UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A ROBUST INTELLIGENT CONTROLLER FOR A SEMI-ACTIVE CAR SUSPENSION SYSTEM

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By

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Chair : Azizan B. As'arry, PhD
Faculty : Engineering

In pursuite of comfortable driving in unpaved and off-roads, intelligent methods are used to improve the suspension systems in the vehicles. Semi-active suspension systems outperformed passive and active suspension systems because it contains an intelligent actuator that can give the appropriate force to dissipate unwanted vibration using intelligent and real-time controllers. This research examines Magneto-rheological (MR) fluid damper with a Fuzzy-PID controller, one of the most extensively intelligent semi-active suspension system's actuators researched. However, the Fuzzy logic algorithm used in the Fuzzy-PID controller cannot be wholly considered as a real-time controller; since it is fuzzy rules are designed offline and according to a previous knowledge base, which may not cope with the instant, unexpected vibrations that may occur. Commonly, the Fuzzy rules are optimized using offline optimization methods such as Differential Evolutionary (DE), Particle Swarms Optimization (PSO), or Artificial Neural Network (ANN) algorithms. In this research, Differential Evolution (DE) algorithm is modified to enhance the Fuzzy logic output gains to increase the performance of PID portion of the Fuzzy-PID controller. To ensure stability and robustness of the developed system, an active force controller (AFC) was added and tested to validate the final AFC-Fuzzy-DE-PID controller. The developed AFC-Fuzzy-DE-PID model was tested in two manners, first by simulation using MATLAB Simulink with sinusoidal and random disturbances. Then the model was tested experimentally in a quarter car test rig using different disturbances by means of a pneumatic actuator as an excitation. The test rig was developed at the control lab, Faculty Of Engineering in UPM. Results of the simulation tests for the developed controller showed that it has improved the vehicle's ride comfort by 23% - 62% better than the Fuzzy-DE-PID controller and both the Fuzzy-PID and the passive system, respectively, in sinusoidal disturbance condition. While in the random disturbance, the AFC-Fuzzy-DE-PID improved the vehicle's ride comfort by 48%, 83%, and 27% better than the Fuzzy-DE-PID, Fuzzy-PID, and the passive system, respectively. In the experimental tests on sinusoidal disturbance, the AFC-Fuzzy-DE-PID improved

the ride comfort by range of 0.4% - 2% better than the Fuzzy-DE-PID, range of 6%-14% better than the Fuzzy-PID, and range of 30%-51% better than the passive system. While on the random disturbance of the experimental test, the ride comfort improved 1%, 3%, and 4% better than the Fuzzy-DE-PID, Fuzzy-PID, and the passive system, respectively. By using this developed controller in any other real-time application, it will improve the performance to the highest levels without the need for a previous knowledge base for designing a real-time Fuzzy-PID controller.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN PENGAWAL CERDAS YANG TEGUH UNTUK SISTEM SUSPENSI KERETA SEPARUH AKTIF

Oleh

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Kaedah pintar adalah salah satu cara untuk menambahbaik sistem suspensi di dalam kenderaan tambahan lagi untuk mencapai pemanduan yang selesa di jalan yang tidak rata dan tidak berturap. Sistem suspensi separa aktif mengatasi sistem sedia ada iaitu pasif dan aktif kerana ia mengandungi penggerak pintar yang mampu untuk memberikan daya yang sesuai untuk mengurangkan getaran yang tidak diingini menggunakan masa-nyata papan pintar. Penyelidikan ini mengkaji peredam bendalir Magneto-rheologi (MR) dengan sistem pintar Fuzzy-PID. Ia merupakan salah satu penggerak sistem suspensi pintar yang telah dikaji secara intensif dan impaknya. Walaubagaimanapun, algoritma logik Fuzzy yang digunakan di dalam pengawal pintar Fuuzy-PID tidak boleh dikategorikan sebagai pengawal masa-nyata sepenuhnya. Ini kerana ia telah direka secara di luar talian dan hanya mengikut pengkalan data yang sedia ada yang mungkin tidak dapat dilihat jika kajian dijalankan untuk getaran serta-merta atau lain-lain faktor yang menyumbang kepadanya. Lazimnya, peraturan Fuuzy dioptimumkan menggunakan kaedah secara luar talian seperti algoritma Evolusi Pembezaan (Differential Evolutionary), Particle Swarms Optimization (PSO), Artificial Neural Network (ANN). Di dalam kajian ini, algoritma Differential Evolution (DE) diubahsuai untuk menganjakkan pengeluaran logik Fuzzy untuk meningkatkan prestasi di peringkat pengawal Fuzzy-PID. Demi memastikan kestabilan dan keteguhan sistem yang dicadangkan, Pengawal Daya Aktif (AFC) telah ditambahkan ke dalam sistem dan diuji untuk mengesahkan peringkat akhir model AFC-Fuzzy-DE-PID. Model AFC-Fuzzy-DE-PID yang telah dicadangkan telah menjalani ujikaji melalui dua cara iaitu pertamanya melalui simulasi menggunakan perisian MATLAB Simulink dengan menggunakan sinusoidal dan rawak. Seterusnya, model tersebut telah menjalani eksperimen menggunakan rig ujikaji suku kereta yang dilengkapi oleh penggerak pneumatik sebagai penguja. Rig ujikaji ini telah dibina di Makmal Kawalan, Fakulti Kejuruteraan di UPM. Keputusan simulasi dan ujikaji kawalan untuk pengawal yang dicadangkan menunjukkan bahawa ia telah menambahbaik keselesaan perjalanan kenderaan sebanyak 23% dan 63% lebih baik berbanding pengawal

Fuzzy-DE-PID, dan juga kedua-dua Fuzzy-PID dan sistem pasif di dalam situasi gangguan sinusoidal. Sementara itu bagi gangguan rawak, AFC-Fuzzy-DE-PID telah meningkatkan keselesaan perjalanan kenderaan sebanyak 48%, 83% dan 27% lebih baik berbanding Fuzzy-DE-PID, Fuzzy-PID dan sistem pasif. Di dalam ujian eksperimen ke atas gangguan sinusoidal, AFC-Fuzzy-DE-PID telah meningkatkan keselesaan tunggangan dengan julat 0.4% ke 2% lebih baik berbanding Fuzzy-DE-PID, julat 6% ke 14% lebih baik berbanding Fuzzy-PID, dan julat 30% ke 51% lebih baik berbanding sistem pasif. Sementara gangguan rawak keatas ujian eksperimen, keselesaan pacuan masing-masing bertambah baik sebanyak 1%, 3% dan 4% berbanding Fuzzy-DE-PID, Fuzzy-PID dan sistem pasif. Dengan menggunakan pengawal yang telah dicadangkan di dalam aplikasi masa-nyata yang lain, ia mampu meningkatkan prestasi ke tahap tertinggi tanpa memerlukan pangkalan data yang sebelumnya untuk merekabentuk pengawal Fuzzy-PID masa-nyata.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

2DOF	2 Degree of Freedom
AFC	Active Force Control
AI	Artificial Intelligence
B	Big
BESD	Bezier Search Differential Evolution Algorithm
CEC	Conference on Evolutionary Computation
DE	Differential Evaluation
DMPSADE	Discrete mutation control parameters self-adaptive DE algorithm
EA	Evolutionary Algorithms
EM	Estimated Mass
EPSDE	Ensemble of parameters self-adaptive DE algorithm
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
GAUSSMF	Gaussian Membership Functions
ICEC	International Conference on Evolutionary Computation
IPP	Integer Programming Problems
ISO	International Organization for Standardization
Kdf	Derivative factor
Kif	Integral factor
Kpf	Proportional factor
L	Low
LPP	Linear Programming Problems

M	Meddle
MF	Membership Function
MR	Magnetorheological
NB	Negative Big
NM	Negative Medium
NP	Number of the Population
NS	Negative Small
RMS	Root Mean Square
PID	Proportional, Integral and Derivative
PB	Positive Big
PM	Positive Medium
PN	Pseudo-Noise
PRBS	Pseudo Random Binary Sequence
PS	Positive Small
PSD	Power Spectral Density
PSO	Particular Swarm Optimization
QPP	Quadratic Programming Problems
SaDE	Self- adaptive Differential Evolution algorithm
TRIMF	Triangular Membership Functions
TRAPMF	Trapezoidal Membership Functions
USA	United State of America
ZE	Zero

CHAPTER 1

INTRODUCTION

1.1 Background and motivation

A vehicle's suspension system also plays a role in supporting the weight of the vehicle and improving ride comfort and smoothness in unstable road conditions (Jamil, Zafar, & Gilani 2018; Tandel et al. 2014) . Suspension systems serve to isolate the car body from road bumps by reducing the forces transferred between the car body and the road (Soliman & Kaldas 2021; Jiregna & Sirata 2020). Since the 1980s, extensive research has been proposed to upgrade suspension systems from passive to active and finally to semi-active his suspension systems..

In passive suspension systems, only robust mechanical components cannot be adjusted for different rough road conditions. Active suspension systems have actuators, such as hydraulic actuators, that make them more flexible in rough road conditions.

Semi-active suspension systems are currently the biggest concern over active suspension systems. This is due to the use of lightweight, energy-saving and intelligent actuators that can be tuned and controlled by modern control algorithms such as fuzzy and PID algorithms. Magnetorheological fluids (MR dampers) widely used in many engineering applications. However, it is hysteresis behavior that has led researchers to widely propose various control strategies to overcome nonlinearities(Genc, 2022; Lopez-Lopez et al., 2022; Tandel et al., 2014). The MR Damper fluid is composed of microscopic magnetic particles dispersed in a liquid capable of changing their rheological properties if exposed to a magnetic field (Genc, 2022) . The dispersed particles magnetized and changed the fluid liquid state into a viscoelastic solid-state (Lopez-Lopez et al., 2022), and once the magnetic field was removed, the fluid returned to its liquid state. Remarkably, by changing the current of the damper, the strength of the magnetic field applied to the MR damper fluid can be adjusted to produce the required damping effect (P. S. Liu & Chen, 2014). Because of these smart properties of the MR damper fluid, it is effectively studied in many suspension system researches (Soliman & Kaldas, 2021; (Jiregna & Sirata, 2020).

The motivation to do this research was to develop a new DE algorithm scheme to build a robust vehicle semi-active suspension system that can overcome the limitation of systems occupied by Fuzzy-PID controllers.

1.2 Problem statement

A fuzzy PID controller is one of the most effective controllers used to control MR dampers for suspension isolation (Rashid et al., 2007). This controller uses a fuzzy logic algorithm to tune the PID controller parameters (Kazemian 2007; Somwanshi et al. 2019; Borase et al. 2021). However, the strategy of the fuzzy logic algorithm consists of input parameters derived from the fuzzy inference system 'FIS'. Optimal starting value (Y. Zhao & Wang, 2019). FIS includes membership rules and membership functions that require prior expertise to design an effective FIS strategy (Talpur et al. 2022; Khairuddin et al. 2021).

The motivation for this study that fuzzy PID controllers are regarded as one of the real-time (or online) optimization techniques (Borase et al. 2021; Hosseinpour and Martynenko 2020; Liu et al. 2021). However, it has the disadvantage that it is a rule base that is usually created in offline mode. Apart from knowledge base requirements, there is no systematic framework or set of rules for building inference systems, making it difficult to react to real-time uncertainties by making instant changes (Angelov, 2004), and this make it not smart enough to cope with instant unexpected disturbances (Somefun et al., 2021) as seen in Figure 1.1. Therefore, adding real-time or online optimization to the fuzzy PID controller will improve the output of fuzzy logic and the automatic adjustment of his PID in response to various uncertain road profile disturbances. DE optimization algorithm used here in this research because of it is simplicity and it is fast results in compare to other optimization methods. However, another issue with using the DE in the Fuzzy-PID controller, which it has the problem of iteration requirements which make it difficult to optimize the Fuzzy-PID instantly. Also the classic DE mutation strategies rely on randomness which lead to time consuming so DE must be modified to have less iteration times to cope with the fast decision requirements of the online applications.

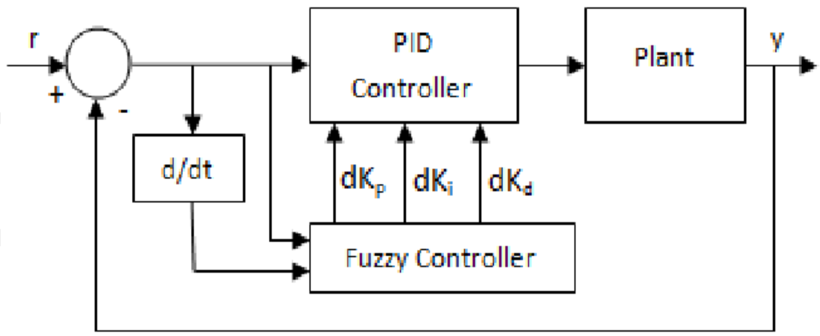

Figure 1.1: In the Fuzzy-PID controller the Fuzzy used to tune the PID parameters automatically (Wahid & Hassan, 2012**).**

1.3 Research objectives

The main objective of this project is to develop the Fuzzy-PID controller using modified DE with AFC to increase the robustness of the suspension system by fulfilling these points:

1. To modify the mutation scheme of the classic Differential Evolution (DE) algorithm in order to increase the optimization process for the online application of this study.

2. To develop a robust intelligent controller for an MR damper model through a simulation study using a Fuzzy-PID controller optimized by DE optimization method (Fuzzy-DE-PID) injected by AFC.

3. To evaluate the performance of the robust intelligent controller on the semi-active suspension system via an experimental test.

4. To verify that the suspension system statistically is in comfort level by using the developed controller according to ISO 2631-1:1997 standards.

1.4 Scope and limitation of the research

- The research mainly focuses on controlling semi-active quarter car suspension system to provide an efficient and robust control system using online DE and AFC.
- The study is limited to a quarter car suspension system with 200 kg representing a lightweight vehicle.
- The controller of the study is AFC-Fuzzy-DE-PID and aims to improve its performance of classical Fuzzy-PID to solve its knowledge base limitation.
- The study aims to reduce the unwanted vertical body vibration generated by sinusoidal and random road profiles.
- The actuator used in this study is the Magnetorheological Fluid Damper (MR Damper).
- The simulation study uses MATLAB/Simulink software.
- An experimental is fully designed and developed based on a mechatronic approach.
- A software-based system (LabVIEW, data acquisition system, Electronic chips) will be applied to the test rig in-the-loop system to control the MR Damper.
- The road disturbance (shaker of the system) is a two-way pneumatic air cylinder controlled by a 12 V electronic solenoid valve.

1.5 Research outline

This thesis consists of five chapters. Chapter 1 is the introduction chapter. This chapter presents the research background, statement of the problem, objectives and scopes of the study, research contributions, methodology of research, and the overall outline of this thesis.

Chapter 2 presents the literature review on related subjects concerning this thesis. In this chapter, the classification of vehicle suspension systems, the selection of damper types, and a review of published articles related to semi-active suspension control strategies are described.

Chapter 3 presents the developed systems methodology, modeling, testing, and validation. First, it introduces the modification methodology to the DE algorithm, then the simulation of the developed controller after adding the modified DE. Then, the experimental test rig of the quarter car is presented in order to validate the simulation results. This chapter also presented the development of a force tracking control system by using AFC controller.

Chapter 4 presents the simulation analysis of the developed control. the simulation model evaluation of the developed controller is carried out using a quarter with a passive system.

Finally, Chapter 5 is the concluding chapter. This chapter summarizes the work done in the entyre study. The recommendations for future research works are also outlined.

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