

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

by

PIETER SCHALK ELS

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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 State Semi-active Suspension System (4S₄)** 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
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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-linéêre 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 ontwerpgebied 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 Stadium Semi-aktiewe Suspensie Stelsel (4S₄) 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.

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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 [$N/^\circ$]
$C_{\alpha r}$	Cornering stiffness of rear tyres [$N/^\circ$]
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 (<i>e.g.</i> $i=1$: small accumulator, $i=2$: large accumulator)
k_s	Spring stiffness [N/m]
k_t	Tyre stiffness [N/m]
$K_{\phi f}$	Front suspension roll stiffness [N/rad]
$K_{\phi r}$	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

4S₄ 4 State Semi-active Suspension System

2WS Two wheel steer

4WS Four wheel steer

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