THE RIDE COMFORT VS. HANDLING COMPROMISE FOR OFF-ROAD VEHICLES

by

PIETER SCHALK ELS

Submitted in partial fulfilment of the requirements for the degree

Philosophiae Doctor (Mechanical Engineering)

in the

FACULTY OF ENGINEERING, THE BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY (EBIT)

UNIVERSITY OF PRETORIA
Pretoria

July 2006

THESIS SUMMARY

Title: The Ride Comfort *vs.* Handling Compromise for Off-Road Vehicles

Author: PIETER SCHALK ELS

Supervisor: Prof. N.J. Theron

Department: Mechanical and Aeronautical Engineering, University of Pretoria

Degree: Philosophiae Doctor (Mechanical Engineering)

This thesis examines the classic ride comfort *vs.* handling compromise when designing a vehicle suspension system. A controllable suspension system, that can, through the use of suitable control algorithms, eliminate this compromise, is proposed and implemented.

It is a well known fact that if a vehicle suspension system is designed for best ride comfort, then handling performance will suffer and vice versa. This is especially true for the class of vehicle that need to perform well both on- and off-road such as Sports Utility Vehicles (SUV's) and wheeled military vehicles. These vehicles form the focus of this investigation.

The ride comfort and handling of a Land Rover Defender 110 Sports Utility Vehicle is investigated using mathematical modelling and field tests. The full vehicle, non-linear mathematical model, built in MSC ADAMS software, is verified against test data, with favourable correlation between modelled and measured results. The model is subsequently modified to incorporate hydropneumatic springs and used to obtain optimised spring and damper characteristics for ride comfort and handling respectively. Ride comfort is optimised by minimising vertical acceleration when driving in a straight line over a rough, off-road terrain profile. Handling is optimised by minimising the body roll angle through a double lane change manoeuvre. It is found that these optimised results are at opposite corners of the design space, *i.e.* ride comfort requires a soft suspension while handling requires a stiff suspension. It is shown that the ride comfort *vs.* handling compromise can only be eliminated by having an active suspension system, or a controllable suspension system that can switch between a soft and a stiff spring, as well as low and high damping. This switching must occur rapidly and automatically without driver intervention.

A prototype **4 S**tate **S**emi-active **S**uspension **S**ystem ($4S_4$) is designed, manufactured, tested and modelled mathematically. This system enables switching between low and high damping, as well as between soft and stiff springs in less than 100 milliseconds.

A control strategy to switch the suspension system between the "ride" mode and the "handling" mode is proposed, implemented on a test vehicle and evaluated during vehicle tests over various on- and off-road terrains and for various handling manoeuvres. The control strategy is found to be simple and cost effective to implement and works extremely well. Improvements of the order of 50% can be achieved for both ride comfort and handling.

SAMEVATTING VAN PROEFSKRIF

Titel: Die Ritgemak *vs.* Hantering Kompromie vir Veldvoertuie

Outeur: PIETER SCHALK ELS

Studieleier: Prof. N.J. Theron

Departement: Meganiese en Lugvaartkundige Ingenieurswese
Universiteit van Pretoria

Graad: PhD in Ingenieurswese (Meganiese Ingenieurswese)

In hierdie proefskrif word die klassieke kompromie wat getref moet word tussen ritgemak en hantering, tydens die ontwerp van ‘n voertuig suspensiestelsel ondersoek. ‘n Beheerbare suspensiestelsel, wat die kompromie kan elimineer deur gebruik te maak van toepaslike beheeralgoritmes, word voorgestel en geïmplementeer.

Dit is ‘n bekende feit dat, wanneer die karakteristieke van ‘n voertuigsuspensiestelsel ontwerp word vir die beste moontlike ritgemak, die hantering nie na wense is nie, en ook omgekeerd. Dit is veral waar vir ‘n spesifieke kategorie van voertuie, soos veldvoertuie en militêre wielvoertuie, wat oor goeie ritgemak en hantering, beide op paaie en in die veld, moet beskik. Die fokus van die huidige studie val op hierdie kategorie voertuie.

Die ritgemak en hantering van ‘n Land Rover Defender 110 veldvoertuig is ondersoek deur gebruik te maak van wiskundige modellering en veldtoetse. Die volvoertuig, nie-lineêre wiskundige model, soos ontwikkel met behulp van MSC ADAMS sagteware, is geverifieer teen eksperimentele data en goeie korrelasie is verkry. Die model is verander ten einde ‘n hidropneumatiese veer-en-demperstelsel te inkorporeer en verder gebruik om optimale veer- en demperkarakteristieke vir onderskeidelik ritgemak en hantering te verkry. Ritgemak is geoptimeer deur in ‘n reguit lyn oor ‘n rowwe veldterreinprofiel te ry, terwyl hantering geoptimeer is deur ‘n dubbelbaanveranderingsmaneuver uit te voer. Die resultaat is dat die geoptimeerde karakteristieke op die twee uiterstes van die ontwerpsgebied lê. Beste ritgemak benodig ‘n sagte suspensie terwyl beste hantering ‘n harde suspensie benodig. Daar word aangedui dat die ritgemak *vs.* hantering kompromie slegs elimineer kan word deur gebruik van ‘n aktiewe suspensiestelsel, of ‘n beheerbare suspensiestelsel wat kan skakel tussen ‘n sagte en stywe veer, asook hoë en lae demping. Dié oorskakeling moet vinnig en outomaties geskied sonder enige ingryping van die voertuigbestuurder.

‘n Prototipe **4 S**tadium **S**emi-aktiewe **S**uspensie **S**telsel ($4S_4$) is ontwerp, vervaardig, getoets en wiskundig gemodelleer. Die stelsel skakel tussen hoë en lae demping, asook tussen ‘n stywe en sagte veer binne 100 millisekondes.

‘n Beheerstrategie wat die suspensiestelsel skakel tussen die “ritgemak” en “hantering” modes is voorgestel, op ‘n toetsvoertuig geïmplementeer en evalueer tydens voertuigtoetse oor verskeie pad- en veldry toestande, asook tydens omrol- en hanteringstoetse. Die beheerstrategie is koste-effektief en maklik om te implementeer en werk besonder goed. Verbeterings in die orde van 50% kan behaal word vir beide ritgemak en hantering.

ACKNOWLEDGEMENTS

The research has been made possible through the generous support and sponsorship of the U.S. Government through its European Research Office of the U.S. Army under Contracts N68171-01-M-5852, N62558-02-M-6372 and N62558-04-P-6004.

Optimisation related investigations were performed under the auspices of the Multi-disciplinary Design Optimisation Group (MDOG) of the Department of Mechanical and Aeronautical Engineering at the University of Pretoria.

A special word of thanks to the following people who contributed in various ways to the project:

- Dr. F.B. Hoogterp and Mr. Bill Mackie, US Army Tank Automotive Command (TACOM)
- Dr. Sam Sampath – European Research Office of the US Army
- Prof. N.J. Theron and Dr. Petro Uys (University of Pretoria)
- Mr. Michael Thoresson, Mr. Werner Misselhorn, Mr. Karl Voigt, Mr. R. Bester and Mr. B.P. Uys (My dedicated post-graduate students)
- Mr Gareth Thomas from Ford Motor Company (Land Rover) South Africa
- My parents without whose continual support and motivation this project would not have been possible

Soli Deo Gloria

TABLE OF CONTENTS

LIST OF SYMBOLS

ENGLISH SYMBOLS:

A	Area [m^2]
a_y	Lateral acceleration [m/s^2]
c_v	Specific heat at constant volume [J/kg.K]
C	Damping coefficient [Ns/m]
$C_{\alpha f}$	Cornering stiffness of front tyres [N/°]
$C_{\alpha r}$	Cornering stiffness of rear tyres [N/°]
f	Fraction
f_n	Natural frequency [Hz]
g	Gravitational constant = 9.81 [m/s^2]
h_1	Distance from centre of gravity to roll axis [m]
i	Index for accumulator or valve to be used (*e.g.* i=1: small accumulator, i=2: large accumulator)
k_s	Spring stiffness [N/m]
k_t	Tyre stiffness [N/m]
$K_{\varphi f}$	Front suspension roll stiffness [N/rad]
$K_{\varphi r}$	Rear suspension roll stiffness [N/rad]
l_f	Horizontal distance from front axle to centre of gravity [m]
l_r	Horizontal distance from rear axle to centre of gravity [m]
M	Sprung mass [kg]

m	Unsprung mass or mass of gas [kg]
P	Pressure [Pa]
P_{accui}	Pressure in accumulator i [Pa]
P_{begin}	Pressure before valve opens [MPa]
P_{end}	Pressure after valve is fully open [MPa]
p	Steering Factor
P_1	Pressure in small accumulator [Pa]
P_2	Main strut pressure [Pa]
P_3	Pressure between valve 2 and valves 3 and 4 [Pa]
P_4	Pressure in large accumulator [Pa]
q	Flow rate [m^3/s]
R	Universal gas constant [J/kg.K]
T	Temperature [K]
V	Volt [V]
V	Volume [m^3]
V_1	Valve 1 – damper bypass valve on small accumulator
V_2	Valve 2 – damper bypass valve on large accumulator
V_3	Valve 3 – Spring valve
V_4	Valve 4 – Spring valve
v	Specific volume [m^3/kg]
W	Vehicle weight [N]
W_b	British Standard BS 6841 vertical acceleration filter
W_f	British Standard BS 6841 motion sickness filter
x	Relative suspension displacement [m]
$\dot{x}$	Relative suspension velocity [m/s]
Y_e	Lateral position error [m]

GREEK SYMBOLS:

φ	Roll angle [rad]
β	Bulk modulus of fluid [Pa]
Δ	Difference
τ	Thermal time constant [s]
ω	Circular frequency [rad/s]

LIST OF ABBREVIATIONS

A

AAP	Average Absorbed Power
ABC	Active Body Control (Mercedes Benz)
ABS	Antilock Braking System
ADAMS	Automatic Dynamic Analysis of Mechanical Systems (Computer software)
ADC	Adaptive Damping Control
ADD	Acceleration Driven Damper
APG	Aberdeen Proving Ground
ARC	Active Roll Control
AWD	All Wheel Drive

B

BS	British Standard
BWR	Benedict-Webb-Rubin

C

CATS	Computer Active Technology Suspension (Jaguar)
CAN	Controller Area Network
cg	Centre of gravity
CDC	Continuous Damping Control (Opel)

CUV Crossover Utility Vehicle

CVRSS Continuously Variable Road Sensing Suspension (Cadillac)

D

DADS Dynamic Analysis and Design System (Computer software)

DC Direct Current

DFT Discrete Fourier Transform

DHS Dynamic Handling System

DIO Digital Input Output

DRC Dynamic Ride Control (Audi)

DSP Digital Signal Processor

DWT Draw Wire Transducer

E

EAS Electronic Air Suspension (Volkswagen / Continental)

ECS Electronic Controlled Suspension (Mitsubishi)

ER Electro-Rheological

ERM Electro-Rheological Magnetic

F

FFT Fast Fourier Transform

Four-C Continuously Controllable Chassis Concept (Volvo)

G

GA Genetic Algorithm

GM General Motors

GPS Global Positioning System

H

HiL	Hardware-in-the-loop
HMMWV	High Mobility Multi-purpose Wheeled Vehicle
HP	Horse Power
HVOF	High Velocity Oxygen Fuel

I

ICS	In Cylinder Sensor
ISO	International Standards Organization

L

LDV	Light Delivery Vehicle
LQO	Linear Quadratic Optimal
LVDT	Linear Variable Differential Transformer

M

MISO	Multiple Input Single Output
MM	Mini Module
MP	Minimum Product
MR	Magneto-Rheological
MTTB	Mobility Technology Test Bed

N

N	Number of points
NAND	Inverted AND gate
NATO	North Atlantic Treaty Organisation
NHTSA	National Highway Traffic Safety Administration (USA)

NRMM	NATO Reference Mobility Model

P

PC	Personal Computer
PD	Proportional Derivative
PID	Proportional Integral Derivative
PSD	Power Spectral Density

R

ReS	Control strategy proposed by Rakheja and Sankar
RMS	Root Mean Square
RRMS	Running Root Mean Square

S

SSF	Static Stability Factor
SSRT	Steady State Rollover Threshold
SUV	Sports Utility Vehicle
SVFB	State Variable FeedBack

T

TACOM	Tank-automotive and Armaments Command of the US Army
TARDEC	Tank-Automotive Research, Development and Engineering Center of the US Army
TRW	Automotive Component Manufacturer

U

USB	Universal Serial Bus

V

VDI	Verein Deutscher Ingenieure (Association of German Engineers)
VDV	Vibration Dose Value
VW	Volkswagen

Z

ZF	German component manufacturer

Other

$4S_4$	4 State Semi-active Suspension System
2WS	Two wheel steer
4WS	Four wheel steer

LIST OF FIGURES

CHAPTER 1 – INTRODUCTION

CHAPTER 2 – THE RIDE COMFORT *VS.* HANDLING COMPROMISE

CHAPTER 4 – THE FOUR-STATE SEMI-ACTIVE SUSPENSION SYSTEM ($4S_4$)

CHAPTER 5 – THE RIDE COMFORT *VS.* HANDLING DECISION

CHAPTER 6 – VEHICLE IMPLEMENTATION

APPENDIX A: HANDLING CRITERIA

LIST OF TABLES

CHAPTER 1 – INTRODUCTION

CHAPTER 2 – THE RIDE COMFORT *VS.* HANDLING COMPROMISE

CHAPTER 3 – POSSIBLE SOLUTIONS TO THE RIDE COMFORT *VS.* HANDLING COMPROMISE

CHAPTER 4 – THE FOUR-STATE SEMI-ACTIVE SUSPENSION SYSTEM ($4S_4$)

CHAPTER 5 – THE RIDE COMFORT *VS.* HANDLING DECISION

CHAPTER 6 – VEHICLE IMPLEMENTATION