An Investigation into the Dynamics of Vehicles With Hydraulically Interconnected Suspensions

by

Wade Alister Smith

Submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

Faculty of Engineering and Information Technology
University of Technology, Sydney

June, 2009

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

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

Production Note:
Signature removed prior to publication.

____

Wade Smith

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. His guidance was invaluable. My co-supervisor, Jeku Jeyakumaran, is also deserving of many thanks. He was always approachable and helpful.

Chris Chapman's expertise in the lab was a tremendous asset to the project, and I greatly appreciate his help. Building the half-car test rig required a lot of work and a couple of iterations, and the UTS workshop staff – Scott, Richard, Darren, Bill and Harold – are to be commended for their efforts. I would also like to thank Greg Koutchavlis for his work in getting the rig *going*. And Matt Rozyn's help with the experimentation and data processing is greatly appreciated. In programming and simulations, I sought help at times from Miao Wang, Zhan Wang and Wenlong Hu. I thank them for that. A special mention should also go to everyone at Kinetic Pty Ltd, and in particular, Ray Munday, Chris Revill and Stuart Price. The financial support of this work by the Australian Research Council (ARC LP0562440) and the University of Technology, Sydney, is gratefully acknowledged.

On the social side, it is hard to know where to begin. I'll always treasure the times in the early days, sitting next to Anthony in the office. More recently, Janitha, Fook, Debbie, Greg, Pete and Thuyen provided great friendship at UTS, while Baden, Sam and Michelle were assiduous in their provision of remote support via email. And I always looked forward to the weekend adventures with Drew, Paul and Jamie.

I would like to thank my parents, Rosemary and Graham, for their love and support over the years. My mother, in particular, deserves special thanks for all her help in the last few months.

Lastly, I want Ulli to know how much I value her company and her support, especially during the writing of this thesis. I intend to return the favour.

Wade Smith

Sydney, December 2008

Table of Contents

List of Figures

List of Tables

Abstract

This thesis examines the dynamics of a particular class of vehicle suspension, namely *hydraulically interconnected suspension* (HIS), often claimed to break the compromise between ride and handling performance. Yet such systems have, until quite recently, received little attention in the academic literature. Ideally, interconnected schemes have the capability, unique among passive suspensions, to provide stiffness and damping characteristics dependent on the all-wheel suspension mode of operation.

The modelling approach proposed here is necessarily multidisciplinary, drawing from multi-body vibration theory and fluid dynamics. A simple half-car model is used to illustrate the basic principles and to demonstrate the application of the methodology. The half-car is treated as a lumped-mass multi-body system and the fluid circuits as continuous line elements. Individual fluid components are modelled using the impedance method, and the relationships between the fluid states at the extremities of each circuit are determined by the transfer matrix method. The resulting set of linear, frequency-dependent state-space equations, which govern the coupled dynamics of the half-car system, are derived and then applied in a variety of ways. This includes a free vibration analysis, ride comfort assessment and multi-objective optimisation. A number of key components that influence HIS performance are identified and a sensitivity analysis of their effects is presented.

Validation of the theoretical modelling is performed in two ways. First, simulations of an identical half-car using an alternative, nonlinear finite element fluid model are conducted. Second, experiments with a unique, purpose-built, half-car test rig are performed. The free and forced vibration results obtained with both methods, in general, agree very well with the proposed linear model.

The methodology presented is found to be an effective and useful way of modelling HIS-equipped vehicles, particularly in the frequency domain. The obtained results suggest that interconnected suspension schemes may provide, at least to some extent, an improved compromise between ride and handling. However, further investigation of this claim, including the development of a detailed full-car model, is recommended as a topic for future studies.

Dear Reader, please forgive me if I have wasted your time.

– Leonard Cohen