MOTION-MODE ENERGY METHOD AND ITS IMPLEMENTATION BASED ON ACTIVE HYDRAULICALLY INTERCONNECTED SUSPENSION

by

Lifu Wang

Submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy

Faculty of Engineering and Information Technology

University of Technology, Sydney

October 2013

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signed:

____

Lifu Wang

Acknowledgements

I would like to take the opportunity to thank a number of people for their assistance, encouragement and support throughout my candidature.

First and foremost, I extend my gratitude to my supervisor, Professor Nong Zhang for his outstanding guidance, encouragement and caring support throughout the duration of this project. Over the years, Nong's personal brand of professional and intellectual excellence became a source of inspiration and role model for my professional and personal development. I also sincerely thank my co-supervisor, Dr Haiping Du, for his first-class and unfailing assistance, guidance and support over the past few years. His extensive experience and dedication have been much appreciated throughout my research.

Chris Chapman's help at the initial stage of this project is gratefully appreciated. Dr Holger Roser's expertise in the lab was a tremendous asset to the project, and I greatly appreciated his help in the test rig design, construction and testing. I would like to thank Dr Paul Walker and Dr Nga Hoang for all of their help and insightful input. My appreciation is also extended to Robert Hill for his help in the field test and for proofreading my papers. Building the test rigs and conducting the field tests required a lot of work, and I would like to thank all the Capstone students that worked with me on this project: Benjamin West, Zhuojie Liang, Stefano Sansone, Yunfei Gao, Michael Lee, Scott Russell, Adam Martinez, William Wait, and Matthias Wong, and also thank two other Ph.D students: Sangzhi Zhu and Guangzhong Xu. Without their dedicated work and help, I could not have conducted such a large scale project. The financial support of this work by the Australian Research Council (ARC DP0988429) and the University of Technology, Sydney, is gratefully acknowledged.

I would like to thank my parents, for their love and support over the years, my grandparents for their encouragement and for serving as such fine role models in my life, and my wife Yupu to whom I owe so much for her continuing love and support. Lastly, I wish to acknowledge the birth of my beautiful daughter Maggie who has made my Ph.D candidature more enjoyable than it would have been without her! I can't wait to see her reading my thesis one day!

Lifu Wang

Sydney, October 2013

List of publications based on this research

Journal articles

[1]. Zhu, S., **Wang, L.**, Zhang, N., and Du, H., "H∞ Control of a Novel Low-cost Roll-plane Active Hydraulically Interconnected Suspension: an Experimental Investigation of Roll Control under Ground Excitation," *SAE International Journal of Passenger Cars- Mechanical Systems*, vol. 6 (2), pp. 882-893, 2013.

[2]. **Wang, L.**, Zhang, N., and Du, H., "Experimental Investigation of a Hydraulically Interconnected Suspension in Vehicle Dynamics and Stability Control," *SAE International Journal of Passenger Cars- Mechanical Systems,* vol. 5 (2), pp. 759-768, 2012.

[3]. Zhang, N., **Wang, L.**, and Du, H., "Motion-Mode Energy Method for Vehicle Dynamics Analysis and Control," accepted by *Vehicle System Dynamics,* September 2013.

[4]. **Wang, L.**, Zhang, N., and Du, H., "Full-Car Application and Field Test of a Roll-Plane Hydraulically Interconnected Suspension," *submitted to Vehicle System Dynamics,* 2013.

[5]. **Wang, L.**, Zhang, N., and Du, H., "Real-time Identification of Vehicle Motion-Modes Using Neural Networks," *submitted to Mechanical Systems and Signal Processing,* 2012.

[6]. Du, H., Zhang, N., and **Wang, L.**, "Switched Control of Vehicle Suspension Based on Motion-Mode Detection," *submitted to Vehicle System Dynamics,* 2013.

Conference papers

[7]. **Wang, L.**, Xu, G., Zhang, N., and Roser, H., "Empirical Analysis of a Roll –plane Hydraulically Interconnected Suspension in Comparison with Anti-roll Bars on a Sport Utility Vehicle: Articulation (Warp) mode," SAE Technical paper 2013-01-0710, Detroit, US, 2013.

[8]. Zheng, M., **Wang, L.**, Zhou, Q., and Zhang, N., "Drop-test based parameter estimation of a two-axis commercial vehicle," the 23rd International Association for Vehicle System Dynamics (IAVSD), Qingdao, China, 19-23 August 2013.

[9]. Xu, G., Zhang, N., Roser, H., and **Wang, L.**, "Simulation study of roll-plane hydraulically interconnected suspension compared with anti-roll bar in articulation mode," the 23rd International Symposium on Dynamics of Vehicles on Roads, IAVSD, Qingdao, China, 19-23 August 2013.

[10]. Xu, G., Roser, H., and **Wang, L.**, "Experimental study of a roll-plane hydraulically interconnected suspension system under vehicle articulation mode," under reviwer of ASME 2013 International Mechanical Engineering Congress and Exposition (IMECE), San Diego, CA, USA, 2013.

[11]. Shao, X., Du, H., Zhang, N., and **Wang, L.**, "Fuzzy Control of Hydraulically Interconnected Suspension with Configuration Switching," under reviwer of the IEEE International Conference on Vehicular Electronics and Safety (ICVES'13), Dongguan, China, 2013.

[12]. Lam, Q. V. C., **Wang, L.**, and Zhang, N., "Experimental implementation of a Fuzzy controller for an active hydraulically interconnected suspension on a sport utility vehicle," the 2013 IEEE Intelligent Vehicles Symposium, Gold Coast, Australia, 23-26 June 2013.

[13]. Hong, H., **Wang, L.**, and Zhang, N., "Investigation of a roll-plane hydraulically interconnected suspension with motion-mode energy method," the 23rd International Symposium on Dynamics of Vehicles on Roads and Tracks, Qingdao, China, 19-23 August 2013.

[14]. Zhang, N., Smith, W., and **Wang, L.**, "Passive and active hydraulically interconnected suspensions and their applications," the 7th Australasian Congress on Applied Mechanics (ACAM 7), Adelaide, Australia, 9-12 December 2012.

[15]. **Wang, L.**, Zhang, N., and Du, H., "Modelling and parameter estimation of an active hydraulic suspension using experimental method," the 7th Australasian Congress on Applied Mechanics, Adelaide, Australia, 9-12 December 2012.

[16]. Roser, H., **Wang, L.**, and Zhang, N., "Empirical analysis of a roll-plane hydraulically interconnected suspension system under vehicle articulation mode," the 7th Australasian Congress on Applied Mechanics (ACAM), 9-12 December 2012.

[17]. Zhang, N., **Wang, L.**, and Hu, W., "Handling analyses of a Vehicle Fitted with a Roll-resistant Hydraulically Interconnected Suspension," IAVSD, Manchester, UK, 14-19 August 2011.

[18]. **Wang, L.**, Zhang, N., and Du, H., "Onboard Detection of Energy Distribution onto Vibration Modes of a Vehicular System," the 14th Asia Pacific Vibration Conference, Hong Kong, 5-8 December 2011.

[19]. Zhang, N., **Wang, L.**, Hu, W., and Ding, F., "Dynamic Characteristics of a Vehicle Fitted with a Roll-Resistant Hydraulically Interconnected Suspension," the First IFToMM Asian Conference on Mechanism and Machine Science, Taipei, Taiwan, 21-25 October 2010.

[20]. Zhang, N., Hu, W., and **Wang, L.**, "Modelling and Simulation of a Full Car Fitted with a Hydraulically Interconnected Suspension undergoing Extreme Manoeuvres," 1st International Conference on Vibration Utilization and Control (ICVUC), Shenyang, China, 19-21 August, 2010.

[21]. **Wang, L.**, Zhang, N., and Du, H., "Modelling, parameter estimation and testing of a vehicle with anti-roll systems," the 6th Australasian Congress on Applied Mechanics, Perth, Australia, 12-15 December 2010.

[22]. Zhang, N., **Wang, L.**, and Du, H., "Modeling of a New Active Suspension for Roll Control," the 13th Asia Pacific Vibration Conference, University of Canterbury, New Zealand, 22-25 November 2009.

[23]. **Wang, L.**, Zhang, N., and Du, H., "Design and Experimental Investigation of Demand Dependent Active Suspension for Vehicle Rollover Control," the 48th IEEE Conference on Decision and Control, Shanghai, P.R. China, pp. 5158-5163, 16-18 December 2009.

Table of Contents

Abstract

Vehicle motion and vibration control is a fundamental motivation for the development of advanced vehicle suspension system, and high performance active suspension with its forcefulness, flexibility and effectiveness is desired to fit the control role. However, the main constraint for the commercial application of these active suspensions is their high component cost and power consumption. The principal idea of this thesis is that by proposing an energy efficient control strategy and a novel active suspension system, the active suspension's initial cost can be reduced and its running power consumption can be minimised.

The new control strategy, designed to improve energy efficiency by prioritizing the dominating vehicle dynamic aspects, is based on a motion-mode energy method (MEM). It classifies vehicle body-wheel motions into several motion-modes according to their modal properties and quantifies the contribution of each motion-mode by its energy intensity in real time. The motion-mode energy and mode contribution ratio are used to determine the control priority on the control of the most dominating motion-mode. Neural networks are trained to implement the MEM in practice in an economical manner, and an MEM-based switched control is proposed to perform the multi-mode control.

The new suspension system developed to implement the MEM-based switched control strategy is called active hydraulically interconnected suspension (active HIS), which is equipped with only one servo valve to reduce the system's cost and energy consumption. In addition, by switching its hydraulic configuration into different modes, the vehicle primary dynamic response can be significantly improved with less power consumption.

Three test facilities have been designed and developed to study this novel suspension system, including a six-channel vehicle dynamic test rig, a multi-functional anti-roll

HIS test rig and a reconfigurable HIS test rig. Test results provided include vehicle parameter estimation, passive anti-roll HIS laboratory and field test, and active HIS anti-roll test. The active HIS is found to be an effective and feasible way of controlling a vehicle’s motion. However, further investigation into this system, including the full-car MEM-based switched control and circuit reconfiguration test, is recommended for future studies.

Abbreviations

ABS	Anti-Lock Brake System
ASCA	Active suspension via control arm
BSR	Buzz, squeak and rattle
CG	Centre of gravity
DOF	Degree of freedom
ESC/ESP	Electronic Stability Control/Program
FFT	Fast Fourier transformation
HIS	Hydraulically interconnected suspension
KDSS	Kinetic dynamic suspension system
LQR	Linear quadratic regulator
LVDT	Linear variable differential transformer
MEM	Motion-mode energy method
MHIS	Multi-function hydraulically interconnected suspension
NI	National Instruments
NN	Neural network
RCF	Rollover critical factor
RHIS	Reconfigurable hydraulically interconnected suspension
RMS	Root mean square
SUV	Sport utility vehicle
SVM	State variable method
UTS	University of Technology, Sydney

List of Symbols

u	Longitudinal velocity of the sprung mass centre of gravity (CG)
v	Lateral velocity of the sprung mass CG
z_s	Vertical displacement of the sprung mass CG
z_{ui}	Vertical displacement of the unsprung masses (i =1, 2, 3, 4)
z_{ii}	Vertical displacement of sprung mass at four suspension mounting points, $ii = fl, fr, rl, rr$
z_{gi}	Road disturbance input for each tire (i =1, 2, 3, 4)
fl, fr, rl, rr	Front-left, Front-right, Rear-left, Rear-right
φ	Roll angle of the sprung mass around its x-axis
θ	Pitch angle of the sprung mass around its y-axis
ψ	Yaw angle of the vehicle
m_s	Vehicle sprung mass
m_{ui}	Vehicle unsprung mass (i =1, 2, 3, 4)
I_{xx}	Moment of inertia about the x-axis of the vehicle sprung mass
I_{yy}	Moment of inertia about the y-axis of the vehicle sprung mass
I_{zz}	Moment of inertia about the z-axis of the vehicle sprung mass
I_{xz}	Product of inertia about the x-z axes of the vehicle sprung mass
I_{zz_u}	Moment of inertia about the z-axis of the vehicle unsprung mass
l_f	Distance from the sprung mass CG to the front axle
l_r	Distance from the sprung mass CG to the rear axle
t_f	1/2 width of the front axle
t_r	1/2 width of the rear axle
h_s	Vertical distance from the sprung mass CG to the roll axis
k_{si}	Spring stiffness for each suspension (i =1, 2, 3, 4)
c_{si}	Damping coefficient for each suspension (i =1, 2, 3, 4)
k_t	Vertical tire stiffness

δ_f	Front tire steer angle
δ_r	Roll induced steer angle at rear
λ_i	System eigenvalues (i =1, 2,$\cdots$7)
ϕ_i	System eigenvectors (i =1, 2,$\cdots$7)
e_{ki}	The kinetic energy in the i^{th} motion-mode (i =1, 2,$\cdots$7)
e_{pi}	The potential energy in the i^{th} motion-mode (i =1, 2,$\cdots$7)
e_i	The total energy in the i^{th} motion-mode (i =1, 2,$\cdots$7)
η_i	The i^{th} mode-ratio
E	The total energy of seven motion-modes
$w, \overline{w}$	Weighting matrices of neural network
w^*, $\overline{w}^*$	The updated weighting matrices during neural network training
τ	The learning constant of the neural network delta training rule
Λ	System eigenvalue matrix
Ψ	System eigenvector matrix
Γ	Modal transition matrix in motion-mode energy method
X	System state vector
$X_{M/H}$	Subsystem state vector, i.e, mechanical subsystem (M) and hydraulic subsystem (H)
p_j^i, q_j^i	Hydraulic pressure p or flow rate q, the subscripts j define the specific location, top/bottom chamber, j =*U/B*, other points, j =*A, C…S*, and the superscripts i denote the relevant hydraulic element: two letters represents a pipeline element; the letter *A1* and *A2* represent two accumulators
T_H, S_H	Coefficient matrices determining the hydraulic system dynamics
F_m	Road input and nonlinear components of the 9-DOF vehicle model
F_h	Coupling coefficient matrix, from mechanical system to hydraulic system
S_{H2M}	Coupling coefficient matrix, from hydraulic system to mechanical system