass. *Journal of Applied Mathematics*, *2014*, 1–10.

Koch, G., Pellegrini, E., Spirk, S., & Lohmann, B. (2010). Design and Modeling of a Quarter-Vehicle Test Rig for Active Suspension Control. *Technical reports on Automatic Control*, *5*(1), 1–28.

Koo, J.-H., Goncalves, F. D., & Ahmadian, M. (2004). Investigation of the Response Time of Magnetorheological Fluid Dampers. (K.-W. Wang, Ed.)*Smart Structures and Materials 2004: Damping and Isolation*, *5386*, 63–71.

Krishnan, A. (2013). A Comparison Between Passive & Semi Active Suspension Systems. *International Journal of Innovative Research in Science, Engineering and Technology*, *2*(6), 2412–2416.

Kumanan, D., & Nagaraj, B. (2013). Tuning of Proportional Integral Derivative Controller based on Firefly Algorithm. *Systems Science & Control Engineering*, *1*(1), 52–56.

Li, C., & Zhao, Q. (2010). Fuzzy Control of Vehicle Semi-Active Suspension with MR Damper. *2010 WASE International Conference on Information Engineering* (Vol. 426). August, 14-15. Beidaihe, Hebei, 426-429.

Li, H., Tang, C., & Yang, D. (2009). Simulation of Semi-Active Air Suspension Based on Neural Network-Adaptive. *2009 Second International Conference on Intelligent Computation Technology and Automation* (Vol. 1). Oct 10-11. Changsha, Hunan, 1-4.

Liu, H., Nonami, K., & Hagiwara, T. (2005). Semi-Active Fuzzy Sliding Mode Control of Full Vehicle and Suspensions. *Journal of Vibration and Control*, *11*(8), 1025–1042.

Long-ming, G., Shi, W.-K., & Wei, L. (2012). Vehicle Base on Magneto-rheological Technology. *9th International Conference of Fuzzy Systems and Knowledge Discovery*. May 29-31.Sichuan, 2565-2568.

Luthra, J., & Pal, S. K. (2011). A Hybrid Firefly Algorithm using Genetic Operators for the Cryptanalysis of a Monoalphabetic Substitution Cipher. *2011 World Congress on Information and Communication Technologies*, 202–206.

Madasamy, G., & Ravichandran, C. S. (2015). Optimal Tuning of PID Controller by Firefly Algorithm in AVR System. *International Journal for Research in Applied Science and Engineering Technology*, *3*(3), 605–609.

Madić, M., Marković, D., & Radovanović, M. (2013). Comparison of Meta-heuristic algorithms for Solving Machiningg Optimization Problems. *Mechanical Engineering*, *11*(1), 29–44.

Magdalena, L. (1997). Adapting the Gain of an FLC With Genetic Algorithms. *International Journal of Approximate Reasoning*, *17*(97), 327–349.

Marcelo, T. A., Rafikov, M., & Manoel Balthazar, J. (2009). An Intelligent Controller Design for Magnetorheological Damper Based on a Quarter-Car. *Journal of Vibration and Control*, *15*(12), 1907–1920.

Masten, M. K. (1998). Electronics: The Intelligence in Intelligent Control. *Annual Reviewa in Control*, *22*, 1–11.

Matsushita, H., & Matsumoto, D. (2012). Network-Structured Firefly Algorithm. *IEEE Workshop on Nonlinear Circuit Networks*, *2*(3), 48–50.

Mazlan, S. A. (2008). *The Behaviour of Magnetorheological Fluids in Squeeze Mode*. PhD Thesis, Dublin City Univercity.

Mazlan, S. A., Ekreem, N. B., & Olabi, A. G. (2007). The Performance of Magnetorheological Fluid in Qqueeze Mode. *Smart Materials and Structures, 16*(5), 1678–1682.

Mitchell, M. (1995). Genetic Algorithms : An Overview 1. *Complexity*, *1*(1), 31–39.

Mitra, A. C., & Benerjee, N. (2014). Vehicle Dynamics for Improvement of Ride Comfort using a Half-Car Bondgraph Model. *International Journal of Researchers, Scientists and Developers, 2*(1), 1–5.

Mori, T., & Nilkhamhang, I. (2007). Adaptive Semi-Active Control of Suspension System with MR Damper. *Adaptation and Learning in Control and Signal Processing*, *9*(1), 191–196.

Naudé, A. F., & Snyman, J. A. (2003). Optimisation of Road Vehicle Passive Suspension Systems. Part 1. Optimisation Algorithm and Vehicle Model. *Applied Mathematical Modelling, 27*(4), 249–261.

Nguyen, Q.-H., Choi, S.-B., & Wereley, N. M. (2008). Optimal Design of Magnetorheological Valves via a Finite Element Method Considering Control Energy and a Time Constant. *Smart Materials and Structures, 17*(2), 1–12.

Pal, S. K., Rai, C. ., & Singh, A. P. (2012). Comparative Study of Firefly Algorithm and Particle Swarm Optimization for Noisy Non-Linear Optimization Problems. *International Journal of Intelligent Systems and Applications*, *4*(10), 50–57.

Panasonic Electric Works AG. (2005). Micro laser displacement sensor. *Micro Laser Displacement Sensor*.

Park, D. W., Choi, S. B., & Choi, Y. T. (2000). A Sliding Mode Control of a Suspension System via Hardware in-the-loop Simulation. *Transactions of the ASME*, *122*, 2–9.

Parlak, Z., Engin, T., & Şahin, İ. (2013). Optimal Magnetorheological Damper Configuration Using the Taguchi Experimental Design Method. *Journal of Mechanical Design*, *135*(8), 1–9.

Priyandoko, G., & Baharom, M. Z. (2013). PSO-Optimized Adaptive Neuro-Fuzzy System for Magneto-rheological Damper Modelling. *International Journal of Applied Electromagnetics and Mechanics*, *41*, 301–312.

Qazi, A. J., Farooqui, U. a., Khan, A., Khan, M. T., Mazhar, F., & Fiaz, A. (2013). Optimization of Semi-active Suspension System Using Particle Swarm Optimization Algorithm. *AASRI Procedia*, *4*, 160–166.

Qazi, A. J., Silva, C. W. De, Khan, A., & Khan, M. T. (2014). Performance Analysis of a Semiactive Suspension System with Particle Swarm Optimization and Fuzzy Logic Control. *The Scientific World Journal*, *2014*, 1–12.

Rahman, M., Mahbubur Rashid, M., Muthalif, A. G. A., & Kasemi, B. (2012). Evaluation of Different Control Policies of Semi-Active MR fluid Damper of a Quarter-Car Model. *Applied Mechanics and Materials*, *165*, 310–315.

Rajeswari, K., & Lakshmi, P. (2010). PSO Optimized Fuzzy Logic Controller for Active Suspension System. *2010 International Conference on Advances in Recent Technologies in Communication and Computing*. Oct 16-17. Kottayam, 278-283.

Rao, T. R. M., Rao, G. V., & Purushottam, A. (2010). Analysis of Passive and Semi Active Controlled Suspension System Forride Comfort in an Omnibus Passing Over a Speed Bum. *International Journal of Research and Reviews in Applied Sciences*, *5*(1), 7–17.

Rashid, M M, Hussain, M. A., Rahim, N. A., & Momoh, J. S. (2007). Development of Semi-Active Car Suspension Control System using Magneto-rheological

Damper Model. *International Journal of Mechanical and Materials Engineering (IJMME)*, *2*(2), 93–108.

Rashid, Muhammad Mahbubur, Rahim, N. A., Hussain, M. A., & Rahman, M. A. (2011). Analysis and Experimental Study of Magnetorheological-Based Damper for Semiactive Suspension System using Fuzzy Hybrids. *IEEE Transactions on Industry Applications*, *47*(2), 1051–1059.

Riahi, A., & Balochian, S. (2012). Control Design of a Semi Active Suspension Using Optimal , PID and Sliding Mode Theory. *Acta Electrotehnica*, 144–147.

Robinson, J., & Rahmat-samii, Y. (2004). Particle Swarm Optimization in Electromagnetics. *IEEE Transaction on Antennas and Propagation*, *52*(2), 397–407.

Rossi, C., & Lucente, G. (2004). H∞ Control of Automotive Semi-Active Suspensions. *Proceedings of the 1st IFAC Symposium on Advances in Automotive Control (AAC)*. Salemo, Italy,1-7.

Saad, M. S., Jamaluddin, H., & Darus, I. Z. M. (2012). PID Controller Tuning using Evolutionary Algorithms. *WSEAS Transaction on Systems and Control*, *7*(4), 139–149.

Samin, P. M. (2010). *Hybrid Stability Augmentation System-Force Control Of Semi-Active Suspension with Magnetorheological Damper*. PhD Thesis, Universiti Teknologi Malaysia.

Schurter, K. C., & Roschke, P. N. (2000). Fuzzy Modeling of a Magnetorheological Damper using ANFIS. *Fuzzy Systems, 2000. FUZZ IEEE 2000. The Ninth IEEE International Conference* (Vol. 1). May 7-10. San Antonio, TX, 122-127.

Senthilnath, J., Omkar, S. N., & Mani, V. (2011). Clustering Using Firefly Algorithm: Performance Study. *Swarm and Evolutionary Computation*, *1*(3), 164–171.

Spencer, B. F., Dyke, S. J., Sain, M. K., & Carlson, J. D. (1997). Phenomenological Model of a Magnetorheological Damper. *Journal of Engineering Mechanics*, 1–23.

Storn, R., & Price, K. (1995). Differential Evolution - A Simple and Efficient Adaptive Scheme for Global Optimization over Continuous Spaces. *ICSI*, *3*, 1–12.

Taylor, P., Elmadany, M. M., & Abduljabbar, Z. S. (1999). Linear Quadratic Gaussian Control of a Quarter-Car Suspension Linear Quadratic Gaussian

Control of a Quarter-Car Suspension. *Vehicle System Dynamics : International Journal of Vehicle Mechanics and Mobility*, *32*(6), 479–497.

Tilahun, S. L., & Ong, H. C. (2012). Modified Firefly Algorithm. *Journal of Applied Mathematics*, 1–12.

Truong, D. Q., & Ahn, K. K. (2012). MR Fluid Damper and its Application to Force Sensorless Damping Control System. *Smart Actuation and Sensing Systems*, 383–424.

Tsang, H. H., Su, R. K. L., & Chandler, A. M. (2006). Simplified Inverse Dynamics Models for MR Fluid Dampers. *Engineering Structures*, *28*(3), 327–341.

Tu, F., Yang, Q., He, C., & Wang, L. (2012). Experimental Study and Design on Automobile Suspension Made of Magneto-Rheological Damper. *Energy Procedia*, *16*, 417–425.

Turkay, S., & Akcay, H. (2007). Effect of Tire Damping on the Ride Performance Potential of Active Suspension Systems. *SICE Annual Conference*. Sept. 17-20. Kagawa University, Japan,1209-1216.

Ubaidillah, Hudha, K., & Jamaluddin, H. (2011). Simulation and experimental evaluation on a skyhook policy-based fuzzy logic control for semi-active suspension system. *Int. J. Structural Engineering*, *2*(3), 243–272.

Unaune, D. R., Pawar, M. J., & Mohite, S. S. (2011). Ride Analysis of Quarter Vehicle Model. *Proceeding of the 1st international Conference on Modern Trends in Industrial Engineering*. November 17-19. Gujarat, India, 1-6.

Verros, G., Natsiavas, S., & Papadimitriou, C. (2005). Design Optimization of Quarter-Car Models with Passive and Semi-Active Suspensions under Random Road Excitation. *Journal of Vibration and Control*, *11*(5), 581–606.

Vranc, D., Peng, Y., & Strmcnik, S. (1999). A New PID Controller Tuning Method Based on Multiple Integrations. *Control Engineering Practice*, *7*, 623–633.

Vékás, L. (2008). Ferrofluids and Magnetorheological Fluids. *Advances in Science and Technology*, *54*, 127–136.

Wei-min, C., Hong-hui, Z., & Rong, L. C. (2005). Modeling of Magneto-rheological Damper with Neural Network. *Journal of China Univerity of Mining and Technology*, *16*, 50–52.

Wen, Y. K. (1976). Method for Random Vibration of Hysteresis Systems. *Journal of Engineering Mechanics (American Society of Civil Engineers)*, *102*(2), 249–263.

Wu, C., Lin, Y. C., & Hsu, D. S. (2008). Performance Test and Mathematical Model Simulation of MR Damper. *The 14th World Conference on Earthquake Engineering*. Oct 12-17. Beijing, China.

Yang, G. (2002). Large-scale MR fluid Dampers : Modeling and Dynamic Performance Considerations. *Engineering Structures, 24*, 309–323.

Yao, J., Shi, W. K., Zheng, J. Q., & Zhou, H. P. (2012). Development of a Sliding Mode Controller for Semi-Active Vehicle Suspensions. *Journal of Vibration and Control*, *19*(8), 1152–1160.

Yao, K., Zhao, X., & Hou, Z. (2009). Damping Characteristics Modeling and Simulation of MR Damper. *2009 International Conference on Information Management, Innovation Management and Industrial Engineering*. Dec 26-29. Xián, 492-495.

Yaseen, S. G., & Al-Slamy, N. M. A. (2008). Ant Colony Optimization. *International Journal of Computer Science and Network Security*, *8*(6), 351–357.

Yatim, H. M., & Darus, I. Z. M. (2014). Self-Tuning Active Vibration Controller using Particle Swarm Optimization for Flexible Manipulator System. *WSEAS Transaction on Systems and Control*, *9*, 55–66.

Ye, M., & Wang, X. (2007). Parameter Estimation of the Bouc–Wen Hysteresis Model using Particle Swarm Optimization. *Smart Materials and Structures*, *16*(6), 2341–2349.

Ye, M. Y., Jiang, H., Xu, Y. S., & Wang, X. D. (2010). Bouc-Wen Hysteresis Model Parameter Identification by Means of Hybrid Intelligent Technique. *Advanced Materials Research*, *108*(1), 1397–1402.

Yerrawar, R. N., Arakerimath, R. R., Rajendra, P. S., & Sambhaji, W. P. (2014). Performance Comparison of Semi-Active Suspension and Active Suspension System using MATLAB / Simulink. *International Journal of Innovative Research in Science, Engineering and Technology*, *3*(12), 18293–18299.

Yi, K., & Song, B. S. (1999). A New Adaptive Sky-hook Control of Vehicle Semi-Active Suspensions. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *213*(3), 293–303.

Yokoyama, M., Hedrick, J. K., Toyama, S., & Hall, E. (2001). A Model Following Sliding Mode Controller for Semi-Active Suspension Systems with MR

Dampers. *Proceedings of the American Control Conference*. Jun 25-27. Arlington, VA, 2652-2657.

Yu, S., Yang, S., & Su, S. (2013). Self-Adaptive Step Firefly Algorithm. *Journal of Applied Mathematics*, *2013*(1), 1–9.

Zareh, S. H., & Sarrafan, A. (2012). Intelligent Neuro-Fuzzy Application in Semi-Active Suspension System. *Fuzzy Logic-Controls, Concepts, Theories and Applications*, 237–252.

Zawartka, M. (2014). Sensitivity Analysis of the MR Damper Model Parameters on the Vibration Transmissibility Characteristic. *Control Conference (ICCC), 2014 15th International Capathian*. May 28-30. Velke Karlovice, 699-704.

Zhang, J. J., & Xu, Z. Q. (2010). Studying of Fuzzy Logic Control Semi-Active Suspension Based on ADAMS/Car and MATLAB/Simulink. *Advanced Materials Research*, *143*, 956–960.