Faculty of Mechanical Engineering

CONTROL OF PNEUMATICALLY ACTUATED ACTIVE SUSPENSION SYSTEM USING MULTIPLE PROPORTIONAL-INTEGRAL WITH KNOWLEDGE-BASED FUZZY

Fitrian Imaduddin

MSc. in Mechanical Engineering

2010
CONTROL OF PNEUMATICALLY ACTUATED ACTIVE SUSPENSION
SYSTEM USING MULTIPLE PROPORTIONAL-INTEGRAL
WITH KNOWLEDGE-BASED FUZZY

FITRIAN IMADUDDIN

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2010
DECLARATION

I declare that this thesis entitle "Control of Pneumatically Actuated Active Suspension System using Multiple Proportional-Integral with Knowledge-based Fuzzy" is the result of my own research except as cited in the references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ........................................
Name : FITRIAN IMADUDDIN
Date : 1 October 2007
DEDICATION

To my beloved mother, father, and brothers
ACKNOWLEDGEMENTS

I would like to express my sincerest gratitude to my main supervisor, Dr. Khisbullah Hudha for his guidance, support, and constant encouragement during my research and to Dr. Janatul Islah Mohammad for serving me as my second supervisor. I also would like to thank Prof. Dr. Hishamuddin Jamaluddin for his advices. I also acknowledge the Ministry of Higher Education (MoHE) for their financial support via Fundamental Research Grant Scheme (FRGS) in this research activity.

I also thank my colleagues at the Faculty of Mechanical Engineering, UTeM, Ubaidillah Fauzi Ahmad and Zulkiflii Abd. Kadir for their outstanding collaboration in the experimental works and also for being a very good sharing partner during my research. Thanks also to my other colleagues at Taman Tasik and Bukit Beruang for providing an enjoyable study environment.

Finally, my deepest grateful and thanks go to my family, Ahmad Dahlan and Umi Sholicatin, my dear parents, and Zamzam Ibnu Sina and (Allahyarham) Ghilman Hunafa, my dear brothers. Their continuous prays and moral supports have been brought me here.
ABSTRACT

This study investigates the use of pneumatically actuated active suspension system to improve ride performance of the vehicle. The main content of this study is the development and application of the Knowledge-Based Fuzzy (KBF) multiple Proportional-Integral (PI) control scheme and the investigation of the force tracking control system that can provide improvement in vehicle ride performance. These two controllers are arranged in a separated control loops called the inner loop controller for force tracking control of the pneumatic actuator and the outer loop controller using KBF multiple PI control to reject the effects of road-induced disturbances. The performance of the proposed controller is compared to the multiple PI controller without KBF scheme and the existing passive suspension system. Simulation studies are presented in time domain simulation while the experimental evaluation is conducted on a full-scale quarter car test rig. In general, it can be reported that the proposed control scheme is able to provide improvement in terms of body states compared to its counterparts. The proposed scheme is also easy to realize in practice due to its simple structure.
ABSTRAK

Penyelidikan ini mengkaji penggunaan sistem suspensi lasak menggunakan pneumatik untuk meningkatkan mutu pemanduan sesuatu kenderaan. Kandungan utama kajian ini adalah pembangunan skim dan aplikasi kawalan fuzzy proportional-integral berperingkat berpandukan pengetahuan (KBF multiple PI control) dan kajian mengenai sistem kawalan pengesian daya yang boleh menghasilkan peningkatan kepada mutu pemanduan kenderaan. Kedua-dua alat kawalan ini disusun dalam suatu gelung kawalan berasingan yang dinamakan pengawal gelung dalaman untuk kawalan daya pneumatik dan pengawal gelung luaran yang disebut KBF multiple PI control untuk menolak kesan daripada gangguan permukaan jalan. Mutu alat kawalan yang dicadangkan dibandingkan dengan alat pengawal multiple PI tanpa skim KBF serta dengan sistem suspensi pasif yang sedia ada. Kajian simulasi ditunjukkan dalam domain masa, manakala penilaian percubaan dijalankan pada quarter-car-test-rig skala penuh. Secara amnya, dapat disimpulkan bahawa skim alat kawalan yang dicadangkan berkemampuan untuk menghasilkan peningkatan yang berkesan dari segi kenyamanan apabila dibandingkan dengan sistem kawalan yang lain. Skim yang dicadangkan juga mudah untuk dijelaskan dalam bentuk latihan kerana bentuknya yang ringkas.
# TABLE OF CONTENT

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td>i</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xxi</td>
</tr>
</tbody>
</table>

## CHAPTER

1. **INTRODUCTION**
   1.1. Introduction
   1.2. Problem Statement
   1.3. Research Background
   1.4. Objectives and Scope of Research
   1.5. Methodology
   1.6. Thesis Outline

vii
2. LITERATURE REVIEW

2.1. Introduction

2.2. Classification of Vehicle Suspension Systems

2.2.1. Passive Suspension

2.2.2. Semi-Active Suspension

2.2.3. Active Suspension

2.3. Actuator Selection in Active Suspension System

2.4. Active Suspension Control Strategies

2.4.1. PID Controller

2.4.2. Linear Control

2.4.3. Non-linear Control

2.4.4. Intelligent Control

2.5. Summary

3. MODELLING AND VALIDATION OF TWO DEGREES OF

FREEDOM QUARTER CAR MODEL

3.1. Introduction

3.2. Quarter Car Modelling

3.3. Quarter Car Validation

3.3.1. Instrumented Quarter Car Test Rig

3.3.2. Validation Procedures

3.3.3. Model Validation Results

3.4. Summary

4. FORCE TRACKING CONTROL OF PNEUMATICALLY

ACTUATED ACTIVE SUSPENSION SYSTEM
4.1. Introduction 36
4.2. Modelling of Pneumatic Actuators 37
4.3. Controller Structure 40
4.4. Simulation Study 43
  4.4.1. Simulation Parameters 43
  4.4.2. Performance Evaluation of Force Tracking Controller 44
4.5. Experimental Evaluation 51
  4.5.1. Instrumented Quarter Car Test Rig 51
  4.5.2. Experimental Results 53
4.6. Summary 62

5. MULTIPLE PROPORTIONAL INTEGRAL CONTROL SYSTEM 64
5.1. Introduction 64
5.2. Controller Design 64
5.3. Simulation Study 66
  5.3.1. Simulation Parameters 66
  5.3.2. Frequency Domain Simulation Results 67
  5.3.3. Time Domain Simulation Results 70
5.4. Experimental Evaluation 75
  5.4.1. Experimental Setup 75
  5.4.2. Experimental Results 75
5.5. Summary 82

6. KNOWLEDGE-BASED FUZZY MULTIPLE PROPORTIONAL INTEGRAL CONTROL SYSTEM 84
6.1. Introduction 84
6.2. Controller Design

6.3. Simulation Study
   6.3.1. Simulation Parameters
   6.3.2. Simulation Results

6.4. Experimental Evaluation
   6.4.1. Experimental Setup
   6.4.2. Experimental Results

6.5. Summary

7. CONCLUSION
   7.1. Introduction
   7.2. Conclusions
   7.3. Summary of Research Contributions
   7.4. Recommendation for Future Works

REFERENCES

LIST OF PUBLICATIONS
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Simulation Parameters of the pneumatic model</td>
<td>43</td>
</tr>
<tr>
<td>4.2</td>
<td>RMS value of desired and actual force of sinusoid function</td>
<td>56</td>
</tr>
<tr>
<td>4.3</td>
<td>RMS value of desired and actual force of square function</td>
<td>59</td>
</tr>
<tr>
<td>4.4</td>
<td>RMS value of desired and actual force of saw-tooth function</td>
<td>62</td>
</tr>
<tr>
<td>5.1</td>
<td>The parameters of the outer-loop PI controller</td>
<td>67</td>
</tr>
<tr>
<td>5.2</td>
<td>Time domain response comparison between various systems for 0.5 Hz</td>
<td>70</td>
</tr>
<tr>
<td>5.3</td>
<td>Time domain response comparison between various systems for 5 Hz</td>
<td>71</td>
</tr>
<tr>
<td>5.4</td>
<td>Time domain response comparison between various systems for 15 Hz</td>
<td>71</td>
</tr>
<tr>
<td>6.1</td>
<td>Input-output characteristics of the ordinary Multiple PI control</td>
<td>85</td>
</tr>
<tr>
<td>6.2</td>
<td>Membership function parameters of absolute body displacement error</td>
<td>89</td>
</tr>
<tr>
<td>6.3</td>
<td>Membership function parameters of absolute body acceleration error</td>
<td>90</td>
</tr>
<tr>
<td>6.4</td>
<td>Prescribed output values of the fuzzy system</td>
<td>90</td>
</tr>
<tr>
<td>6.5</td>
<td>RMS comparison between passive, multiple PI active and KBF multiple PI active for 0.5 Hz</td>
<td>92</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>RMS comparison between passive, multiple PI active and KBF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>multiple PI active for 5 Hz</td>
<td></td>
</tr>
<tr>
<td>6.7</td>
<td>RMS comparison between passive, multiple PI active and KBF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>multiple PI active for 15 Hz</td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>RMS comparison of body displacement and body acceleration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>between KBF multiple PI and its counterparts</td>
<td></td>
</tr>
<tr>
<td>6.9</td>
<td>RMS comparison of suspension deflection and wheel acceleration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>between KBF multiple PI and its counterparts</td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Passive Quarter Car Model</td>
<td>22</td>
</tr>
<tr>
<td>3.2</td>
<td>Active Quarter Car Model</td>
<td>23</td>
</tr>
<tr>
<td>3.3</td>
<td>Instrumented Quarter Car Test Rig</td>
<td>25</td>
</tr>
<tr>
<td>3.4</td>
<td>Validation results for body displacement at 0.94 Hz</td>
<td>27</td>
</tr>
<tr>
<td>3.5</td>
<td>Validation results for body displacement at 1.18 Hz</td>
<td>27</td>
</tr>
<tr>
<td>3.6</td>
<td>Validation results for body displacement at 1.42 Hz</td>
<td>27</td>
</tr>
<tr>
<td>3.7</td>
<td>Validation results for body displacement at 1.66 Hz</td>
<td>28</td>
</tr>
<tr>
<td>3.8</td>
<td>Validation results for body displacement at 1.89 Hz</td>
<td>28</td>
</tr>
<tr>
<td>3.9</td>
<td>Validation results for body acceleration at 0.94 Hz</td>
<td>29</td>
</tr>
<tr>
<td>3.10</td>
<td>Validation results for body acceleration at 1.18 Hz</td>
<td>29</td>
</tr>
<tr>
<td>3.11</td>
<td>Validation results for body acceleration at 1.42 Hz</td>
<td>29</td>
</tr>
<tr>
<td>3.12</td>
<td>Validation results for body acceleration at 1.66 Hz</td>
<td>30</td>
</tr>
<tr>
<td>3.13</td>
<td>Validation results for body acceleration at 1.89 Hz</td>
<td>30</td>
</tr>
<tr>
<td>3.14</td>
<td>Validation results for suspension deflection at 0.94 Hz</td>
<td>31</td>
</tr>
<tr>
<td>3.15</td>
<td>Validation results for suspension deflection at 1.18 Hz</td>
<td>31</td>
</tr>
<tr>
<td>3.16</td>
<td>Validation results for suspension deflection at 1.42 Hz</td>
<td>31</td>
</tr>
<tr>
<td>3.17</td>
<td>Validation results for suspension deflection at 1.66 Hz</td>
<td>32</td>
</tr>
<tr>
<td>3.18</td>
<td>Validation results for suspension deflection at 1.89 Hz</td>
<td>32</td>
</tr>
<tr>
<td>3.19</td>
<td>Validation results for wheel acceleration at 0.94 Hz</td>
<td>33</td>
</tr>
</tbody>
</table>
3.20 Validation results for wheel acceleration at 1.18 Hz
3.21 Validation results for wheel acceleration at 1.42 Hz
3.22 Validation results for wheel acceleration at 1.66 Hz
3.23 Validation results for wheel acceleration at 1.89 Hz

4.1 Schematic representation of pneumatic actuator with force tracking control

4.2 Control structure of force tracking control with PI controller

4.3 Control structure of force tracking control with on-off controller

4.4 Force tracking performance comparison at 600 N peak forces for sinusoid function; (a) on-off controller, (b) PI controller

4.5 Force tracking performance comparison at 600 N peak forces for square function; (a) on-off controller, (b) PI controller

4.6 Force tracking performance comparison at 600 N peak forces for saw-tooth function; (a) on-off controller, (b) PI controller

4.7 Force tracking performance comparison at 800 N peak forces for sinusoid function; (a) on-off controller, (b) PI controller

4.8 Force tracking performance comparison at 800 N peak forces for square function; (a) on-off controller, (b) PI controller

4.9 Force tracking performance comparison at 800 N peak forces for saw-tooth function; (a) on-off controller, (b) PI controller

4.10 1-DOF Quarter Car Test Rig

4.11 Schematic representation of pneumatic actuator with force tracking control using proportional valve

4.12 Performance of force tracking control system in 600 N sinusoid functions
4.13 Performance of force tracking control system in 800 N sinusoid functions
4.14 Performance of force tracking control system in 1000 N sinusoid functions
4.15 Performance of force tracking control system in 1200 N sinusoid functions
4.16 Performance of force tracking control system in 1400 N sinusoid functions
4.17 Performance of force tracking control system in 1600 N sinusoid functions
4.18 Performance of force tracking control system in 600 N square functions
4.19 Performance of force tracking control system in 800 N square functions
4.20 Performance of force tracking control system in 1000 N square functions
4.21 Performance of force tracking control system in 1200 N square functions
4.22 Performance of force tracking control system in 1400 N square functions
4.23 Performance of force tracking control system in 1600 N square functions
4.24 Performance of force tracking control system in 600 N saw-tooth functions
4.25 Performance of force tracking control system in 800 N saw-tooth functions

4.26 Performance of force tracking control system in 1000 N saw-tooth functions

4.27 Performance of force tracking control system in 1200 N saw-tooth functions

4.28 Performance of force tracking control system in 1400 N saw-tooth functions

4.29 Performance of force tracking control system in 1600 N saw-tooth functions

5.1 Overall control structure of multiple PI control

5.2 Frequency domain response comparison between multi-order active and passive suspension

5.3 Frequency domain response comparison between multi-order, passive and zero-order system

5.4 Frequency domain response comparison between multi-order, passive and first-order system

5.5 Frequency domain response comparison between multi-order, passive and second-order system

5.6 Body displacement of 0.5 Hz sinusoid road profile

5.7 Body acceleration of 0.5 Hz sinusoid road profile

5.8 Body displacement of 5 Hz sinusoid road profile

5.9 Body acceleration of 5 Hz sinusoid road profile

5.10 Body displacement of 15 Hz sinusoid road profile

5.11 Body acceleration of 15 Hz sinusoid road profile
5.12 Body displacement of multi-order active and passive suspension at 1.42 Hz
5.13 Body acceleration of multi-order active and passive suspension at 1.42 Hz
5.14 Suspension deflection of multi-order active and passive suspension at 1.42 Hz
5.15 Wheel acceleration of multi-order active and passive suspension at 1.42 Hz
5.16 Body displacement of multi-order active and passive suspension at 1.65 Hz
5.17 Body acceleration of multi-order active and passive suspension at 1.65 Hz
5.18 Suspension deflection of multi-order active and passive suspension at 1.65 Hz
5.19 Wheel acceleration of multi-order active and passive suspension at 1.65 Hz
5.20 Body displacement of multi-order active and passive suspension at 1.88 Hz
5.21 Body acceleration of multi-order active and passive suspension at 1.88 Hz
5.22 Suspension deflection of multi-order active and passive suspension at 1.88 Hz
5.23 Wheel acceleration of multi-order active and passive suspension at 1.88 Hz
Overall Controller structure of knowledge-based fuzzy multiple PI control

Surface map of proposed fuzzy system

Responses comparison between passive, Multiple PI active, and KBF Multiple PI active of 0.5 Hz sinusoid road profile; (a) body displacement, (b) body acceleration, (c) suspension deflection, and (d) wheel acceleration

Responses comparison between passive, Multiple PI active, and KBF Multiple PI active of 5 Hz sinusoid road profile; (a) body displacement, (b) body acceleration, (c) suspension deflection, and (d) wheel acceleration

Responses comparison between passive, Multiple PI active, and KBF Multiple PI active of 15 Hz sinusoid road profile; (a) body displacement, (b) body acceleration, (c) suspension deflection, and (d) wheel acceleration

Body displacement performances comparison between KBF multiple PI and its counterparts at 0.94 Hz

Body acceleration performances comparison at 0.94 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

Suspension deflection performances comparison between KBF multiple PI and its counterparts at 0.94 Hz

Wheel acceleration performances comparison at 0.94 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive
6.10  Body displacement performances comparison between KBF multiple PI and its counterparts at 1.18 Hz

6.11  Body acceleration performances comparison at 1.18 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

6.12  Suspension deflection performances comparison between KBF multiple PI and its counterparts at 1.18 Hz

6.13  Wheel acceleration performances comparison at 1.18 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

6.14  Body displacement performances comparison between KBF multiple PI and its counterparts at 1.42 Hz

6.15  Body acceleration performances comparison at 1.42 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

6.16  Suspension deflection performances comparison between KBF multiple PI and its counterparts at 1.42 Hz

6.17  Wheel acceleration performances comparison at 1.42 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

6.18  Body displacement performances comparison between KBF multiple PI and its counterparts at 1.66 Hz

6.19  Body acceleration performances comparison at 1.66 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

6.20  Suspension deflection performances comparison between KBF multiple PI and its counterparts at 1.66 Hz
6.21 Wheel acceleration performances comparison at 1.66 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

6.22 Body displacement performances comparison between KBF multiple PI and its counterparts at 1.89 Hz

6.23 Body acceleration performances comparison at 1.89 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive

6.24 Suspension deflection performances comparison between KBF multiple PI and its counterparts at 1.89 Hz

6.25 Wheel acceleration performances comparison at 1.89 Hz; (a) between multiple PI and passive, (b) between KBF multiple PI and passive
LIST OF SYMBOLS

$\alpha_{in}$ - Heat transfer coefficient for compression

$\alpha_{in}$ - Heat transfer coefficient for expansion

$\mu_A$ - Functional mathematical form of a membership function

$A$ - Piston effective areas

$A_{vi,in}$ - Valve areas for input path

$A_{vi,in}$ - Valve areas for exhaust path

$\beta$ - Viscous friction coefficient of the pneumatic cylinder

$c^i_j$ - Center (mean) of the membership function

$\sigma^i_j$ - Spread (deviation) of the membership function

$\theta$ - Representation of fuzzy parameters (center and spread)

$b_i$ - Output membership function for $i$-th rule

$C_1$ - Coefficient for unchoked flow

$C_2$ - Coefficient for choked flow

$C_f$ - Non-dimensional discharge coefficient

$C_s$ - Stiffness value of the passive damper

$e$ - errors
$e_z$ - body displacement errors

$e_v$ - body velocity errors

$e_a$ - body acceleration errors

$f$ - regulated scaling factor of knowledge-based fuzzy scheme

$F$ - External force against pneumatic actuator

$F_p$ - Augmented force from the actuator

$F_f$ - Coulomb friction force of the pneumatic cylinder

$K_f$ - Integral Constant

$K_p$ - Proportional Constant

$K_s$ - Stiffness value of the passive spring

$L$ - Stroke length of the piston

$M$ - Mass of the pneumatic piston

$M_u$ - Mass of the wheel axle (unsprung mass)

$M_s$ - Mass of the vehicle body (sprung mass)

$\dot{m}_r$ - Mass flow rate of air

$P_1$ - Pressures of the air in the first chamber of pneumatic cylinder

$P_2$ - Pressures of the air in the second chamber of pneumatic cylinder

$P_{cr}$ - Critical pressure ratio

$P_d$ - Downstream pressures

$P_s$ - Supply pressure

$P_u$ - Upstream pressures

$R$ - Ideal gas constant
RMS - Root Mean Square

\( V_{01} \) - Inactive volume at the end of the stroke and admission ports of the pneumatic

\( V_{c} \) - Control Signal

\( x \) - Piston position relative to the middle of the stroke

\( Z_{u} \) - Vertical displacement of the wheel axle

\( Z_{s} \) - Vertical displacement of the vehicle body

\( Z_{r} \) - Vertical displacement of road profile

\( \dot{Z}_{u} \) - Vertical velocity of the wheel axle

\( \dot{Z}_{s} \) - Vertical velocity of the vehicle body

\( \ddot{Z}_{r} \) - Vertical velocity of road profile

\( \ddot{Z}_{u} \) - Vertical acceleration of the wheel axle

\( \ddot{Z}_{s} \) - Vertical acceleration of the vehicle body