Faculty of Engineering and Information Technology

An Investigation into the Roll Control of Vehicles with Hydraulically Interconnected Suspensions

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An Investigation into the Roll Control of Vehicles with Hydraulically Interconnected Suspensions

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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:

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Sangzhi Zhu

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Publications and Conference Contributions

The following publications are part of the thesis

Peer reviewed international scientific journal publications

[1] **Zhu, S.,** Wang, L., Zhang, N., & 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***, 6(2013-01-1238), 882-893, 2013.

[2] **Zhu, S.,** Du, H., Zhang, N., & Wang, L., Development of A New Model for Roll-Plane Active Hydraulically Interconnected Suspension. ***SAE International Journal of Passenger Cars-Mechanical Systems***, *7*(2014-01-0053), 447-457, 2014.

[3] **Zhu, S.,** Xu, G., Tkachev, A., Wang, L., & Zhang, N., Road Holding Ability Comparison of a Roll-Plane Hydraulically Interconnected Suspension and Anti-Roll Bars. ***Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering***, (Major revision, Manuscript ID JAUTO-15-0463).

[4] Liang, J., Wu, J., Zhang, N., Luo, Z. & **Zhu, S.,** Interval uncertain analysis of active hydraulically interconnected suspension system. ***Advances in Mechanical Engineering.*** 8(5), 2016: 1687814016646331.

Peer reviewed international scientific conference publications

[1] **Zhu, S.,** Du, H., & Zhang, N. (2014, July). Development and Implementation of Fuzzy, Fuzzy PID and LQR Controllers for a Roll-plane Active Hydraulically Interconnected Suspension. In *2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE),* (pp. 2017-2024). IEEE.

[2] Zhang, N., **Zhu, S.** & Liang, J., (2015, November). Experimental Investigation of a Roll-plane Hydraulically Interconnected Suspension and Anti-roll Bars in Warp Mode. In *16th Asia Pacific Vibration Conference* (pp.566-570), Hanoi, Vietnam.

Abstract

This thesis presents the investigation into a roll-plane hydraulically interconnected suspension (HIS), which is safety-oriented and designed for the vehicle with a high centre of gravity (CG) and a low rollover threshold.

As a potential replacement of anti-roll bars, the HIS possesses the ability to resist the roll motion of the vehicle body during cornering or sharp turning by improving the vehicle roll stiffness. The previous research has concluded that the HIS is superior to the anti-roll bars in terms of the anti-roll performance, but its road holding performance has not been thoroughly studied. In this research, the modelling, modal analysis and simulations are conducted to compare the road holding ability of the HIS and anti-roll bars. A multi-function HIS test rig is developed and mounted on a typical Sports Utility Vehicle (SUV). The related experiments are implemented on a four-post test rig. Both the simulation and experiment results confirmed that the HIS is better than anti-roll bars from the perspective of the road holding performance.

To overcome the drawback of the HIS that it is unable to handle the large roll motion and the vehicle roll caused by uneven roads, the HIS is then developed to be actively controlled by a control unit. Only one servo valve is included in the control unit of the active HIS so that the system's cost and energy consumption are much lower in comparison with the conventional active suspensions with four independent motor-actuators. An output feedback H∞ controller is developed based on an empirically estimated active HIS model at a half-car level. The active HIS controlled by the designed H∞ controller is experimentally validated on the test rig with considerable roll angle reductions.

For further verifying the controllability of the active HIS and also comparing the effect of different categories of control methods on the active HIS, other three representative control algorithms are also applied to the active HIS equipped vehicle. They are the classic control methods: proportional-integral-derivative (PID) control, the optimal control algorithm: linear-quadratic regulator (LQR) control and the intelligent control algorithm: fuzzy logic control. The obtained fuzzy, fuzzy-PID and LQR controllers are implemented in simulations. The experiments of the fuzzy and fuzzy-PID controllers are also conducted. The fuzzy-PID controller presents the most promising and stable control performance among these three controllers.

After that, an attempt is made to improve the control performance of the model-based controllers to enhance the roll resistance ability of the active HIS further. A nine-degrees-of-freedom (nine-DOF) model that can capture the physical characteristics of the active HIS more accurately is developed. The new system model that addresses the relation between the flow change and pressure variation of the hydraulic system, and the viscous resistance of the fluid is also included. Then an H∞ controller and an LQR controller are designed based on the new model and validated in simulations. The experiment of the H∞ controller is also performed on the test rig and the H∞ controller derived from the new model is compared with the H∞ controller derived from the old model. The results show that the H∞ controller based on the new model improves the control performance slightly.

Lastly, an effort is made to reduce the effects of the time delay caused by the fluid system by considering the system time delay when developing the controller. Delay-independent and delay-dependent H∞ state feedback controllers are designed and applied to the half car

model. The simulation validations of the obtained controllers are carried out in MATLAB. It is found that the developed delay-dependent H∞ controller can provide stable and acceptably good control performance even with system time delay.

Keywords: Interconnected suspension, active suspension, vehicle handling, warp mode, roll mode, H∞ control.

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Nomenclature

Global abbreviations used in this thesis

ADAMS	=	Automatic Dynamic Analysis of Mechanical Systems
ARE	=	Algebraic Riccati equation
ASCA	=	Active suspension via control arm
Bar	=	Unit of pressure equal to 100 kPa
CAD	=	Computer-aided design
CG	=	Centre of gravity
DDAS	=	Demand Dependent Active Suspension
DOF	=	Degrees of freedom
DRC	=	Dynamic Ride Control
ESP	=	Electronic Stability Program
HBMC	=	Hydraulic Body Motion Control Suspension
HIS	=	Hydraulically Interconnected Suspension
H∞	=	H infinity
LABView	=	Data logging and analysis software by National Instruments
LMI	=	Linear matrix inequality
LQR	=	Linear-quadratic regulator
LQG	=	Linear-quadratic-Gaussian

LVDT	=	Linear variable displacement transducer
MD	=	Medium
NI	=	National Instruments
NL	=	Negative large
NM	=	Negative medium
NS	=	Negative small
NVL	=	Negative very large
PID	=	Proportional-integral-derivative
PL	=	Positive large
PM	=	Positive medium
PS	=	Positive small
PVL	=	Positive very large
SUV	=	Sports utility vehicle
T-S	=	Takagi-Sugeno
UTS	=	University of Technology Sydney
ZS	=	Zero
3D	=	Three dimensional
4WDs	=	Four-wheel drive vehicles